Architectural Requirements for Supply Chain Management (SCM) Systems in a Circular Economy

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ABSTRACT

Global transition toward circular economy (CE) has fundamentally changed the operation requirements of Supply Chain Management (SCM) systems and the architecture requirements to enable such transition are still largely under-explored. The traditional SCM structure is fundamentally unsuitable to deal with the bidirectional logistics, multi-lifecycles use of resources, and multi-stakeholder collaboration that circular logistics require. Although there are a number of studies that have focused on a single enabling technology like Blockchain, the Internet of Things (IoT), Building Information Modelling (BIM), and Artificial Intelligence (AI), a comprehensive integrated architectural framework that covers the technical, organizational and governance aspects have not yet been developed. The purpose of this study is thus to identify and validate the fundamental architectural needs for SCM systems to fulfill the principles of the circular economy. By applying a Model-Based Systems Engineering (MBSE) methodology, the research consolidates 102 peer-reviewed papers found in Scopus, IEEE Xplore, SpringerLink and ScienceDirect that were relevant to Industry 4.0, digital construction and sustainable logistics between 2016 and 2025. Each requirement identified is confirmed through structured requirement, structured block definition, and structured activity diagrams through mapping to the literature that has been used as a source for the requirement and to the architectural components that support it. These core, interdependent needs traceability and provenance, lifecycle visibility and resource reuse, interoperability and standards, and security and trust are identified in the analysis and integrated solutions, as opposed to individual solutions, are required to achieve operational benefits. The study moves away from the focus on individual technologies and offers a conceptual blueprint for designing resilient, transparent, and sustainable circular supply chain systems; it recognizes that the framework is conceptually rather than empirically validated.

Keywords: Circular Economy, Supply Chain Management, Architectural Frameworks, Internet of Things (IoT), Building Information Modelling (BIM)

INTRODUCTION

The success of Industry 4.0 has revolutionized the production and logistics worldwide. One of the key principles of the transition from the “take-make-dispose” economic model to the Circular Economy (CE): resource efficiency, waste minimization and continuous material recirculation (Alhamami et al., 2018; Erbel et al., 2020; Geissdoerfer et al., 2018).

Traditional Supply Chain Management (SCM) deals with the management of a series of activities across an organization to ensure that all activities are optimized to achieve the very best procurement benefits, performance and customer satisfaction. The traditional SCM designs, however, use one-way linear processes that are not suitable for reverse logistics and to reuse resources in a circular economy (Khedr & Sheeja, 2024). While there may be some inaccuracies in systems that are so fragmented, those inaccuracies are going to be passed down the supply chain network leading to high end-user risks (Radivojevic et al., 2022) and further contributing to the construction and industrial waste streams (Alhamami et al., 2018; Toland & Collery, 2023).

In addition, the idea of SCM needs to be reconsidered, and SCM should be “smart” systems, not only controlling the movement of products to the final consumer, but also the reverse process of product recycling, refurbishment,

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and deconstruction (Ali & Badinelli, 2016; Erbel et al., 2020). CSCM, which comprises of five key circular strategies, translates them into practice: Closing the cycles through recycling; slowing the cycles through refurbishment or remanufacturing; intensifying the cycles through maximized usage; narrowing the cycles through minimised utilization of resources; and dematerializing the cycles through service substitution (Farooque et al., 2019; Geissdoerfer et al., 2018). Circular SCM systems, unlike linear SCM systems, are required to address the characteristics of multi-lifecycle and understated flow of material in the circular systems involving product, component and raw materials in various stages of life cycles (Rangga Primadasa et al., 2024). The bi-directionality poses multiple challenges to system architects to verify several requirements in different communication patterns and multi-level simulation processes (Erbel et al., 2020).

While the principles of CE have interest in both academia and industry, there are still gaps in the knowledge of how to operationalize the principles of CSCM at the system architecture level. The implementation of the circular economy (CE) is facing a number of cultural, technological, policy, knowledge and market barriers (Wang et al., 2020). One of the latest systematic reviews also reveal knowledge gaps and constraints in the existing knowledge on the digitalization of processes, specifically on handling return flows with a large number of relevant actors (Taddei et al., 2024). Reverse logistics, products' return with different attributes, and logistics complexity are among the most complex parts of moving towards circular value-preserving models (Perau et al., 2025). Farooque et al (2019) however noted that there was a gap in the literature in regard to the use of enabling technologies in CSCM, which is a focus of this study.

Past research revealed the potential of each technology but there is a need for evidence linking the convergence of the technologies (IoT, BIM, Blockchain and AI) to an integrated architectural framework with a technical, organisational and legal dimension. The aim of this study is to identify, validate and investigate the key design principles that can help on how linear supply chain systems can be transformed into resilient, transparent and sustainable circular supply chains, through the Application of Model Based Systems Engineering (MBSE) methodology and a systematic review of 102 peer reviewed sources. The lessons learnt can be applied by system architects, actors in the supply chain and policy makers to scale-up the concepts of circular economy into actual operations.

LITERATURE REVIEW: ENABLING TECHNOLOGIES AND ARCHITECTURAL REQUIREMENTS

It is necessary to rethink technology infrastructure to implement circular supply chain architectures. But traditional SCM systems are not applicable on the circular economy systems due to the complexity of the bidirectional flow on the system. The present review is categorized in three thematic pillars, (1) enabling technologies like IoT, BIM, Blockchain and AI, (2) base architectural requirements for circular SCM and (3) research gaps and implementation challenges inspiring this research.

Enabling Technologies for Circular Supply Chain Management

Iot and Cyber-Physical Systems

The IoT, which is the sensory layer of smart systems in the modern SCM systems, is a combination of physical and virtual space, where devices and smart sensors are connected to one another, providing a connectivity between physical space and virtual space (Sundmaeker et al., 2016). Through SCM, IoT can be applied to assets to track them in real time by using RFID and NFC and to monitor the performance of the asset and can be used to create smart construction objects (SCs) that help the flow of information over the asset's life cycle (Banerjee & Nayaka, 2022). In circular supply chains in particular, IoT can help to gather detailed information about the product like its condition, location and usage, all of which are crucial for making decisions on the best end-of-life solution, including refurbishment, remanufacturing or recycling (Dave et al., 2016). In the case of public sector or industrial applications that have complicated requirements, there exists a need for scalable IoT architecture frameworks (Das et al., 2023). But, interoperability among devices, standardization of data, and the energy usage of the sensor networks are still unsolved issues which are able to jeopardise sustainability goals if not properly managed.

Edge computing architectures are also crucial for integrating IoT into circular supply chains, as they handle data from sensors more near the source than just in the cloud. Further, the use of edge computing further reduces the bandwidth consumption and latency of the circular material tracking system, supporting capacities to make informed decisions about product recovery at end-of-life stages in real time. Besides, the LPWAN (low power wide area network) technologies such as LoRaWAN and NB-IoT also offer the opportunity of using sensor networks in scenarios where current networks are not available in industry. The developments cover a wide range of possibilities for implementing IoT on sites other than manufacturing where it has traditionally been the target for digitization of circular supply chains, such as management and recovery of construction waste and recovery of waste from agricultural processes (Dave et al., 2016; Das et al., 2023).

Building Information Modelling and Digital Twins

Building Information Modelling (BIM) has evolved from the 3D design world to the whole asset lifecycle management system for infrastructure and products. BIM-based IoT architecture systems have demonstrated capabilities for structural performance assessment, predictive facility maintenance and creation of digital twins to reduce rework and improve decision making for the management of ageing infrastructure (Robertshaw et al., 2023). Moreover, BIM is considered as a critical element for sustainability targets in terms of material environments and suppliers nears (Alhamami et al., 2018). Importantly, BIM systems capable of integration with look-ahead planning have been proven to be facilitating reduction of material flow process duration by 16.1% (Chen et al., 2020), which is directly applicable from the circular material operations, where time of material is critical during the process. Beyond the original design, the use of BIM can help to record the materials and assemblies for the entire life cycle thoroughly, and also support the decision-making process at the end of life, such as resource recovery, including material passports to follow circular design principles (Ali & Badinelli, 2016). However, the adoption of BIM faces certain challenges including, implementation cost, lack of interoperability standards and the prevailing digital skills gap (Alhamami et al., 2018).

This is a great advancement of BIM and Digital twin synergy in lifecycle visibility. However, BIM distinctions do not end there: a digital twin can continuously collect real-time data and simulate the course of structural decay over time and schedule maintenance tasks, unlike traditional BIM models (Robertshaw et al., 2023). For circular construction scenarios such materials can directly contribute to the design-for-disassembly approach: The project team can have a continuous digital record of the condition of each material throughout the life of the project, which enables them to plan for selective deconstruction and not destruction at the end-of-life, thereby enabling the recovery of higher value materials. Alhamani et al. (2018) also suggest that the implementation of sustainability performance indicators in BIM models helps project stakeholders to consider materials in view of the circular economy benchmarks in the design phase, moving the consideration of circular economy to the upstream of the project, not as an afterthought once the project is already built.

Blockchain and Decentralized Trust Mechanisms

One of the major issues with global supply chains is the lack of transparency, which blockchain technology can help remedy by offering a decentralized trust system. It facilitates the tracking and authentication of product origins and adherence to regulations throughout various production phases, helping organizations establish the traceability and security of their products. It ensures the traceability and security of the product, making it easier for organizations to prove its source and conformity to requirements at different stages of the production process (Salzano et al., 2024). Circular supply chains (CSCs) are of special importance in the context of blockchain, as it is essential to build trust in material qualities and origin for the functioning of secondary markets (Saberi et al., 2020). Shared business logic can be achieved through frameworks like Hyperledger Fabric and R3 Corda, which allows for an equitable multi-stakeholder collaboration (Solanki et al., 2025). Smart contracts and PKI also assist in further automating procedure streams in various industries (Azevedo et al., 2023). In spite of this, the engineering costs, scalability issues, and stakeholder resistance to the adoption of decentralized transparency models are still significant barriers (Taddei et al., 2024). The energy consumption of proof-of-work consensus mechanisms also poses sustainability concerns, but newer proof-of-stake methods hold potential.

In addition to providing traceability of transactions, blockchain can be used in circular SCM to facilitate the automation of compliance verification via smart contracts. Smart contracts can automatically initiate actions in the downstream processes, such as releasing payments, allocating recycling facilities, or issuing customs clearance documents, when pre-defined conditions are met (Azevedo et al., 2023). This automation helps to eliminate administrative friction in multi-party circular loops and minimize the chances of fraudulent compliance reporting. In secondary raw material markets, where the adopters are wary of paying a premium price for recycled material without quality assurance information, blockchain-based provenance information has shown it can help overcome the lack of trust between material producers and industrial buyers, thus raising the demand for recycled material and increasing the economic feasibility of reverse logistics operations (Saberi et al., 2020; Solanki et al., 2025).

Artificial Intelligence and Advanced Analytics

The functions of SCM that can directly benefit the objectives of circular economy are gaining importance in the use of AI and deep learning, such as automated quality assessment, predictive maintenance and optimal pathways for material recovery through intelligent sorting (Baskaran & Nguyen, 2025). AI also plays a pivotal role in circular scenarios, addressing the uncertainty that exists in reverse logistics, where the condition, quality, and timing of returns are notoriously unpredictable. AI is also combined with Intent Based Networking (IBN) to support large, heterogeneous ICT supply chains by converting high-level requirements into dynamic access control policies (Amiri, 2025; Gupta, 2025). One challenge, however, is that the efficacy of the AI systems is strongly reliant on the quality of the training data; the less data available, the less effective the system will be, especially when considering that there is limited historical data on product returns and material recovery in developing circular supply chains.

The relevance of reinforcement learning and generative AI in circular SCM goes beyond the quality classification. Predictive recirculation models, developed using information from the sensors, maintenance systems, and market demand data, will be able to predict the optimal redeployment time for each component, reducing the idle time of recovered components in reverse logistics holding facilities. SCM systems with the help of AI technology can significantly enhance the accuracy of forecasting and optimisation of resource allocation especially in the context of circular economy, where the variability in returns adds to the demand uncertainty. (Chen et al., 2020). Furthermore, AI-powered dynamic routing algorithms can optimize reverse logistics networks on the fly with changing product return flows, minimizing transportation costs and carbon emissions from inefficient reverse logistics directly addressing the carbon reduction needs of the circular economy (Khedr & Sheeja, 2024; Baskaran & Nguyen, 2025).

Core Architectural Requirements for Circular Supply Chain Management

The real benefit of the technologies mentioned above is when they are combined in a coherent architectural context. The three key elements that support circular SCM systems are traceability and transparency, orchestration and coordination, and data ecosystems and interoperability.

Traceability and Transparency through Blockchain and Digital Product Passports

Traceability, which means tracking materials and products throughout their entire life cycle – is the foundation of circular SCM. The consensus of the researchers, including Azevedo et al. (2023), is that Blockchain is a key enabler, as it helps to improve the information symmetry among the stakeholders involved in the product lifecycle (manufacturers, logistics providers, recyclers, and auditors), and enhance the verification of product authenticity. With the introduction of Digital Product Passports (DPPs), circular economy considerations are now being integrated into lifecycle management and information regarding the materials and components are being recorded throughout multiple lifecycles, making it a part of the modern architectural design. Immutable records of provenance, quality certifications and histories of transformation can be added to DPPs, which allow decisions to be made on re-use and recycling at each lifecycle stage (Salzano et al., 2024). The real-time tracking comes from the integration of RFID and NFC components, and decentralized ledger frameworks enable the management of shared business logic without a central authority (Solanki et al., 2025). Therefore, architects' need for traceability can be presented as a two-fold demand: one that is physical (RFID, NFC, environmental sensors) and one that is digital (Distributed ledgers, smart contracts, cryptographic hashing).

Implementing DPPs is a governance challenge and provides architectural opportunities. In terms of opportunities, DPPs can serve as long-term, digital representations of individual parts, which continue to link to ownership changes and transformation throughout the product lifecycle. For sectors like aviation, construction, and electronics where the provenance of the parts is specified by regulation, the verification infrastructure that DPPs offer can back up circularity claims to regulators, insurers and end customers alike. Governance is also fragmented by industry with the need for cross-industry coordination considered an important factor in resolving issues of data ownership and access rights and cost-sharing among supply chain participants, which technical architecture alone cannot provide (Salzano et al., 2024; Taddei et al., 2024). Architectural design, therefore, needs to include governance structures, as well as technical aspects, and need to ensure that DPP schemas are interoperable between sectors, while the costs associated with maintaining digital provenance records are shared equitably between the stakeholders who benefit from their use.

Orchestration and Coordination via Supply Chain Control Towers

SCM systems need to be able to orchestrate complexly to deal with the dynamism of the circular flows. Supply Chain Control Towers (SCCTs) are integrated platforms that offer visibility and coordination throughout complex supply chains. SCCTs are coupled with the latest analytics and use them as orchestration mechanisms to increase the visibility and responsiveness of forward and reverse logistics processes (Baskaran & Nguyen, 2025). SCCTs are particularly important in circular contexts as they involve the bi-directional and non-linear nature of material flows products can re-enter the supply chain at different stages depending on condition and recovery infrastructure. The architectural challenge is to design flexible interfaces that are able to aggregate data from different streams and have data sovereignty and competitive sensitivities for several players such as manufacturers, logistics providers, recycling facilities, refurbishment centres and regulatory authorities. In medical device logistics, RFID integration has proven to be effective in reducing processing times by 75% (Baskaran & Nguyen, 2025).

As SCCTs become more AI-augmented, they offer greater benefit in a circular supply chain. Modern SCCTs can also evolve from reactive exception management to scenario planning, using machine learning models that continually learn from past disruption patterns and can predict bottlenecks in reverse logistics. Predictive models incorporated into an SCCT, for example, can be used to detect early warning signs of pressure on capacity at refurbishment centres, and automatically divert returned products to other recovery centers, ensuring material quality and reducing lead times. Khedr and Sheeja (2024) state that the application of deep learning architectures to data from SCM can greatly enhance supply chain resilience as it enables adaptive responses to demand volatility, which is particularly important in circular systems where the condition of the returned goods adds another layer of complexity and uncertainty on top of the variability of demand. These developments enable SCCTs to be more than a visibility instrument, but to also play an active role in orchestrating circular material flows.

Data Ecosystems and Interoperability

Data ecosystems are essential for circular supply chains, where they play a crucial role in handling a wide range of data, such as product specifications, usage data, maintenance histories, and end-of-life conditions. One of the biggest challenges is the lack of standardization in data exchange protocols, making it difficult to track materials effectively across various stages of design, construction, and operation (Banerjee & Nayaka, 2022). To this end, an open network-model approach to data control is required, which offers a single point for data sovereignty management across multiple relationships, instead of hub-model architectures that create a bottleneck and single point of failure (SPF) (Sundmaeker et al., 2016). The architectural designs need to be compatible with automatic model checking according to standards like building SMART's mvdXML 1.1, so that stakeholders will provide compatible data at the right moment during the architectural design process. The transition from hub-models to network-models promotes data sovereignty for organizations, thus giving them control over sensitive business data and the possibility to join collaborative circular ventures (Salzano et al., 2024). As a result of data flows being multi-organizational, security is an intrinsic architectural issue, which necessitates the use of cryptographic mechanisms and AI-based access control systems.

However, semantic alignment (not only syntactic) between the various data models of the actors is also necessary for true interoperability in circular SCM. For instance, if a temperature sensor is deployed on a reusable container, it can communicate using MQTT, a warehouse management system can expose REST APIs, and a blockchain ledger can use gRPC; without a shared semantic layer (achieved through ontologies like the Web Ontology Language (OWL) or the Sensor Things API), data becomes machine-unreadable across system boundaries (Banerjee & Nayaka, 2022; Sundmaeker et al., 2016). Open-source middleware frameworks and sector-specific ontologies are therefore not just enhancements but essential architectural elements. Moreover, interoperability gaps in data can introduce systemic risk, raising the likelihood of cascading errors in multi-tier supply chains, as highlighted by Radivojevic et al. (2022). In addition to the technical architectural solutions identified above, these gaps need to be closed through a coordinated effort with industry consortia and regulatory bodies to invest in shared reference ontologies and API standardization projects.

Research Gaps and Implementation Challenges

Although more and more literature has been written on each technology, there is still a lack of understanding on how to operationalize these in integrated architectural systems. Existing research is mostly centered on specific technologies/technical aspects or specific circular processes (e.g., blockchain for traceability or IoT for monitoring) without taking into account a comprehensive framework that addresses fundamental architectural needs across technical, organizational and legal aspects (Farooque et al., 2019; Taddei et al., 2024). An approach that considers technologies one by one is not particularly useful to the systems architect's problem of designing end-to-end circular SCM systems.

These knowledge gaps are compounded by a number of implementation barriers. The engineering expenses become high, posing financial challenges especially for small and medium enterprises (Solanki et al., 2025). A culture of adversarial relationships and risk avoidance is seen keenly in construction and manufacturing and is hampering the sharing of information that is needed to enable circular loops to occur (Toland & Collery, 2023). Stakeholders' hesitation to engage with decentralized transparency measures is due to concerns regarding competitive intelligence and lack of perceived immediate value (Taddei et al., 2024). Last, yet not least, there is a significant gap between the expectation of the industry and the educational programmes with regard to BIM applications for energy efficiency and sustainability strategies (Alhamami et al., 2018).

The aim of this study is to answer the previous ones and explore the convergence of the enabling technologies (IoT, BIM, Blockchain, and AI) under an integrated architectural framework. This study uses MBSE and systematic literature analysis to uncover key principles in design that can help realize the theoretical vision for high-end supply chains of resilient, transparent, and sustainable circular supply chains in practice.

METHODOLOGY

Research Design

This study employs a Systematic Literature Review (SLR) integrated with a Model-Based Systems Engineering (MBSE) analytical framework to identify, analyse, and validate the architectural requirements of Supply Chain Management (SCM) systems operating within a Circular Economy (CE) environment. The research adopts a qualitative-interpretivist epistemology, where knowledge is understood as being constructed through the synthesis and interpretation of scholarly discourse rather than through direct measurement of observable phenomena. This epistemological position is appropriate for architectural requirement research because the objective is not to evaluate a single implemented system, but rather to determine the structural and functional conditions necessary for circular SCM systems to operate effectively (Amiri, 2025; Kizgin & Vietor, 2025).

The central research problem addressed in this study is the architectural mismatch between traditional linear SCM systems and the bidirectional, multi-stakeholder operational requirements of circular economies (Farooque et al., 2019). Conventional SCM architectures are primarily designed for forward logistics optimisation, whereas circular systems require integrated support for reverse logistics, lifecycle visibility, traceability, interoperability, and distributed stakeholder coordination. Addressing this complexity requires a methodology capable of modelling interdependent system behaviours, interfaces, and constraints in a coherent and traceable manner.

MBSE was therefore selected as the primary analytical framework because it provides a model-centric approach for representing system structure, behaviour, requirements, and interactions within an integrated environment (Amiri, 2025). Unlike document-centric methodologies, MBSE supports continuous traceability between identified requirements and their associated architectural components, enabling validation and refinement across multiple abstraction layers. This capability is particularly important in circular SCM contexts, where operational effectiveness depends heavily on the interaction between digital technologies, organisational actors, and lifecycle management processes.

Several alternative research design approaches were evaluated before selecting the SLR-MBSE strategy adopted in this study. Table 3.1 summarises the comparative strengths, limitations, and suitability of the major approaches considered.

Table 3.1: Comparison of Research Design Approaches Considered

Design Approach	Strengths	Limitations	Suitability for This Study
Systematic Literature Review (SLR)	Reproducible; covers broad evidence base	No primary data collection	HIGH – selected
Case Study	Rich contextual data	Limited generalisation	MEDIUM
Survey/Questionnaire	Quantifiable responses	Requires defined population	LOW – architectural scope is conceptual
Experiment / Simulation	Causal inference	Requires working prototype	LOW – no implementation stage

Source: Authors' adaptation based on Bryman (2016) and Amiri (2025).

The comparison demonstrates that while case studies and surveys provide contextual or quantitative insights, they are less suitable for investigating broad architectural requirements spanning multiple technologies and industrial domains. Similarly, experimental approaches require implemented prototypes, which fall outside the conceptual scope of this research. In contrast, the SLR approach enables systematic synthesis across a large body of interdisciplinary literature, making it more appropriate for identifying recurring architectural patterns, technological relationships, and system-level requirements relevant to circular SCM environments.

Sample and Sampling Strategy

Within a systematic literature review, the research sample consists of the body of scholarly publications selected for analysis. This study adopted a purposive sampling strategy guided by predefined inclusion and exclusion criteria to ensure topical relevance, methodological consistency, and academic quality (Tranfield et al., 2003). The sampling strategy was designed to capture literature situated at the intersection of circular economy research, digital supply chain technologies, and systems engineering methodologies.

Inclusion Criteria

Studies were included if they (a) were published in peer-reviewed journals or conference proceedings indexed in Scopus, IEEE Xplore, SpringerLink, or ScienceDirect; (b) were published between 2016 and 2025 to reflect the contemporary Industry 4.0 landscape; (c) addressed at least one of the following topics: circular supply chain management, IoT/BIM/Blockchain/AI in logistics, MBSE for supply chain systems, reverse logistics architecture, or digital product passports; and (d) were written in English.

Exclusion Criteria

Studies were excluded if they were (a) non-peer-reviewed grey literature, practitioner reports, or news articles; (b) focused exclusively on sectors outside the scope of this study (e.g., purely financial or healthcare systems with no supply chain dimension); or (c) duplicates of already included sources.

Sampling Outcome

Application of the inclusion and exclusion criteria resulted in a final corpus of 102 scholarly sources spanning five major technology domains. Table 3.2 presents the distribution of selected studies across publication periods and technology categories.

Table 3.2: Sample Distribution by Technology Domain and Publication Period

Technology Domain	2016–2019	2020–2022	2023–2025	Total
IoT & Cyber-Physical Systems	8	9	6	23
BIM & Digital Twins	7	8	7	22
Blockchain & Decentralised Trust	4	8	10	22
Artificial Intelligence & Analytics	3	6	9	18
MBSE & Systems Engineering	2	5	10	17
Total	**24**	**36**	**42**	**102**

Source: Authors' compilation from Scopus, IEEE Xplore, SpringerLink, and ScienceDirect (2016–2025).

The distribution reflects a clear evolution in circular SCM research. Early literature (2016–2019) is dominated by IoT and BIM studies, focusing on sensing and lifecycle modelling. The period from 2020–2022 shows diversification into blockchain and AI, indicating a shift toward decentralised trust and predictive analytics. The most recent period (2023–2025) shows a marked increase in MBSE-related work, suggesting growing emphasis on integrated system architecture rather than isolated technological solutions.

Research Instrument

Because this study employs a SLR rather than primary data collection, the research instrument is the thematic coding framework and the MBSE requirement traceability matrix. These instruments structure the extraction and analysis of data from the sampled literature, fulfilling the same function that a questionnaire or interview guide would serve in primary research (Kitchenham & Charters, 2007).

Thematic Coding Framework

Following the axial coding procedure described by Strauss and Corbin (1998), each source was coded against four predefined architectural dimensions: (1) traceability and provenance mechanisms, (2) lifecycle visibility and resource reuse enablers, (3) interoperability and standards requirements, and (4) security and trust mechanisms. These dimensions were derived deductively from the research questions posed in Chapter I and inductively refined through an initial pilot review of twenty sources. Each coded passage was further tagged by enabling technology (IoT, BIM, Blockchain, AI), system layer (sensing, decision, collaborative, transparency), and evidence type (empirical, conceptual, or case-study).

MBSE Requirement Traceability Matrix

A requirement traceability matrix (RTM) was constructed using SysML notation concepts to map each identified requirement to its literature source, the system function it enables, and the architectural component it constrains. This instrument ensures that the architectural requirements presented later on are not ad hoc assertions but traceable propositions grounded in the reviewed evidence. Table 3.3 presents a representative excerpt of the RTM.

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Table 3.3: Excerpt from the MBSE Requirement Traceability Matrix

Requirement ID	Requirement Statement	Source(s)	System Layer	SysML Diagram Type
REQ-TR-01	The system shall record every material custody transfer on an immutable distributed ledger	Azevedo et al. (2023); Salzano et al. (2024)	Transparency	Activity / BDD
REQ-TR-02	The system shall use RFID/NFC to capture real-time asset location and condition data	Baskaran & Nguyen (2025); Sundmaeker et al. (2016)	Sensing	Activity / IBD
REQ-LV-01	The system shall maintain a digital material passport for every tracked asset	Alhamami et al. (2018); Banerjee & Nayaka (2022)	Collaborative	BDD / Parametric
REQ-IO-01	The system shall support IFC and mvdXML for BIM data exchange	Banerjee & Nayaka (2022); Alhamami et al. (2018)	Collaborative	Interface / Sequence
REQ-SE-01	The system shall enforce TLS encryption for all inter-node communications	Sapra et al. (2022); Solanki et al. (2025)	Security	Requirement / Activity

BDD = Block Definition Diagram; IBD = Internal Block Diagram; TLS = Transport Layer Security.

Data Collection Procedure

Data collection proceeded in three sequential stages, consistent with the SLR protocol described by Tranfield et al. (2003) and the MBSE integration approach advocated by Amiri (2025).

Stage 1 – Database Search and Record Retrieval

Systematic searches were executed across Scopus, IEEE Xplore, SpringerLink, and ScienceDirect using twelve keyword combinations, including “circular supply chain architecture”, “MBSE supply chain”, “blockchain traceability circular economy”, “digital twin lifecycle management”, “IoT reverse logistics”, and “BIM circular construction”. Boolean operators (AND/OR) were used to broaden or narrow result sets. A total of 618 records were retrieved in the initial search.

Stage 2 – Screening and Eligibility Assessment

Retrieved records were screened in two sub-stages. First, title and abstract screening removed 387 records that were off-topic, duplicates, or non-peer-reviewed, leaving 231 candidates. Second, full-text assessment of these 231 papers against the inclusion/exclusion criteria retained 102 sources for final analysis. Inter-rater reliability was maintained through a double-blind review of a random 20% sub-sample by two independent researchers, achieving a Cohen’s kappa of 0.81, indicating strong agreement (Landis & Koch, 1977).

Stage 3 – Data Extraction and Coding

For each retained source, a standardised data extraction form was completed, capturing: bibliographic details, study context, enabling technologies discussed, architectural requirements identified, key findings, and limitations. Extracted data were then coded using the thematic coding framework (Section 3.3.1) and mapped to the MBSE RTM (Section 3.3.2). NVivo 14 was used to support coding consistency and pattern identification across the 102 sources.

Table 3.4: Data Collection Timeline and Activities

Phase	Activity	Duration	Output
1 – Protocol Design	Define RQs, inclusion/exclusion criteria, coding framework, RTM template	2 weeks	SLR protocol document
2 – Database Search	Execute searches; export records; deduplicate	1 week	618 records (deduplicated: 487)
3 – Title/Abstract Screen	Apply inclusion/exclusion; exclude off-topic records	2 weeks	231 candidates
4 – Full-Text Review	Read full papers; apply eligibility criteria; inter-rater check	3 weeks	102 final sources
5 – Data Extraction & Coding	Complete extraction forms; axial coding; RTM population	3 weeks	Coded dataset; RTM
6 – Synthesis & Validation	Thematic synthesis; MBSE mapping; cross-check with Chapters I & V	2 weeks	Chapter III & IV draft

Thematic Synthesis and MBSE Integration

The thematic synthesis stage employed qualitative axial coding to categorise enabling technologies into four architectural domains (Table 3.5) as discussed previously. This classification supports MBSE requirement structuring by mapping technological capabilities directly to system functions within circular SCM architectures (Amiri, 2025; Kizgin & Vietor, 2025).

Table 3.5: Technology Classification by Architectural Domain

Architectural Domain	Technologies Classified	System Function	Key Sources
Data Collection	IoT, RFID, NFC, Environmental Sensors	Real-time asset sensing and location tracking	Sundmaeker et al. (2016); Baskaran & Nguyen (2025)
Decision-Oriented	AI, Machine Learning, Predictive Analytics	Adaptive planning and lifecycle forecasting	Chen et al. (2020); Gupta (2025)
Collaborative	BIM, Digital Twins, Digital Product Passports	Lifecycle coordination and multi-stakeholder integration	Alhamami et al. (2018); Banerjee & Nayaka (2022)
Transparency	Blockchain, Smart Contracts, Decentralised Ledgers	Trust generation and provenance assurance	Azevedo et al. (2023); Salzano et al. (2024)

The integration of MBSE with the SLR ensures methodological triangulation, strengthening both theoretical validity and practical applicability. MBSE provides the structural modelling framework that defines system architecture, while the SLR provides empirical grounding from existing technological and theoretical literature. Together, these approaches form a hybrid analytical framework that ensures both system-level rigor and domain-specific relevance. The following chapter, Chapter IV, applies this methodological foundation to derive and articulate the four core architectural requirements.

Validity, Reliability, and Ethical Considerations

Internal Validity

Internal validity is strengthened through the RTM, which ensures every requirement is traceable to its evidentiary source. The double-blind inter-rater reliability check (Cohen's $\kappa = 0.81$) further reduces subjective coding bias (Landis & Koch, 1977). Cross-referencing findings with Chapter V's discussion of operational outcomes provides additional confirmation that the identified requirements align with reported empirical effects.

External Validity

The purposive sample covers multiple industry sectors (construction, manufacturing, logistics, agriculture, healthcare) and four enabling technology domains, enhancing the generalisability of the architectural framework beyond any single industry. As noted in Chapter VI, the evidence base is nevertheless weighted toward construction and manufacturing, which is a limitation acknowledged for future research.

Reliability

Reliability is addressed through the detailed SLR protocol (Section 3.4), which specifies reproducible search strings, database sources, and screening criteria. A secondary researcher independently replicated Stage 1 and Stage 2 on a 20% sub-sample, achieving consistent results. The standardised data extraction form further ensures that information retrieval is uniform across sources.

Ethical Considerations

This study analyses publicly available peer-reviewed literature and does not involve human participants, animal subjects, or sensitive personal data. All sources are fully cited, and no data fabrication, falsification, or plagiarism has occurred. The research complies with standard academic integrity requirements.

Core Architectural Requirements

The transition from linear to circular supply chain management necessitates a fundamental rearchitecting of information systems. As established in Chapter I, traditional linear models are increasingly inadequate for managing the complexities of resource reuse, bidirectional inventory flows, and multi-stakeholder collaboration (Farooque et al., 2019; Geissdoerfer et al., 2018).

Drawing on the SLR corpus of 102 sources and structured through the MBSE framework, this chapter establishes four core architectural requirements: (1) Traceability and Provenance; (2) Lifecycle Visibility and Resource Reuse; (3) Interoperability and Standards; and (4) Security and Trust. Each section presents the conceptual foundation, supporting evidence, a visual mapping, and an MBSE traceability reference. Section 4.5 presents an integrated synthesis.

Figure 4.1: Overview of the Four Core Architectural Requirements and Their Technology Enablers

Architectural Requirement	Primary Technologies	Key Outcome	MBSE Diagram
(1) Traceability & Provenance	Blockchain, RFID, NFC, Smart Contracts	End-to-end material accountability across all lifecycle stages	Activity / BDD
(2) Lifecycle Visibility & Resource Reuse	BIM, Digital Twins, IoT, AI/ML	Intelligent resource management and predictive recirculation	Activity / Parametric

(3) Interoperability & Standards	IFC, mvdXML, API gateways, Decentralised networks	Seamless cross-platform and cross-stakeholder data exchange	Interface / Sequence
4.4 Security & Trust	TLS, AES, Blockchain, AI-driven IBN, RBAC	Operational continuity, data integrity, and stakeholder trust	Requirement / Activity

BDD = Block Definition Diagram; IBN = Intent-Based Networking; RBAC = Role-Based Access Control.

Traceability and Provenance

Traceability and provenance constitute the foundational architectural requirements within circular SCM because circular operations depend heavily on the ability to monitor materials throughout both forward and reverse logistics flows.

Unlike traditional linear supply chains, where tracking typically ends at the point of sale, circular systems require continuous tracking of reused, refurbished, and recycled materials to ensure sustainability compliance and operational accountability (Azevedo et al., 2023). Without robust traceability, claims of circularity become unverifiable, and risks of fraud, greenwashing, and material leakage escalate significantly.

Azevedo et al. (2023) demonstrated that blockchain architectures reduce information asymmetry among stakeholders, manufacturers, logistics providers, recyclers, and auditors while strengthening product authenticity verification.

By distributing ledger copies across multiple nodes, blockchain eliminates single points of failure and prevents retroactive alteration of transaction histories. Salzano et al. (2024) further showed that when each material transfer is cryptographically signed and time-stamped, audit trails become computationally impractical to falsify. Solanki et al. (2025) added that decentralised verification mechanisms such as Hyperledger Fabric and R3 Corda strengthen trust relationships among competitors and complementors within circular value webs without requiring centralised governance structures.

IoT-enabled sensing technologies also play a critical role in supporting lifecycle operations. Sundmaeker et al. (2016) demonstrate that IoT infrastructures enable continuous communication between physical assets and digital platforms, thereby enhancing operational visibility across supply chains. In addition, Baskaran and Nguyen (2025) provide empirical evidence that integrating RFID-tagged components with blockchain-based provenance systems significantly improves reverse logistics efficiency, reporting a 75% reduction in processing time and an 87.5% reduction in audit completion time compared to conventional barcode-based approaches. These findings directly reinforce the efficiency improvements discussed in the subsequent analysis of operational outcomes.

The integration of these technologies can be conceptualised as a dual-layer traceability architecture consisting of both physical sensing and digital verification mechanisms. As illustrated in Table 4.2, the proposed architecture combines real-time sensing technologies with distributed verification infrastructures to ensure continuous lifecycle visibility and immutable provenance recording throughout circular supply chain operations.

Table 4.2: Dual-Layer Traceability Architecture — Physical Sensing and Digital Verification

Layer	Components	Function	Technology Standards
Layer 1: Physical Sensing	RFID tags, NFC chips, Environmental sensors (temperature, humidity, shock, GPS)	Real-time capture of asset location, condition, and movement data	EPC Gen2 RFID; ISO 15693 NFC; MQTT / CoAP protocols

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Layer 2: Digital Verification	Distributed ledger nodes, Smart contracts, Cryptographic hashing, Off-chain storage (e.g., IPFS)	Immutable recording, time-stamping, and multi-party verification of all custody transfers	Hyperledger Fabric v2.x; Ethereum ERC-721 (DPP tokens); SHA-256 hashing

Source: Authors' synthesis from Azevedo et al. (2023), Salzano et al. (2024), and Sundmaeker et al. (2016).

To further substantiate the traceability and provenance requirement, Table 4.3 summarises the major empirical findings from the reviewed literature and links them directly to the proposed architectural requirements (REQ-TR). The table demonstrates the complementary roles played by blockchain, IoT, RFID, and decentralised ledger technologies in enabling reliable circular SCM operations.

Table 4.3: Evidence Summary — Traceability and Provenance Requirement

Source	**Technology Focus**	**Key Finding**	**Relevance to REQ-TR**
Azevedo et al. (2023)	Blockchain / SLR	Blockchain reduces information asymmetry and strengthens product authenticity across 87 cases reviewed	REQ-TR-01: Immutable ledger mandate
Salzano et al. (2024)	Blockchain / Circular Economy	Cryptographic signing improves chain-of-custody validation in distributed industrial ecosystems	REQ-TR-01: Cryptographic time-stamping
Solanki et al. (2025)	Hyperledger Fabric / R3 Corda	Permissioned blockchains enable multi-org collaboration without centralised governance	REQ-TR-01: Decentralised trust model
Sundmaeker et al. (2016)	IoT Architecture	IoT bridges physical-digital gap, enabling real-time asset visibility across supply networks	REQ-TR-02: Sensing layer mandate
Baskaran & Nguyen (2025)	RFID / Medical Logistics	RFID-blockchain integration cuts processing time 75%, audit time 87.5%	REQ-TR-02: RFID/NFC mandate
Saberi et al. (2020)	Blockchain / Fashion SCM	Blockchain-enabled CSCM improves circularity monitoring in fast-fashion contexts	REQ-TR-01: Lifecycle recording

REQ-TR = Traceability Requirement; CSCM = Circular Supply Chain Management.

Collectively, the reviewed studies indicate that effective traceability architectures require the integration of blockchain, IoT, and digital identity mechanisms. A blockchain-only approach lacks real-world sensing granularity, while an IoT-only approach lacks immutable record-keeping and tamper resistance.

As such, traceability and provenance should be conceptualised as a dual-layer architectural requirement comprising a physical sensing layer, including RFID, NFC, and environmental sensors, and a digital verification layer based on distributed ledgers, smart contracts, and cryptographic hashing.

The evidence summarised in Table 4.1 further reinforces that no single technology is sufficient on its own, and that integrated system architectures are necessary to ensure operational transparency, auditability, and lifecycle accountability within circular supply chains.

Within the MBSE framework, this requirement is represented through Activity Diagrams for reverse logistics processes and Block Definition Diagrams for sensor and ledger subsystems.

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Lifecycle Visibility and Resource Reuse

Lifecycle visibility is a fundamental requirement in circular SCM because it enables end-to-end understanding of how assets evolve across multiple value recovery stages. Unlike traditional supply chains, which primarily optimise production and distribution efficiency, circular systems depend on continuous knowledge of product condition, composition, and location throughout reuse, refurbishment, deconstruction, and recycling cycles. This extended visibility is essential for determining optimal recovery pathways and preventing premature disposal or inefficient material reintegration.

The literature on lifecycle visibility reveals a clear shift from static information management toward integrated and intelligent lifecycle systems. Early research such as Alhamami et al. (2018) highlights the role of BIM IoT integration in bridging the gap between digital models and real-world construction activities, particularly in waste-intensive sectors such as construction and demolition. More recent studies, including Banerjee and Nayaka (2022), extend this perspective by emphasising lifecycle-oriented BIM systems that embed digital material passports containing detailed component-level information, including composition, condition, and disassembly instructions. This progression reflects a broader transition from documentation-based approaches to structured reuse-oriented lifecycle intelligence.

From a systems perspective, lifecycle visibility can be interpreted as a multi-layer decision architecture rather than a single monitoring function. At the operational level, BIM acts as the structured data backbone, while IoT devices provide real-time physical condition updates. On top of this, digital twin systems introduce dynamic simulation capabilities that continuously align physical asset behaviour with virtual representations. Robertshaw et al. (2023) demonstrate that this synchronisation enables a shift from reactive maintenance strategies to predictive maintenance and recirculation planning. In parallel, Chen et al. (2020) show that integrating BIM with predictive planning mechanisms can reduce material flow process durations by 16.1%, reinforcing the operational value of lifecycle-informed decision-making.

Table 4.4 illustrates this layered integration of BIM, IoT, AI, and digital twin technologies. Rather than operating independently, each layer contributes to a continuous feedback loop where design information informs operational monitoring, operational data informs simulation models, and simulation outputs guide recovery and reuse decisions. This transforms lifecycle visibility from passive tracking into an active optimisation mechanism for circular resource management.

Table 4.4: BIM-IoT-AI Integration Model for Lifecycle Visibility

Layer	Technology	Data Input	Decision Output	Circular Economy Benefit
Design Layer	BIM (Revit / ArchiCAD)	Material specs, component dimensions, supplier data, red-list status	Material passport creation; design-for-disassembly specification	Enables end-of-life recovery planning from day one
Operational Layer	IoT Sensors + RFID	Real-time temperature, stress, location, usage cycle counts	Condition assessment; maintenance scheduling	Prevents premature disposal; extends asset lifespan
Simulation Layer	Digital Twins	Live IoT feed + BIM model + historical degradation data	Predictive recirculation windows; failure forecasting	Optimises timing of material re-entry into supply chain
Analytics Layer	AI / Machine Learning	Historical maintenance logs; return patterns; demand signals	Automated recovery pathway recommendation (reuse/refurb/recycle)	Maximises recovered material value

Source: Authors' synthesis from Alhamami et al. (2018), Robertshaw et al. (2023), and Chen et al. (2020).

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The empirical evidence further reinforces the importance of lifecycle visibility as a multi-technology capability rather than a standalone system. Table 4.5 summarises key findings across the literature and highlights how different technologies contribute to distinct aspects of circular lifecycle management, including coordination, scheduling, predictive maintenance, and organisational readiness.

Table 4.5: Evidence Summary — Lifecycle Visibility and Resource Reuse Requirement

Source	Technology	Key Finding	Relevance to REQ-LV
Alhamami et al. (2018)	BIM-IoT Integration	BIM-IoT improves lifecycle coordination and reduces rework in circular construction	REQ-LV-01: Digital material passports
Banerjee & Nayaka (2022)	BIM / Circular Construction	BIM lifecycle inventories improve deconstruction planning and material recovery	REQ-LV-01: Material passport mandate
Chen et al. (2020)	BIM + Look-ahead Planning	BIM-linked planning reduces material flow durations by 16.1%	REQ-LV-02: Lifecycle scheduling
Robertshaw et al. (2023)	BIM-IoT / Digital Twins	Digital twins enable predictive maintenance and real-time asset condition monitoring	REQ-LV-03: Digital twin integration
Alhamami et al. (2020)	BIM Education / Workforce	Skills gap limits BIM adoption; adapted training required for sustainability strategies	REQ-LV-04: Human-layer constraint

REQ-LV = Lifecycle Visibility Requirement.

While Figure 4.1 presents evidence at the level of individual studies, it does not capture the broader distributional patterns across the literature. To address this limitation, a cross-study frequency analysis was conducted based on the full SLR corpus (n = 102), enabling the identification of dominant and emerging technology clusters within lifecycle visibility research. This aggregated perspective provides a higher-level understanding of how different technologies are represented across studies, and highlights their relative maturity and adoption within circular SCM architectures.

Figure 4.1: Frequency of Lifecycle Visibility Technologies Cited Across SLR Corpus (n=102)

Technology	Distribution	Value
BIM / Digital Twins		74%
IoT / RFID / NFC		68%
AI / Predictive Analytics		52%
Blockchain / DLT		61%
Digital Product Passports		38%

Values represent percentage of the 102 sources that discuss each technology in a lifecycle visibility context. Source: Authors' coding.

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Beyond presenting distributional evidence, Figure 4.4 provides a deeper indication of the maturity and functional stratification of lifecycle visibility technologies within circular SCM research. BIM and digital twin technologies (74%) dominate the literature, reflecting their established role as structural and simulation foundations for lifecycle modelling. IoT, RFID, and NFC technologies (68%) closely follow, reinforcing their position as primary enablers of real-time data acquisition from physical assets.

In comparison, blockchain and distributed ledger technologies (61%) occupy a secondary but still substantial position, indicating their importance in trust, verification, and auditability, while remaining dependent on upstream sensing and modelling infrastructures. AI and predictive analytics (52%) represent a mid-stage capability, increasingly used for optimisation and forecasting but not yet universally embedded in lifecycle systems. Digital product passports (38%) show the lowest adoption, suggesting a conceptual-to-implementation gap where policy-driven circular economy instruments have not yet fully matured into widely deployed technical standards.

Overall, the distribution confirms that lifecycle visibility is not enabled by a single dominant technology but instead emerges from a layered ecosystem of sensing, modelling, verification, and intelligence capabilities operating at different stages of maturity and integration.

The literature therefore suggests that effective lifecycle visibility architectures require the concurrent integration of BIM, IoT, AI, and digital twin technologies. No single technology is sufficient: BIM provides the structured data schema, IoT supplies live sensing, AI enables predictive modelling, and digital twins provide a dynamic simulation environment. Together, these technologies transform lifecycle visibility from passive record-keeping into active decision support for circularity. Within the MBSE framework, this requirement is captured through Activity Diagrams for deconstruction and recycling processes, and Parametric Diagrams for lifecycle forecasting models.

Interoperability and Standards

Interoperability remains one of the most persistent challenges in circular supply chain management due to the reliance on continuous information exchange across highly fragmented stakeholder networks. Unlike traditional linear supply chains, circular systems require manufacturers, logistics providers, recyclers, contractors, and regulatory bodies to share data across multiple lifecycle stages and heterogeneous technology platforms. In the absence of standardised communication mechanisms, information becomes isolated within organisational silos, thereby undermining traceability and lifecycle visibility capabilities.

The literature consistently positions interoperability not merely as a technical compatibility issue, but as a structural requirement for enabling coordinated circular operations. Banerjee and Nayaka (2022) identify Industry Foundation Classes (IFC) and mvdXML as foundational BIM interoperability standards that facilitate automated model validation and cross-platform data exchange. IFC functions as a neutral and open data schema developed by buildingSMART, enabling model interoperability across platforms such as Autodesk Revit, Tekla, and ArchiCAD. Complementing this, mvdXML defines workflow-specific subsets of IFC information, allowing stakeholders to exchange only operationally relevant data rather than entire models. This selective exchange mechanism becomes particularly important in circular SCM environments where organisations may need access to material composition data without exposing proprietary design information.

The importance of standardisation is further reinforced by Alhamami et al. (2018), who found that inconsistent implementation of interoperability standards contributes directly to data fragmentation and inefficient cross-platform coordination. A broader pattern emerging from the literature suggests that interoperability failures are rarely caused by the absence of technology itself; instead, they arise from incompatible data structures, inconsistent semantics, and isolated system architectures that prevent seamless communication between stakeholders.

At the network architecture level, the literature also demonstrates a transition away from traditional centralised integration models toward decentralised and federated communication structures. Sundmaeker et al. (2016) argue that hub-based architectures become increasingly ineffective within large-scale IoT ecosystems because

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they introduce scalability limitations and single points of failure. In contrast, decentralised peer-to-peer and federated network models distribute communication responsibilities across multiple nodes, improving resilience and scalability. Salzano et al. (2024) extend this perspective through blockchain-enabled architectures that allow organisations to maintain data sovereignty while selectively sharing cryptographic proofs for verification purposes. This is particularly relevant within circular SCM systems, where organisations often require collaboration without fully relinquishing control over proprietary operational data.

Table 4.6 illustrates the architectural distinction between traditional hub-and-spoke integration models and proposed federated interoperability architectures. The comparison demonstrates how decentralised structures better support circular SCM requirements by reducing bottlenecks, improving scalability, and enabling collaborative trust relationships across organisational boundaries.

Table 4.6: Interoperability Architecture Hub and Spoke vs. Federated Network Models

Architecture Type	**Structure**	**Data Sovereignty**	**Scalability**	**Suitability for Circular SCM**
Hub-and-Spoke (Traditional)	Central ESB / ERP receives and distributes all data	Low – all data passes through central owner	Limited – hub is a bottleneck	POOR – creates single point of failure; incompatible with multi-org trust needs
Federated Network (Proposed)	Peer-to-peer nodes with shared standards (IFC, mvdXML, Sensor Thing API)	High – each org controls its own data; shares cryptographic proofs only	High – nodes added without architectural redesign	STRONG – supports competitive co-operation and decentralised trust

ESB = Enterprise Service Bus; ERP = Enterprise Resource Planning. Source: Authors' synthesis from Sundmaeker et al. (2016) and Salzano et al. (2024).

While Table 4.7 conceptualises interoperability at the architectural level, Table 4.3 identifies the specific standards and protocols most frequently associated with interoperable circular SCM systems within the SLR corpus. Together, these standards form the technical foundation enabling communication between BIM platforms, IoT infrastructures, blockchain systems, and enterprise applications.

Table 4.7: Key Interoperability Standards Identified in the SLR Corpus

Standard / Protocol	**Domain**	**Function**	**Relevant Source(s)**
IFC (ISO 16739)	BIM / Construction	Neutral, open format for building and infrastructure model exchange across software platforms	Banerjee & Nayaka (2022); Alhamami et al. (2018)
mvdXML 1.1 (buildingSMART)	BIM / Workflow	Defines IFC model view requirements for specific workflows (e.g., structural analysis, deconstruction)	Banerjee & Nayaka (2022)
MQTT / CoAP	IoT / Sensing	Lightweight messaging protocols for constrained IoT devices in logistics and warehouse environments	Sundmaeker et al. (2016); Dave et al. (2016)

OWL / Sensor Thing API	Semantic Interoperability	Ontologies enabling machine-readable data alignment across heterogeneous systems	Sundmaeker et al. (2016)
Hyperledger Fabric / R3 Corda	Blockchain / Trust	Permissioned DLT frameworks enabling shared business logic without single-entity governance	Solanki et al. (2025); Azevedo et al. (2023)
REST / gRPC APIs	System Integration	Interface standards for connecting WMS, blockchain, and BIM platforms	Baskaran & Nguyen (2025)

DLT = Distributed Ledger Technology; WMS = Warehouse Management System; OWL = Web Ontology Language.

A clear pattern emerging from Table 4.7 is that interoperability within circular SCM extends beyond simple file compatibility. Instead, the literature points toward a layered interoperability ecosystem comprising data standards (IFC), workflow specifications (mvdXML), communication protocols (MQTT / CoAP), semantic alignment mechanisms (OWL), distributed trust infrastructures (Hyperledger Fabric / R3 Corda), and application-level integration interfaces (REST / gRPC APIs). This indicates that interoperability must be approached as a multi-layer architectural capability rather than a standalone software feature.

In turn, the literature suggests that future circular SCM architectures must prioritise standardisation, semantic consistency, and decentralised communication models to support scalable multi-stakeholder integration. Effective interoperability therefore depends not only on technical connectivity, but also on governance structures that balance information sharing with organisational autonomy. Within the MBSE framework, this requirement is represented through Block Definition Diagrams showing interface relationships between subsystems and Sequence Diagrams illustrating cross-platform data exchanges between BIM, IoT, blockchain, and enterprise systems.

Security and Trust

Security and trust represent foundational architectural requirements in circular SCM systems because increasing digitalisation exposes supply chains to cybersecurity vulnerabilities, data privacy concerns, and operational risks. As discussed in Chapter I, the integration of IoT devices, cloud infrastructures, blockchain platforms, and cross-organisational data exchange mechanisms significantly expands the attack surface of modern SCM ecosystems (Sapra et al., 2022). These risks become even more pronounced within circular supply chains, where information frequently flows between multiple independent stakeholders, including manufacturers, recyclers, logistics providers, contractors, and regulatory agencies. In such environments, concerns regarding industrial espionage, data leakage, unauthorised access, and provenance manipulation become major barriers to collaboration and trust.

The literature consistently frames security in circular SCM not only as a technical defence mechanism, but also as an operational enabler of inter-organisational trust. Sapra et al. (2022) identified IoT-enabled SCM environments as particularly vulnerable due to weak authentication protocols, unsecured communication channels, and the complexity of distributed device ecosystems. Their findings emphasise the importance of layered cybersecurity controls, including Transport Layer Security (TLS) for protecting data in transit, Advanced Encryption Standard (AES) for securing stored information, intrusion detection systems, and Security Information and Event Management (SIEM) frameworks for continuous monitoring and incident response. Without these protections, compromised IoT devices could inject false operational data into the system, such as incorrectly classifying hazardous waste as recyclable feedstock, thereby creating significant downstream safety and compliance risks.

Alongside cybersecurity controls, blockchain technologies are increasingly positioned as trust-enabling infrastructures within circular SCM architectures. Azevedo et al. (2023) demonstrated that blockchain improves information integrity through immutable transaction recording mechanisms that prevent unauthorised modification of provenance data. Once custody transfers are cryptographically hashed and validated through distributed consensus protocols, retroactive tampering becomes computationally infeasible within properly governed permissioned blockchain environments. Salzano et al. (2024) further extend this argument by showing that decentralised trust architectures reduce fraud risks in multi-organisational ecosystems, particularly in applications involving sustainability certification, waste export validation, and conflict mineral compliance.

The literature also indicates a growing shift toward adaptive and intelligence-driven security architectures. Solanki et al. (2025) proposed Intent-Based Networking (IBN) as an AI-driven approach capable of translating organisational security policies into automated network enforcement mechanisms. Within circular SCM environments, this allows security rules, such as restricting access to sensitive material composition data only to authorised recyclers, to be dynamically enforced through automated segmentation, credential rotation, and firewall reconfiguration. Compared with static security models, IBN architectures improve responsiveness to emerging threats and support behavioural anomaly detection for identifying previously unknown attack patterns.

Rather than functioning independently, these technologies collectively form a layered security architecture that protects devices, communications, applications, data repositories, and governance processes simultaneously. Table 4.8 summarises the major threat categories identified in the literature alongside their corresponding architectural controls and industry standards.

Table 4.8: Security Framework for Circular SCM Threats, Controls, and Standards

Threat Category	Example Attack Vector	Architectural Control	Industry Standard
Device Compromise	IoT sensor firmware modification or spoofing	Hardware-based roots of trust; device identity certificates; TLS 1.3 encryption	IEC 62443; NIST SP 800-82
Data Tampering	Falsification of provenance or custody records	Blockchain immutable ledger; SHA-256 hashing; cryptographic time-stamping	ISO 27001; Hyperledger Fabric v2.x
Unauthorised Access	Insider threat accessing competitor material data	Role-Based Access Control (RBAC); Attribute-Based Access Control (ABAC); zero-trust architecture	NIST SP 800-207; ISO 27001
Network Intrusion	Man-in-the-middle attack on API communications	TLS 1.3; mutual authentication; API gateway with rate limiting	OWASP API Security Top 10; NIST CSF
Supply Chain Fraud	False sustainability certificates or green-washing claims	Smart-contract-enforced compliance verification; AI anomaly detection	EU ESPR (Digital Product Passport regulation)

NIST = National Institute of Standards and Technology; CSF = Cybersecurity Framework; ESPR = Ecodesign for Sustainable Products Regulation (EU 2024/1781).

Table 4.8 demonstrates that security threats within circular SCM are multidimensional, spanning physical devices, communication infrastructures, application systems, and organisational governance. A key pattern emerging from the literature is that no single security mechanism sufficiently addresses all risk categories. Instead, effective protection requires the coordinated integration of cryptographic controls, identity management systems, AI-driven monitoring, and governance frameworks operating simultaneously across multiple architectural layers.

To further conceptualise this layered approach, Table 4.9 illustrates the security architecture layers identified across the reviewed studies. The figure demonstrates how cybersecurity responsibilities are distributed from the physical device level through communication, application, and governance layers, thereby reinforcing the principle of defence-in-depth within circular SCM systems.

Table 4.9: Security Architecture Layers in Circular SCM Systems

Security Layer	Scope	Technology Controls	Key Sources
Device Layer	IoT sensors, RFID readers, NFC chips at physical nodes	Firmware signing; TPM chips; device certificates; encrypted MQTT	Sapra et al. (2022); Sundmaeker et al. (2016)
Communication Layer	Data in transit between nodes, systems, and organisations	TLS 1.3; mutual TLS (mTLS); VPN tunnels; API gateway authentication	Sapra et al. (2022); Solanki et al. (2025)
Application Layer	SCM software, BIM platforms, WMS, ERP systems	RBAC / ABAC; OAuth 2.0; SIEM monitoring; audit logs	Solanki et al. (2025); Gupta (2025)
Data Layer	Stored records, ledger entries, material passports, BIM files	AES-256 encryption at rest; blockchain immutability; IPFS off-chain storage	Azevedo et al. (2023); Salzano et al. (2024)
Governance Layer	Policies, contracts, regulatory compliance across organisations	Smart contracts; IBN policy enforcement; ISO 27001 ISMS; NIST CSF	Solanki et al. (2025); Saberi et al. (2020)

ISMS = Information Security Management System; TPM = Trusted Platform Module; IPFS = InterPlanetary File System.

The layered distribution shown in Figure 4.6 reinforces the argument that security in circular SCM cannot be treated as a standalone technical module added after system deployment. Instead, security and trust must be embedded directly into the architectural design of sensing infrastructures, communication protocols, data governance mechanisms, and organisational workflows. The literature therefore supports a security-by-design approach in which blockchain enables immutable logging, AI-driven systems support adaptive threat detection, and RBAC/ABAC mechanisms ensure controlled access to sensitive lifecycle information.

Within the MBSE framework, these requirements are represented through Requirement Diagrams linking security constraints to system components, Block Definition Diagrams illustrating protected subsystem interfaces, and Activity Diagrams modelling secure information exchange processes across organisational boundaries.

Summary and Integrated Architectural Synthesis

The four architectural requirements identified in this chapter, namely traceability and provenance, lifecycle visibility and resource reuse, interoperability and standards, and security and trust, should not be interpreted as isolated technological capabilities. Rather, the literature demonstrates that they function as an interconnected architectural ecosystem in which the effectiveness of one requirement depends heavily on the implementation of the others. Circular SCM systems therefore require simultaneous integration across these dimensions in order to achieve operational continuity, transparency, and resilience.

Traceability and provenance establish the foundational ability to monitor material movements and verify chain-of-custody information across reverse logistics processes. However, traceability alone is insufficient if lifecycle visibility mechanisms are absent, because location and ownership records provide limited value without contextual insight into material condition, reuse potential, and recovery timing. Similarly, lifecycle visibility depends heavily on interoperability standards to ensure that BIM models, IoT sensor outputs, digital twin simulations, and enterprise systems can exchange information consistently across organisational boundaries. Without interoperability, lifecycle intelligence remains fragmented within isolated platforms and cannot support coordinated circular decision-making.

Security and trust further reinforce the entire architectural structure by ensuring the integrity, confidentiality, and reliability of exchanged information. Open interoperability frameworks without embedded cybersecurity protections increase exposure to unauthorised access, data tampering, and supply chain fraud. Conversely, security mechanisms alone cannot fully support collaborative circular ecosystems unless supported by trust-enabling infrastructures such as blockchain, cryptographic verification, and transparent governance frameworks. As a result, the literature consistently positions these four requirements as mutually reinforcing components rather than standalone implementation domains.

Table 4.10 summarises these interdependencies by illustrating how each requirement contributes to and depends upon the others within an integrated circular SCM architecture.

Figure 4.10: Interdependency Matrix of the Four Core Architectural Requirements

	Traceability (1)	**Lifecycle Visibility (2)**	**Interoperability (3)**	**Security & Trust (4)**
Traceability (1)	—	Provenance records enable material reuse decisions	Ledger data must be exchangeable across platforms	Immutable records build stakeholder trust
Lifecycle Visibility (2)	Material passports require traceable provenance data	—	BIM/DT data must flow between organisations	Lifecycle data requires access control
Interoperability (3)	Cross-platform APIs enable traceability sharing	IFC/mvdXML enable BIM data exchange	—	Open interfaces increase attack surface
Security & Trust (4)	Blockchain secures provenance integrity	Encrypted channels protect lifecycle records	Security standards enable trusted data sharing	—

DT = Digital Twin; BIM = Building Information Modelling. Source: Authors' synthesis.

The interdependency matrix also highlights an important systems-level insight emerging from the SLR corpus: architectural weaknesses in one requirement area frequently propagate into others. For example, poor interoperability standards weaken lifecycle visibility by restricting data exchange, while inadequate security controls undermine trust in provenance systems. This interconnectedness explains why partial or isolated implementation strategies often fail to produce meaningful circular SCM outcomes despite substantial technological investment.

The MBSE methodology adopted provides the structured modelling framework necessary to integrate these requirements into a coherent system architecture. Rather than treating traceability, visibility, interoperability, and security as separate implementation projects, MBSE enables them to be represented as interacting subsystems connected through formal interfaces, workflows, constraints, and behavioural relationships. Table 4.11 presents the complete MBSE mapping developed in this study, linking each architectural requirement to its corresponding SysML diagram type as well as its conceptual role within the overall system architecture.

Table 4.11: MBSE Mapping of Core Architectural Requirements to Research Chapters

Requirement	SysML Diagram(s)	Key System Dependency	Observed Outcome	Design Implication
(1) Traceability & Provenance	Activity (reverse logistics); Block Definition (sensor/ledger)	Linear SCM lacks reverse flow tracking (Farooque et al., 2019)	75% processing time reduction (Baskaran & Nguyen, 2025)	Future DPP schema standardisation needed
(2) Lifecycle Visibility	Activity (deconstruction); Parametric (forecasting)	CE demands full-lifecycle asset management (Alhamami et al., 2018)	16.1% material flow duration reduction (Chen et al., 2020)	Digital twin pilot validations required
(3) Interoperability	Interface (subsystem relations); Sequence (data exchange)	Fragmented architectures cause data errors (Radivojević et al., 2022)	Adoption barriers: fragmentation compounds cost (Taddei et al., 2024)	Shared reference architectures needed
(4) Security & Trust	Requirement (constraints); Activity (secure flows)	Multi-stakeholder CE requires verified provenance (Chapter I, para 3)	Stakeholder reluctance driven by data exposure fears (Taddei et al., 2024)	Governance incentive mechanisms needed

DPP = Digital Product Passport; CE = Circular Economy. Source: Authors' MBSE synthesis.

Collectively, the findings demonstrate that circular supply chain transformation cannot be achieved through isolated technology adoption or incremental digitalisation efforts. Instead, successful implementation requires architecture-led integration in which sensing infrastructures, lifecycle intelligence systems, interoperability protocols, and security mechanisms operate as a coordinated system.

These requirements are not optional enhancements but foundational conditions for achieving efficiency, resilience, and sustainability in circular supply chain systems. The literature indicates that future implementation strategies must prioritise coordinated investment, shared interoperability standards, collaborative governance structures, workforce capability development, and phased validation through pilot ecosystems. Without such integrated approaches, circular SCM initiatives risk remaining fragmented, technologically incompatible, and operationally unsustainable despite significant investment in individual digital technologies (Lahane et al., 2020; Nascimento et al., 2019).

DISCUSSION

Theoretical Contributions

The findings should be read as more than a confirmation that digital technologies are useful for circular SCM. Their main theoretical implication is that circularity is an architectural problem: reverse flows, multi-lifecycle records, and shared decision rights cannot be managed through isolated deployments of IoT, BIM, blockchain, or AI. This aligns with Farooque et al. (2019) and Taddei et al. (2024), who argue that technology-by-technology approaches leave major gaps in the operationalisation of circular supply chains. The present synthesis extends those arguments by identifying the architectural conditions under which the technologies become mutually reinforcing. Traceability and provenance establish confidence in product histories; lifecycle visibility shows when and where resources can be reused; interoperability allows actors to exchange those records; and security and trust protect the information relationships on which collaboration depends. The so what factor is therefore that the four requirements are not parallel findings but a systems logic for converting circular economy principles into executable SCM design.

This interpretation also strengthens the link between the findings and MBSE theory. Earlier studies often describe digital technologies as capabilities, but MBSE reframes them as requirements, interfaces, constraints, and behavioural flows that can be traced across the system architecture (Amiri, 2025; Kizgin & Vietor, 2025). The value of MBSE is not merely methodological neatness; it makes the interdependence between requirements visible. For example, traceability without interoperability produces a closed database rather than a shared circular network, while interoperability without security can expose sensitive commercial data and weaken stakeholder confidence. The study therefore agrees with Nascimento et al. (2019) that Industry 4.0 technologies enable circular practices only when embedded in an integrated operational model, but it adds that the model must also be represented as a traceable architecture. This advances existing literature by moving the debate from whether a technology can support circular SCM to how multiple requirements must be configured together.

The study also qualifies some claims made by leading circular economy and supply chain authors. Geissdoerfer et al. (2018) and Farooque et al. (2019) position circular SCM as a shift from linear throughput to value-preserving loops, and the present findings support that view. However, the evidence reviewed here suggests that the shift is not only strategic or environmental; it is also informational. Circular value cannot be preserved unless the system knows the provenance, condition, ownership, and compliance status of each material or component. Similarly, Govindan and Hasanagic (2018) identify knowledge gaps as a major barrier to circular implementation. This study agrees, but it specifies that the knowledge gap is partly architectural: firms often lack a shared model of what data must be captured, how it should move, who governs it, and how decisions should be triggered. The theoretical contribution is therefore a more operational account of circular SCM, one that links sustainability goals to requirements engineering and systems integration.

Practical and Policy Implications

For practitioners, the findings indicate that circular SCM performance depends on reducing information friction across organisational boundaries. The operational gains reported in the literature are meaningful because they show what happens when architectural requirements are joined rather than treated separately. RFID-enabled tracking in medical device logistics reduced processing times by approximately 75% and audit completion times by 87.5%, demonstrating how automated provenance records can remove manual reconciliation from both forward and reverse logistics (Baskaran & Nguyen, 2025). BIM-linked look-ahead planning reduced material flow process durations by 16.1%, showing that lifecycle visibility matters most when it is connected to production scheduling and stakeholder coordination (Chen et al., 2020). These results do not imply that every firm will obtain the same efficiency gains immediately. Rather, they suggest that gains are most likely where organisations combine digital sensing, shared records, interoperable data exchange, and clear decision rules so that recovered materials can be evaluated and routed before their value deteriorates.

The most direct practitioner recommendation is therefore to avoid piecemeal technology adoption. Firms should begin with an architectural roadmap that maps the four core requirements to business processes, system interfaces, and governance responsibilities. A blockchain layer should not be procured before the organisation has defined what provenance data must be captured, how Digital Product Passports will be maintained, who can access them, and how those records will connect to BIM, IoT, analytics, and enterprise planning systems. Similarly, predictive analytics and digital twin functions are only useful when the underlying data are timely, standardised, and trusted. Robertshaw et al. (2023) show that digital twins can shift maintenance from a reactive to a predictive posture; in circular SCM, this matters because better timing supports redeployment, refurbishment, and recycling decisions. The practical contribution of this study is thus an implementation logic: practitioners should design the data foundation, interoperability rules, security controls, and decision workflows together, then phase the technology investment around that architecture.

A staged implementation pathway follows from this logic. First, organisations should identify the circular decisions that create the highest value, such as whether a returned component should be reused, refurbished, recycled, or scrapped. Second, they should specify the data needed for those decisions, including location, condition, material composition, ownership, certification, and risk status. Third, they should design interfaces that allow this data to move across organisational boundaries without forcing all actors into a single platform. Fourth, they should embed access control, auditability, and responsibility rules before scaling the system. This sequence turns the findings into a practical design method. It also prevents the common failure in which a firm invests in a digital tool but leaves unresolved the data standards, governance rights, and workflow changes needed to realise value. In circular SCM, the architecture is not an IT back-office issue; it is the mechanism through which circular strategy becomes operational behaviour.

For policymakers, the findings support a clear policy recommendation: circular SCM should be governed through shared reference architectures and interoperable standards rather than through fragmented incentives for single technologies. Public agencies and industry bodies can accelerate adoption by developing common Digital Product Passport schemas, open API requirements, sector-specific ontologies, and procurement rules that reward traceable reuse and verified material recovery. Such standards would reduce the bespoke integration costs that currently burden especially small and medium-sized enterprises (Solanki et al., 2025). They would also address the stakeholder reluctance identified by Taddei et al. (2024), because common governance rules can define data ownership, access rights, liability, and confidentiality before firms are asked to disclose commercially sensitive information. In this sense, policy should not only subsidise digital tools; it should create the institutional conditions under which those tools can be trusted across organisational boundaries.

Human, Organisational, and Future Research Implications

A further implication is that circular SCM architecture must include the human layer. The literature on BIM adoption shows that technology maturity does not translate automatically into circular capability when practitioners lack the skills to populate, interpret, and act on digital information (Alhamami et al., 2018; Alhamami et al., 2020). Bag et al. (2021) similarly show that advanced manufacturing capabilities depend on workforce competence and management commitment. These findings mean that skills development is not a supporting activity but part of the architecture itself. Training programmes, professional certification, and cross-organisational learning mechanisms should be designed alongside system deployment so that operators, project managers, recyclers, auditors, and suppliers understand the same data definitions and decision rules. Toland and Collery (2023) further suggest that adversarial industry cultures can undermine collaboration even where technical tools are available. Practical implementation must therefore combine system design with relationship governance, including early stakeholder engagement, transparent value-sharing mechanisms, and routines for resolving disputes over data quality or cost allocation.

The discussion also identifies research avenues opened by the study. First, future work should test the proposed architecture in live supply chain pilots, since conceptual MBSE validation cannot fully capture behavioural resistance, integration costs, or the distribution of benefits between actors. Second, sector-specific studies are needed to examine whether the same requirement structure applies in electronics, textiles, food, and healthcare, where product lifecycles, regulatory pressure, and recovery economics differ from construction and manufacturing. Third, researchers should examine how governance mechanisms influence adoption. Kouhizadeh et al. (2021) demonstrate that technological, organisational, and environmental barriers cluster together, which means technical performance should be evaluated alongside financing models, data-sharing agreements, workforce capability, and incentives. The policy pitch that follows from the results is simple: circular SCM transformation should be treated as an architecture-led public-private programme, not as a collection of independent digitalisation projects. Only then can the theoretical promise of circularity become a practical, scalable supply chain capability.

CONCLUSION

This study set out to identify, validate, and explain the core architectural requirements that enable Supply Chain Management systems to support the transition from linear production and logistics models to a circular economy. In relation to that objective, the paper concludes that circular SCM cannot be achieved through isolated adoption of blockchain, IoT, BIM, digital twins, AI, or lean tools. The central finding is that four requirements - traceability and provenance, lifecycle visibility and resource reuse, interoperability and standards, and security and trust - operate as an integrated architectural logic. Traceability records where products and materials have been; lifecycle visibility shows their condition and future recovery potential; interoperability allows these records to move across firms, platforms, and sectors; and security protects the trust relationships that make shared circular operations possible. This conclusion directly answers the problem introduced at the beginning of the paper: traditional linear SCM architectures are not structurally prepared for reverse logistics, multi-lifecycle resource flows, and multi-stakeholder decision-making. By combining a systematic literature review with Model-Based Systems Engineering, the study contributes theoretically by shifting attention from individual enabling technologies to the relationships between requirements, and it contributes methodologically by showing how dispersed literature can be organised into a traceable system architecture (Amiri, 2025; Kizgin & Vietor, 2025). The reviewed evidence also supports a specific operational conclusion: integrated architectures can generate measurable benefits, including reduced processing times, shorter audit cycles, improved material flow coordination, and more reliable lifecycle decisions (Baskaran & Nguyen, 2025; Chen et al., 2020). At the global level, the significance of the findings is that sustainable supply chains require information systems capable of preserving value across repeated cycles of use, recovery, and redeployment. At the specific level, the study indicates that practitioners should design circular SCM as a socio-technical architecture in which digital infrastructure, governance arrangements, workforce capability, and trust-building mechanisms are developed together rather than sequentially. The unique contribution of the research is therefore not the identification of another digital tool, but the clarification of how multiple tools, actors, and rules must be connected if circular economy principles are to become executable supply chain practice. The findings further show that the four requirements are mutually reinforcing conditions rather than a menu of options: a system that records provenance but cannot exchange it across platforms remains a silo, a system that exchanges data but lacks secure governance creates new trust risks, and a system that uses analytics without reliable lifecycle data may optimise the wrong decision.

Several limitations should be acknowledged, and they also define the next stage of work. First, the research is based on a synthesis of peer-reviewed literature rather than primary empirical data, so the proposed architecture has not yet been tested in a live industrial implementation. Second, the evidence base is concentrated heavily in construction, manufacturing, logistics, and related Industry 4.0 contexts, which may limit the direct generalisability of the conclusions to sectors such as textiles, electronics, food, or consumer goods. Third, the review is bounded by the selected databases, English-language sources, and the 2016-2025 publication window, which means that relevant grey literature, policy documents, and recent implementation experiments may not be fully represented. A further limitation is that MBSE provides conceptual and structural validation, but it does not by itself measure adoption costs, user acceptance, data quality problems, or the political difficulty of coordinating firms with unequal power and incentives. These limitations do not weaken the value of the findings; rather, they turn the study into work in progress and clarify the future research agenda. Future studies should validate the framework through pilot projects that connect Digital Product Passports, IoT sensing, BIM or digital twin records, analytics, and secure data exchange in real circular supply chain settings. Researchers should also compare sectors to determine which requirements are universal and which must be adapted to different product lifecycles, regulatory regimes, and recovery economics.

On the practical side, firms should adopt an architecture-led roadmap that begins with shared data definitions, interoperability standards, access rights, and governance rules before committing to large-scale technology procurement. Policymakers should support this transition by promoting common standards, procurement incentives for verified reuse, support mechanisms for small and medium-sized enterprises, and education programmes that close the digital skills gap identified in the literature (Alhamami et al., 2020; Lahane et al., 2020; Taddei et al., 2024; Toland & Collery, 2023). The overall recommendation is therefore that circular SCM transformation should be treated as a coordinated socio-technical programme. A practical implementation agenda should move on three tracks: technical standardisation through shared semantics, APIs, and Digital Product Passport schemas; organisational capability through cross-functional training, data stewardship, and stakeholder agreements; and policy coordination through minimum interoperability expectations and incentives that reduce adoption risk. Future work can also develop maturity models and cost-benefit evidence to help firms judge when they are ready to scale from pilots to network-wide circular operations. When architectural requirements are designed together, supply chains are better positioned to become resilient, transparent, resource-efficient, and genuinely sustainable; when they are treated separately, circularity remains a principle without an operational system capable of delivering it. In this way, the conclusion closes the loop with the original research problem: the transition to circular SCM is achievable only when architectural integration, organisational readiness, and policy support move together.

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