THE USE OF BLOCKCHAIN TECHNOLOGY (NON-FUNGIBLE TOKENS AND SMART CONTRACTS) IN A SUPPLY CHAIN ENVIRONMENT - A FRAMEWORK

by

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Dedication

This thesis is dedicated to my beloved wife and children, whose unwavering support, understanding, and encouragement have been my solid foundation of this journey. Their love has given me the space and freedom to pursue my research with dedication and passion. This work would not have been possible without their constant presence and belief in me.

I also dedicate this work to my dear parents, whose guidance and support have shaped my pursuit of knowledge throughout my life. In particular, I honor the memory of my father, who recently passed away and cannot witness the result of this effort. His belief in me and his constant encouragement to continue learning have been an enduring source of inspiration. This thesis stands as a testament to the values and curiosity he instilled in me.

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ABSTRACT

THE USE OF BLOCKCHAIN TECHNOLOGY (NON-FUNGIBLE TOKENS AND SMART CONTRACTS) IN A SUPPLY CHAIN ENVIRONMENT

- A FRAMEWORK

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Global supply chains are increasingly complex, often struggling with limited transparency, insecure data sharing, and inefficient processes. In response to these challenges, this research develops two novel blockchain-based artifacts—ProductNFT and ContainerNFT—that assign unique digital identities to products and containers, enabling authenticated lifecycle tracking and automated, near-real-time container and warehouse logistics management. These artifacts address existing gaps by enabling product authentication, strengthening origin, and enhancing operational agility, capabilities not currently offered by traditional SCM and PLM frameworks.

Designed using Design Science Research (DSR) methodology and guided by Systems Theory, the work introduces two key artifacts: ProductNFT, which creates a secure, tamper-evident "digital twin" for each product, ensuring transparent lifecycle tracking and verifiable authenticity, and ContainerNFT, which employs smart contracts for automated container handling, improved inventory precision, and streamlined warehouse operations. Validated in a simulated multinational hydraulics production environment, these artifacts significantly improve inventory accuracy, expedite logistics coordination, and enhance quality control responsiveness.

Beyond achieving operational gains, this research delivers a structured framework to address critical scalability, interoperability, and data privacy challenges in blockchain-enabled supply chains. The study underscores how private or consortium blockchain networks can enable secure, efficient, and compliant operations, advancing transparency, risk management, and strategic innovation by explicitly engaging SCM and PLM stakeholders and aligning with their needs.

Overall, the findings underscore a strategic shift towards data-driven decision-making. By bridging the gap between blockchain's theoretical promise and practical application, ProductNFT and ContainerNFT pave the way for more resilient, trusted, and future-ready supply chains and PLM systems, offering tangible benefits to industry practitioners and unlocking new opportunities for sustainable competitive advantage.

Keywords: Blockchain Technology, Supply Chain Management, Product Lifecycle Management, Digital Twins, Non-Fungible Tokens, Smart Contracts, Design Science Research, Systems Theory

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LIST OF ABBREVIATIONS

Abbreviation	Description
API	Application Programming Interface
BCT	Blockchain Technology
BIMF-PSC	Blockchain-Informed Information Management Framework for Precast Supply Chain
BOM	Bill of Materials
dApp	Decentralized Application
DAO	Decentralized Autonomous Organization
DLT	Distributed Ledger Technology
DPoS	Delegated Proof of Stake
DSR	Design Science Research
DT	Digital Twin
DTA	Digital Twin Aggregate
DTE	Digital Twin Environment
DTI	Digital Twin Instance
DTP	Digital Twin Prototype
ECC	Elliptic Curve Cryptography
EDI	Electronic Data Interchange
EEA	Enterprise Ethereum Alliance
ERP	Enterprise Resource Planning
ETLCL	Emerging Technology Literature Classification Level
GBBC	Global Blockchain Business Council
GDPR	General Data Protection Regulation

IBPx	Integrated Business Planning and Execution
IoT	Internet of Things
KPI	Key Performance Indicator
MM	Manufacturers Manager
MSM	Mirrored Spaces Model
NFT	Non-fungible Token
PLM	Produce Lifecycle Management
PM	Products Manager
POA	Proof of Authority
POC	Proof of Concept
POMS	Product Ownership Management System
RFID	Radio-Frequency Identification
ROI	Return on Investment
RSA	Rivest-Shamir-Adleman
SCM	Supply Chain Management
SME	Small and Medium-sized Enterprise
SSCM	Sustainable Supply Chain Management
ZKP	Zero-Knowledge Proof

CHAPTER I:
INTRODUCTION

1.1 Introduction

The industrial landscape has undergone significant transformations in recent decades, with digitalization leading to many changes. The digital twin emerges as a revolutionary development among the innovative concepts introduced by digitalization. Conceptualized initially by Dr. Michael Grieves in 2005 and progressively refined (Grieves, 2005), digital twins represent a paradigm shift in interacting with and understanding physical systems. These virtual replicas of physical objects or systems encapsulate all observable elements and data, bridging the physical and digital realms (Gray and Rumpe, 2022). This enables real-time monitoring, remote control, and predictive analysis across various industries, including NASA's utilization of complex system simulations (Shafto *et al.*, 2010).

The evolution of digital concepts has led to other technologies, notably blockchain, which was introduced in 2008 (Nakamoto, 2008; Puthal *et al.*, 2018). Blockchain technology, celebrated for its traceability, transparency, and trust (Chang *et al.*, 2022; Lohmer *et al.*, 2022; Menon and Jain, 2021), can significantly augment the functionality of digital twins. Additionally, non-fungible tokens (NFTs), which leverage blockchain's smart contract technology, represent a new digital frontier. NFTs, unique digital assets verifying ownership and authenticity (Anjum and Rehmani, 2022), mirror the concept of digital twins for digital assets, encompassing metadata and ownership details. Integrating digital twin and NFT technology promises substantial advancements in diverse sectors, including supply chain management, product design, and healthcare.

However, the adoption of these novel technologies presents challenges. The complexity of blockchain and the disruptive nature of digital twins and NFTs can elicit a mix of apprehension and curiosity among stakeholders. Concerns such as the fear of missing out (FOMO) or fear of failure might overshadow the technologies' potential advantages (Chang *et al.*, 2022). The early adoption phase's high failure rate of blockchain-based projects may further deter exploration (James, 2018; Lohmer *et al.*, 2022).

Despite these hurdles, the promise of digital twins and NFTs is undeniable. Their early implementation stages may see successes or failures. Still, their prospects for success are markedly improved with appropriate frameworks and best practices. Such frameworks are indispensable for businesses, offering guidance through the complexities of new technologies to harness their benefits effectively. For example, Gartner's Strategic Technology Trends for 2023 underscores the importance of blockchain, particularly Metaverse technology, over the next few years (Groombridge, 2022). However, with only an 8% success rate for blockchain-based projects in 2018 (James, 2018), there is a clear imperative for enhanced implementation strategies.

This research aims to bridge the gap by equipping organizations with the essential tools and insights required to enhance the success rate of deploying Blockchain-based technology digital twin projects. With a focus on applications within supply chain and product lifecycle management, this study is poised to deliver actionable insights and recommendations to facilitate successful implementations and fully leverage these technologies' advantages.

Within the supply chain management domain, digital twins offer unprecedented real-time visibility into the flow of goods from inception to delivery. This capability is instrumental in identifying bottlenecks, forecasting disruptions, and refining logistics operations (Kajba *et al.*, 2023; Srai *et al.*, 2019). Integrating NFTs with digital twins further fortifies the authenticity of goods, combats counterfeiting, and bolsters consumer confidence.

In product lifecycle management, the utility of digital twins extends to enhancing product design, testing, and maintenance processes. They facilitate virtual prototyping, diminish the reliance on physical trials, and yield critical data for augmenting product quality and durability (Minerva *et al.*, 2020). The synergy of NFTs ensures secure storage and transfer of product designs and intellectual property, fostering an environment ripe for innovation and collaborative endeavors (Far *et al.*, 2022; Gebreab *et al.*, 2022).

Nevertheless, a deep understanding of effectively implementing digital twin (Dalibor *et al.*, 2022; Mayer, 2022) and NFT technologies (Far *et al.*, 2022; Tan, 2022) is imperative for organizations to tap into these benefits. This entails navigating the intricacies of blockchain technology, steering through the organizational shifts (Kshetri, 2018) prompted by digital transformation, and addressing the legal and ethical considerations surrounding data privacy and ownership.

This study aims to develop a structured framework for digital twin technology integration, leveraging insights from recent research, notably Fuller *et al.* (2020), on digital twins' values, challenges, and enablers. It seeks to simplify the complexities of digital twin adoption. It offers clear guidance for organizations by exploring blockchain-based digital twin insights from Yaghy *et al.* (2023). The research highlights the potential benefits and challenges of incorporating digital twin technologies. It aims to expand the knowledge base on digital twins and Non-Fungible Tokens (NFTs), presenting a broad view of their strategic benefits to foster innovation and efficiency.

1.2 Research Problem

1.2.1. The Importance of Trust, Transparency, and Authenticity in Supply Chain Management and Product Lifecycle Management

In the dynamic context of global markets, the principles of trust, transparency, and authenticity have risen to paramount importance, especially within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). The principles of trust, transparency, and authenticity are fundamental to the success of business operations, underpinning the integrity of supply chains, assuring product quality, and nurturing the relationship of trust between enterprises and their clientele (de Boissieu *et al.*, 2021).

Trust serves as the bedrock of business interactions, particularly within SCM and PLM, where engagements span a multitude of stakeholders. Beyond mere belief in reliability or truth, trust within these domains is rooted in confidence in the dependability and integrity of all parties involved—from suppliers to manufacturers and distributors. It encompasses the expectation that these entities will meet their responsibilities, honor commitments, and conduct operations fairly and ethically. Trust facilitates collaboration, information sharing, and collective striving towards shared objectives. The absence of trust can precipitate breakdowns, inefficiencies, disputes, and missed opportunities within the supply chain (Harbert, 2020).

Transparency is indispensable for upholding accountability and ensuring visibility throughout the supply chain, allowing for tracking product progress from inception to delivery. It entails the uninhibited exchange of information, including strategic plans, processes, data, and performance indicators. It renders operations accessible to all stakeholders for informed decision-making. Transparency aids in pinpointing issues, enhancing performance, and cultivating trust among stakeholders. Nonetheless, attaining transparency poses challenges, particularly in intricate, globally dispersed supply chains encompassing numerous stakeholders where transparency is essential for coordination (Chang *et al.*, 2022; Harbert, 2020).

In today's digital age, authenticity is crucial for validating product origins and quality, safeguarding brands, and protecting consumers. Ensuring product authenticity in SCM and PLM means guaranteeing the genuineness of products, compliance with stipulated standards, and protection against counterfeiting or fraud. This aspect holds significant weight in sectors prone to counterfeiting, such as fashion, luxury goods, and pharmaceuticals (Alnuaimi *et al.*, 2022). Consumer demand for authenticity and willingness to pay a premium for genuine products further underscores its importance (Colicev, 2022).

Achieving these objectives in an increasingly complex and globalized business environment is a significant challenge (Brown, 2019; Harbert, 2020; Kraft *et al.*, 2022). Traditional methods of maintaining trust, transparency, and authenticity are becoming less effective due to the growing complexity of supply chains, the increasing speed of product development, and the rising threat of counterfeiting and fraud. These challenges underscore the need for innovative solutions, such as blockchain technology, to enhance trust, transparency, and authenticity in SCM and PLM.

1.2.2. The Potential of Blockchain Technology

Introduced in 2008 by Nakamoto, blockchain technology emerges as a viable solution to numerous challenges within Supply Chain Management (SCM) and Product Lifecycle Management (PLM) (Kshetri, 2018; Rajput *et al.*, 2022), offering a secure and transparent mechanism for recording transactions via distributed ledger systems (Nakamoto, 2008; Puthal *et al.*, 2018; Rajput *et al.*, 2022). Fundamentally, blockchain is a distributed ledger that logs transactions across a network of computers or nodes, ensuring that records cannot be retroactively altered without modifying all subsequent blocks. This attribute of immutability positions blockchain as a dependable source of truth, creating an unalterable history of transactions that is invaluable in SCM and PLM, among other fields, where product provenance and history are essential for maintaining quality and authenticity (Ahmed and MacCarthy, 2022; Chang *et al.*, 2022; Singh *et al.*, 2022).

Unlike centralized databases governed by single entities, the decentralized architecture of blockchain is maintained across a network of nodes, each harboring a complete copy of the ledger. This decentralization bolsters security by eliminating singular points of failure susceptible to hacking and enhances transparency, allowing all network nodes to verify and audit transactions independently (Ali *et al.*, 2019; Chen, Zhang, *et al.*, 2022; Singh *et al.*, 2023).

A pivotal aspect of blockchain's security framework is the employment of cryptographic algorithms that secure transactions. Each transaction is cryptographically linked to its predecessor via a hash, serving as a unique digital signature. This sequential linking forms a tamper-resistant chain of transactions or blocks, where altering a single record necessitates the modification of all subsequent records—a computationally prohibitive task (Puthal *et al.*, 2018; Werbach, 2018). Such cryptographic protection further solidifies the trust in blockchain technology.

Blockchain facilitates using smart contracts programmable scripts that autonomously execute specified actions upon fulfilling predefined conditions (Alharby and van Moorsel, 2017; Khan *et al.*, 2021). Smart contracts streamline numerous SCM and PLM processes, minimizing manual oversight, enhancing operational efficiency, and mitigating error risks (Koirala *et al.*, 2019).

Blockchain technology's secure, transparent, and immutable transaction record fosters stakeholder trust, streamlines operational procedures, and enhances product traceability, laying the foundation for innovative business models such as peer-to-peer marketplaces, token-based economies, and decentralized autonomous organizations (DAOs). However, realizing blockchain's full potential within Supply Chain Management

(SCM) and Product Lifecycle Management (PLM) involves overcoming technical complexities, regulatory uncertainties, and organizational change. Continued research, development, and the formulation of best practices are crucial for navigating these challenges and harnessing blockchain's capabilities effectively.

Organizations aiming to integrate blockchain into SCM and PLM must consider data categorization, adoption challenges, and industry-specific non-functional requirements (Teisserenc and Sepasgozar, 2021). The importance of understanding blockchain's role in future supply chains is highlighted through a systematic literature review and identification of research agendas (Wang *et al.*, 2018). The significance of blockchain in meeting SCM objectives, requiring top-management support and coordination among stakeholders, is further emphasized (Kshetri, 2018; Yadlapalli *et al.*, 2022). The optimization of supply chains through blockchain application in operations and SCM is supported by content analysis (Lohmer *et al.*, 2022), and the synergistic combination of enterprise resource planning and blockchain technologies is stressed for maximizing impact (Singh *et al.*, 2022). Additionally, blockchain's role in enhancing supply chain security and privacy is underlined within the digital twin context (Wang *et al.*, 2022).

In alignment with the foundational principles and potential of blockchain technology, as Nakamoto (2008) introduced, this expanded perspective emphasizes blockchain's technical merits. It addresses the practical challenges and strategic implications of its adoption in SCM and PLM. By undertaking further research and understanding industry-specific needs, organizations can navigate the complexities of blockchain integration, leveraging its decentralized, secure, and transparent nature to foster innovation and efficiency in supply chain and product lifecycle processes.

1.2.3. The Evolution of Blockchain: From Bitcoin to Ethereum to NFTs

The expansion of blockchain technology's potential was notably advanced with the launch of Ethereum and its smart contracts in 2014 (Buterin, 2014). Ethereum diverged from Bitcoin's primary focus as a digital currency by positioning itself as a platform for decentralized applications (dApps). Its blockchain is engineered for transaction recording, storing, and executing computer programs known as smart contracts (Centobelli *et al.*, 2021; Puthal *et al.*, 2018; Radziwill, 2018).

Smart contracts, essentially self-executing contracts with the terms of the agreement embedded in code, operate autonomously on the blockchain, executing actions when pre-set conditions are met. This capability diminishes the reliance on intermediaries, streamlines processes, limits human error, and fosters efficiency—all while enhancing transparency and traceability. These attributes render smart contracts particularly beneficial for SCM and PLM applications, where process automation and efficiency are paramount.

The advent of smart contracts on the Ethereum blockchain constituted a pivotal evolution in blockchain technology. Introducing non-fungible tokens (NFTs) in 2018 amplified the blockchain's application spectrum (Entriken *et al.*, 2018; Radomski *et al.*, 2018). NFTs, distinct digital assets that verify ownership and authenticity via blockchain, contrast with fungible cryptocurrencies like Bitcoin or Ether due to their uniqueness and inability to be exchanged on a like-for-like basis. NFTs are ideally suited for representing tangible assets such as artwork, real estate, and intellectual property, offering unparalleled applications across various domains.

For instance, NFTs can symbolize unique IoT devices within the Internet of Things (IoT), facilitating secure and transparent ownership and management. In healthcare, NFTs could represent individual health records, bolstering data security and patient privacy. Similarly, in intellectual property management, NFTs enable artists and creators to authenticate ownership and explore new monetization avenues (Chokshi, n.d.; Jaribion *et al.*, 2022; Teisserenc and Sepasgozar, 2022).

The progression from blockchain's initial role as a digital currency to its contemporary utility in smart contracts and NFTs underscores the adaptability and expansive potential of the technology. Nevertheless, it also brings to light blockchain's intricacies and implementation hurdles. As blockchain technology advances, comprehending these challenges and devising effective strategies remains critical.

1.2.4. The Metaverse and the Future of Blockchain Technology

Gartner's Top 10 Strategic Technology Trends for 2023 (Groombridge, 2022) underscores the Metaverse, a blockchain-based platform, as a pivotal area for future exploration. Envisioned as a collective virtual shared environment, the Metaverse emerges from the fusion of enhanced physical reality with a consistent virtual presence, encapsulating virtual worlds, augmented reality, and the internet. Gartner forecasts that businesses will increasingly leverage the Metaverse to fortify and expand their brands within the next two to three years, driving revenue growth.

The Metaverse heralds a new era in digital evolution, offering unparalleled opportunities for businesses to create immersive and interactive customer experiences. This convergence of physical and digital realms enables a unified space for real-time interaction across geographical boundaries, reshaping communication, collaboration, and commerce modes. Such integration is essential for evolving business-customer and inter-business engagements (Cheng *et al.*, 2022)

Blockchain technology is instrumental in the Metaverse's development, offering a secure, transparent, and unalterable ledger for digital transactions, which is crucial for asserting ownership and lineage of digital assets within the Metaverse. It facilitates the emergence of decentralized economic systems, where digital assets can be securely and transparently exchanged.

Moreover, blockchain enhances user experiences in the Metaverse, enabling personal digital identity creation, personal data control, and digital asset management. It also supports the deployment of smart contracts to automate Metaverse interactions, streamlining and enriching user engagement.

Nonetheless, the evolution of the Metaverse is not without its challenges, ranging from the technical—such as the demand for advanced computing and networking infrastructure and interoperability among diverse Metaverse platforms—to legal and regulatory hurdles, including intellectual property protection, data privacy, and the prevention of illegal activities. Additionally, there are social and ethical considerations, like ensuring inclusivity, countering misinformation, and addressing the broader societal implications of the Metaverse.

Despite the challenges, integrating blockchain technology and Digital Twins within the Metaverse is poised to revolutionize virtual reality extensions. This synergy is expected to introduce new dimensions of interaction, collaboration, and commerce in the digital sphere, offering significant business opportunities. Understanding and navigating the complexities of Metaverse and blockchain technology will be crucial for leveraging these opportunities (Aloqaily *et al.*, 2022).

1.2.5. The Challenges of Implementing Blockchain Technology

Blockchain technology possesses the capability to fundamentally transform Supply Chain Management (SCM) and Product Lifecycle Management (PLM), as suggested by Wang *et al.* (2018). Nevertheless, the practical deployment of this technology encounters obstacles across technical, organizational, legal, and ethical dimensions, as identified by Rejeb *et al.* (2021). From a technical perspective, the intricate architecture of blockchain necessitates substantial modifications to extant Information Technology infrastructures, raising issues related to scalability and compatibility with legacy systems (Queiroz *et al.*, 2019). On an organizational level, blockchain implementation demands significant process alterations and the alignment of stakeholder interests, thereby underscoring the critical role of educational and training programs in improving comprehension and acceptance (Al Amin *et al.*, 2023).

Legal and regulatory challenges are primarily attributed to the decentralized nature of blockchain networks, which have implications for data privacy and compliance with regulations (Upadhyay *et al.*, 2021; Upadhyay, 2020). Ethical concerns are centered around the potential of blockchain to enhance transparency and fairness while presenting risks associated with illicit activities and environmental impacts (Lohmer *et al.*, 2022). The absence of established best practices further complicates these challenges, highlighting the necessity for meticulous planning and skilled execution (Yadlapalli *et al.*, 2022).

Resolving these challenges mandates strategic approaches rooted in an exhaustive understanding of blockchain technology and its broader implications (Ali *et al.*, 2019). The role of systematic literature reviews and the development of research frameworks are pivotal in guiding the efficacious integration of blockchain into SCM and PLM (Treiblmaier, 2018). As the applications of blockchain technology continue to evolve and garner broader acceptance, continual adaptation and adherence to emerging best practices become paramount for its successful implementation (Bodkhe *et al.*, 2020).

Although blockchain technology harbors the potential to revolutionize SCM and PLM, overcoming its multifaceted challenges necessitates a comprehensive and interdisciplinary strategy. By navigating through technical complexities, fostering organizational alignment, confronting legal and ethical issues, and establishing best practices, organizations can fully exploit the benefits of blockchain technology to optimize supply chain processes and product lifecycle management.

1.3 Purpose of Research

The main focus of this research is to investigate how blockchain technology is incorporated into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) by using Non-Fungible Tokens (NFTs) and smart contracts to create a digital twin environment (DTE). Using Design Science Research (DSR) and System Theory, this study aims to develop and assess creative blockchain frameworks to tackle critical issues in SCM and PLM, such as improving trust, transparency, and authenticity (Chang *et al.*, 2022; Khan *et al.*, 2021).

The research project has set out to accomplish several important goals. These goals include creating and validating a blockchain-focused framework designed to elevate transparency, efficiency, and authenticity in SCM and PLM processes (Chang *et al.*, 2022). Another objective is pinpointing the implementation challenges when integrating blockchain technologies and offering practical solutions (Rejeb *et al.*, 2021). Lastly, the study evaluates how NFTs and smart contracts can improve SCM and PLM operations by testing their effectiveness in real-world scenarios (Chen, Zhang, *et al.*, 2022).

In addition, the research endeavors to make valuable contributions to both theoretical and practical dimensions by closing the divide between theoretical possibilities and practical implementation of blockchain applications in SCM and PLM (Surjandy *et al.*, 2019). Through achieving these goals, the study offers a comprehensive structure for successfully integrating blockchain technologies in SCM and PLM, ultimately boosting operational efficiency and strategic effectiveness in these pivotal business areas (Turjo *et al.*, 2021).

1.4 Significance of the Study

1.4.1 Research Gaps in Earlier Studies

The discourse surrounding blockchain technology and Non-Fungible Tokens (NFTs) predominantly encompasses their foundational concepts and intrinsic capabilities, as highlighted in existing research. Numerous studies and reviews commend the potential and envisage future applications, engaging in speculative discussions about the value NFTs may add to brands or processes (Colicev, 2022). Such inquiries stimulate further exploration into the specific brands that might benefit and how NFTs' social impact could either add value or align theoretically with brand concepts. Investigative efforts, such as those by Nadini *et al.* (2021), dig into market dynamics and specific use cases within the art trade, revealing critical insights into NFTs' role and utility. Far *et al.* (2022) characterize NFTs as a captivating innovation, drawing attention from millions, and broadly discuss the potential applications within industries, including blockchain, smart contracts, NFTs, and the Metaverse.

Among these discussions, Regner *et al.* (2019) stand out by advancing beyond theoretical applications to present a concrete use case involving event tickets. Regner *et al.*'s (2019) work outlines the decision-making and design process and introduces an intriguing prototype to demonstrate the concept's viability. While acknowledging the prototype's simplicity, which may limit its applicability as a universal model for projects beyond the domain of ticket sales, their study nonetheless validates the general utility of the technology.

This landscape of research underscores a critical gap: while the conceptual understanding of blockchain and NFTs is well-articulated, and their potential within various industries is acknowledged (Anjum and Rehmani, 2022; Harbert, 2019; Menon and Jain, 2021; Treiblmaier, 2018), concrete examples of application remain scarce. Though focused and narrowly applied, Regner *et al.*'s (2019) contribution is an initial but vital bridge between theoretical potential and practical implementation. It illuminates the path for further empirical investigations that could extend these technologies' applicability across broader sectors. Such endeavors enrich the academic discourse and offer pragmatic insights for industries seeking to harness the benefits of blockchain and NFTs, thereby expanding the scope of their impact and utility in real-world settings.

1.4.2 The Novelty of this Research

The digital twin concept, which involves creating digital simulations of real-world objects or processes, has been increasingly recognized for its potential to enhance operational efficiency and decision-making processes (Chen, Zhang, *et al.*, 2022; Mayer, 2022; Tao *et al.*, 2018). Concurrently, Non-Fungible Tokens (NFTs) have emerged as a novel means to represent digital ownership of both tangible and intellectual properties, introducing a new paradigm in the management of digital assets (Anjum and Rehmani, 2022; Gonserkewitz *et al.*, 2022).

This research explores the integration of NFTs within a blockchain-based digital twin environment, mainly focusing on applying smart contracts and evaluating NFT standards such as ERC-721 and ERC-1155. These standards will be scrutinized within generalized supply chain management use cases to assess their practicality, identify potential challenges, and determine their overall usability.

1.4.3 Practical Application

The conclusion of this investigation yields a comprehensive framework alongside a set of best practice guidelines designed to facilitate the implementation of complex use cases in supply chain and product lifecycle management processes. Specifically, this framework enables the translation and simulation of assembled or complex products comprising multiple base materials or subcomponents within a blockchain technology-based digital twin environment, such as the Metaverse.

By bridging the capabilities of digital twins with the unique properties of NFTs through blockchain technology, this research seeks to unlock innovative avenues for managing and simulating product lifecycles and supply chain operations. The envisioned framework and guidelines will provide a structured approach to leveraging these technologies and aim to enhance transparency, efficiency, and authenticity within these critical business processes. Through this pioneering exploration, the study aspires to contribute significantly to the theoretical understanding and practical application of blockchain technology, digital twins, and NFTs in revolutionizing supply chain and product lifecycle management.

1.5 Research Purpose and Questions

The study, leveraging the Design Science Research (DSR) methodology and System Theory, undertakes a comprehensive investigation into the incorporation of blockchain technology within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). It focuses on the transformative potential of non-fungible tokens (NFTs) and smart contracts within these sectors. It aims to critically assess their contributions to elevating trust, transparency, and authenticity levels across SCM and PLM processes. This research approach is characterized by a meticulous process encompassing the design, development, and evaluation of blockchain-based artifacts, aiming to offer practical solutions and frameworks for organizations looking to leverage blockchain technology (Teisserenc and Sepasgozar, 2021).

The DSR methodology provides a structured framework that emphasizes the creation and evaluation of technological artifacts to address practical problems, incorporating an iterative process of artifact creation, testing, refinement, and re-evaluation to ensure solutions are both effective and practical (Dresch *et al.*, 2015; Hevner *et al.*, 2004; Teisserenc and Sepasgozar, 2021). System Theory offers a holistic perspective for understanding the complexities and interdependencies within SCM and PLM systems, underscoring the importance of considering broader implications of blockchain integration, such as its impact on organizational processes, stakeholder interactions, and the overall value chain (Hofkirchner, 2005; Kowch, 2023; Kshetri, 2018).

Focusing on NFTs and smart contracts, the study explores how these blockchain technologies can innovate SCM and PLM practices. NFTs can provide a robust mechanism for certifying the authenticity and ownership of products, while smart contracts promise to streamline operations and enhance contractual compliance across supply and distribution networks. The ultimate goal is to explain how blockchain can revolutionize SCM and PLM by fostering an environment of enhanced trust, transparency, and authenticity.

1.5.1 Research Questions

1. Integration of Blockchain Technologies in SCM and PLM:

   How can NFTs and smart contracts seamlessly incorporate into SCM and PLM systems to bolster transparency, efficiency, and authenticity?

   This question is addressed in Section 4.1 of the Results chapter, where the integration of blockchain artifacts is discussed in-depth.

2. Challenges and Solutions in Adoption:

   What are the challenges in adopting blockchain technologies within SCM and PLM, and what innovative solutions and best practices can address these challenges?

   This question is explored in Sections 4.2 and 5.3, where adoption challenges and proposed solutions are outlined.

3. Impact on Operational and Strategic Dimensions:

   What are the broader implications of blockchain technologies on SCM and PLM, particularly their effects on operational processes and strategic decision-making?

Findings relevant to this question are presented in Section 4.3 and discussed in Section 5.4.

4. Theoretical and Practical Contributions:

   How can the findings consolidate into a cohesive framework that advances blockchain's theoretical understanding and practical application in SCM and PLM? This question is addressed comprehensively in Sections 4.4, 5.5, and 6.2

By addressing these questions, the research provides a holistic view of the potential and challenges of blockchain in SCM and PLM, contributing valuable insights into the practical implementation of blockchain technology. The outcomes of this research include blockchain technology-based artifacts that demonstrate tangible improvements in SCM and PLM processes, thereby serving as a valuable resource for practitioners in the field and paving the way for more innovative, secure, and efficient practices (Teisserenc and Sepasgozar, 2021).

CHAPTER II:

REVIEW OF LITERATURE

2.1 Introduction

The rapid evolution of digital technologies is severely reshaping the landscape of Supply Chain Management (SCM) and Product Lifecycle Management (PLM). Innovations such as blockchain technology, non-fungible tokens (NFTs), smart contracts, and digital twins disrupt traditional operational models and offer unique new opportunities for efficiency, transparency, and security. This section initiates a comprehensive literature review to explore these emerging technologies' potential integration into SCM and PLM frameworks.

2.1.1 Purpose and Scope of the Literature Review

Within the dynamically evolving domains of Supply Chain Management (SCM) and Product Lifecycle Management (PLM), a significant transformation is being catalyzed by advancements in digital technologies (Kshetri, 2018). Central to this revolution are blockchain technology and its derivatives, such as non-fungible tokens (NFTs) and smart contracts, alongside the nascent concept of digital twins. This literature review intends to meticulously analyze the extant academic discourse on incorporating blockchain, NFTs, smart contracts, and digital twins within SCM and PLM frameworks. This investigation is aimed at delineating the current confluence of technology and practice, pinpointing lacunae in scholarly research, and devising a comprehensive framework for the efficacious integration of these technologies into supply chain infrastructures, thereby laying a robust foundation for further scholarly exploration (Grieves and Vickers, 2016; Nakamoto, 2008; Radziwill, 2018).

The scope of this review spans seminal works, empirical research, and ongoing dialogues that illuminate the technical complexities, practical applications, challenges, and future directions of blockchain technology, NFTs, smart contracts, and digital twins within SCM and PLM contexts. Notably, blockchain technology is recognized for its potential to effectuate a paradigm shift in supply chain activities by enhancing transparency, traceability, and security across the supply chain network (Behnke and Janssen, 2019; Kshetri, 2018). Furthermore, integrating digital twins into supply chain management is anticipated to augment visibility and optimize operations within intricate supply chain networks (Della Valle and Oliver, 2021; Wu *et al.*, 2023).

Through a comprehensive analytical process, this review aspires to forge a foundational understanding that will underpin subsequent segments of this scholarly investigation. By integrating insights from authoritative sources, this review contributes to the evolving discourse on the transformative impact of blockchain, NFTs, smart contracts, and digital twins in redefining SCM and PLM practices.

2.1.2 Relevance of Blockchain and Digital Twins in Modern SCM and PLM

Within the complex framework of contemporary supply chain management (SCM) and product lifecycle management (PLM), digital innovation catalyzes profound transformations. Blockchain technology, characterized by its foundational principles of decentralization, immutability, and transparency, redefines trust and transactional integrity paradigms in SCM environments (Kshetri, 2018). Its capacity for secure, intermediary-free recording and verification of transactions across multiple stakeholders tackles the enduring challenges of traceability and fraud within supply chains. Moreover, the emergence of Non-Fungible Tokens (NFTs) facilitates the digital or physical representation of unique assets on the blockchain, opening new avenues for asset management and ownership verification. Additionally, smart contracts, as extensions of blockchain technology, automate and enforce contractual obligations autonomously, ensuring compliance with predetermined conditions, thus enhancing operational efficiency and reducing inconsistencies (Werbach, 2018).

In parallel, the advent of digital twins is transforming PLM by providing a dynamic digital representation of physical assets, enabling real-time monitoring, simulation, and analysis. This advancement supports refined product design, anticipates performance, and underpins proactive maintenance and optimization across the product's lifespan (Tao *et al.*, 2018). Integrating blockchain technology with digital twins amplifies their benefits, imbuing them with superior security, trustworthiness, and data integrity and ensuring the digital counterpart accurately reflects the physical object.

The synergy between blockchain and digital twins presents unparalleled opportunities, heralding the advent of more resilient, transparent, and efficient supply chains and fostering innovative approaches to longstanding challenges in product development, manufacture, and service. Investigating this nexus is not merely academic; it is a pivotal endeavor in directing the future of SCM and PLM towards robust, agile, and adaptable systems in the face of a swiftly changing digital era.

2.2 Blockchain Fundamentals

2.2.1 Brief History of Ledgers

The concept of a ledger, foundational to bookkeeping, dates back at least 5,000 years, with some of the earliest recorded instances of quantities found on Mesopotamian clay tablets from around 3200 BC, organized in rows and columns (LLFOURN, 2018). By approximately 1340 AD, merchants and moneylenders in northern Italy devised a revolutionary accounting method—the double-entry system. This innovation introduced a logical relationship between ledger entries by recording each transaction as a credit and a debit. Carruthers and Espeland (1991) highlight that the Marxist economist Werner

Sombart was among the first to link this accounting method to the emergence of what is today recognized as capitalism.

Ledgers have found their application across various spheres of life, most notably in banking, financial markets, and trading sectors. Notably, the Bank of England initiated its first cashbook in 1694 to meticulously document its financial transactions and values (Carruthers and Espeland, 1991), marking a significant milestone in the evolution of ledger use in modern financial systems.

2.2.2 Understanding Blockchain Core Concepts

Blockchain, or distributed ledger technology, represents a significant advancement from traditional ledgers, incorporating a cryptographically secured digital platform for recording transactions (Puthal *et al.*, 2018). As an electronic peer-to-peer payment system introduced by Nakamoto (2008), Blockchain technology facilitates financial transactions between two parties without requiring a third-party authority to oversee or verify the transactions. The network's architecture, comprising distributed nodes, ensures transaction transparency, traceability, authenticity, and trustworthiness (Centobelli *et al.*, 2021). Unlike classical ledgers or conventional database storage that centralizes data in a single location, distributed ledger technology disseminates and synchronizes data across all nodes or computers within the network, enhancing security and trust since the data's authenticity relies on the collective verification of the entire network rather than on a solitary system or entity (Puthal *et al.*, 2018; Zanni *et al.*, 2019).

This technology's unique method of storing transactions in blocks, interconnected through cryptographic hash values (*Figure 1*), not only defines the structure of a blockchain but also contributes to its characteristic immutability (Ali *et al.*, 2019; Chang *et al.*, 2022). In *Figure 1*, each block represents a set of validated transactions; the arrows between blocks illustrate the cryptographic reference hash value linking each block to its predecessor. This visual chain emphasizes that altering one block would invalidate all subsequent blocks, reinforcing the blockchain's tamper-resistant nature. *Figure 1* provides a visual baseline for understanding how data is securely chained over time. Papers such as Chang *et al.* identified the benefits of blockchain. (2022), Centobelli *et al.* (2021), and Puthal *et al.* (2018) encompass transparency, auditability, and traceability alongside autonomy, decentralization, immutability, and irreversibility, positioning blockchain as a transformative force in digital transaction management and beyond.

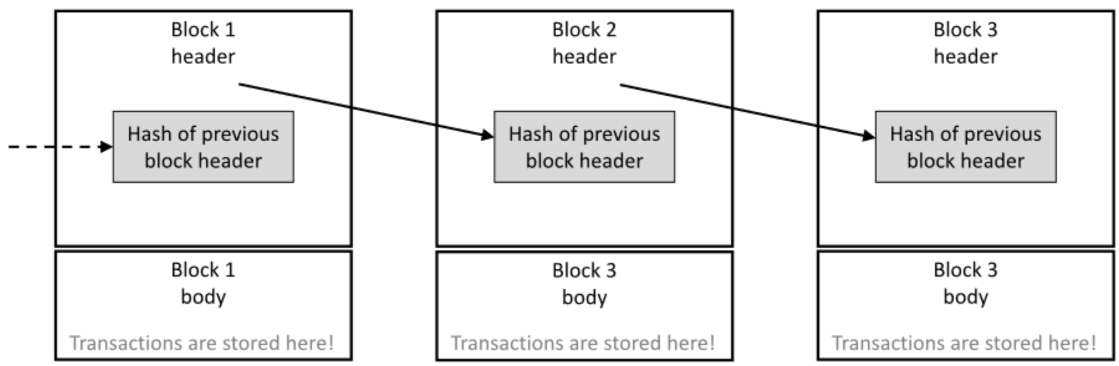

Figure 1.
Logical representation of a Blockchain (Source: Ali et al., 2019)

2.2.3 Smart Contracts

Smart contracts, as extensions of blockchain technology, present an innovative mechanism for automating and enforcing contractual obligations autonomously within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). The concept, fundamentally designed to satisfy common contractual conditions such as payment terms and enforcement mechanisms, has evolved significantly since its conceptualization by Szabo (1994). Smart contracts reduce transaction costs and the need for trusted intermediaries, making them crucial in the modern digital transformation of SCM and PLM processes (Szabo, 1994).

The essence of smart contracts in SCM is their ability to automate complex processes, enhancing operational efficiency and reducing inconsistencies that typically arise from human intervention. For example, smart contracts can automatically execute transactions when predetermined conditions are met, such as releasing payments upon receiving goods, thereby ensuring compliance with agreed terms without delay (Werbach, 2018). In PLM, these contracts can manage rights and warranties automatically across the product's lifecycle, thus adding a layer of efficiency and security (Rouhani and Deters, 2019; Taherdoost, 2023).

Research highlights the transformative potential of smart contracts in reshaping business operations by embedding trust and transparency in transactions (Koirala *et al.*, 2019). The decentralization aspect inherent in blockchain technology, coupled with the autonomous execution of contracts, offers robust solutions to historical challenges such as fraud and arbitration costs. Smart contracts are not just theoretical constructs but have practical implications in fields such as finance, real estate, and international trade, where they contribute significantly to reducing transaction times and costs (Khan *et al.*, 2021).

However, the application of smart contracts goes beyond mere automation. They are pivotal in facilitating dynamic and complex interactions within digital ecosystems, particularly in environments with high uncertainty and risk (Voshmgir, 2016). This capability is especially relevant in SCM and PLM, where verifying product authenticity and compliance with regulatory standards are paramount. Alharby and van Moorsel (2017) demonstrate that smart contracts can effectively minimize the risk of malicious exceptions and accidental oversights, ensuring that all parties adhere to the agreed standards and terms.

The integration of smart contracts into SCM systems has also been noted for its potential to foster significant improvements in traceability and accountability (Kõlvart *et al.*, 2016). By automating the documentation and verification processes, smart contracts ensure that every transaction or modification is recorded in the blockchain's immutable ledger, thus enhancing the integrity and traceability of supply chains.

Despite the promising advancements, implementing smart contracts is not free of challenges. Issues such as code security, transaction privacy, legal validity, and the interoperability of smart contracts with existing legal frameworks remain critical areas requiring ongoing research and development (Alharby and van Moorsel, 2017; Rouhani and Deters, 2019). Moreover, the technical complexity of designing smart contracts that are both secure and efficient poses significant hurdles, necessitating a multidisciplinary approach, including security reviews of their development and deployment (Koirala *et al.*, 2019).

Smart contracts represent a significant evolution in the automation and execution of legal agreements within the digital age. They offer substantial benefits in terms of operational efficiency, reduced need for intermediaries, and enhanced compliance with contractual obligations. Continued exploration and refinement of this technology are essential to overcome existing challenges and fully realize its potential within SCM and PLM. The evolving research landscape, characterized by contributions from Khan *et al.* (2021) and Koirala *et al.* (2019), suggests a promising future where smart contracts could become fundamental components of digital transaction systems across various industries.

2.2.4 Non-Fungible Tokens (NFTs)

Unlike cryptocurrencies, non-fungible tokens (NFTs) represent a profound advancement in blockchain technology, primarily distinguishing themselves by their uniqueness and inability to be exchanged on a one-to-one basis. This distinct non-tangible attribute allows NFTs to effectively certify the ownership and originality of digital assets (Wang and Lau, 2023). As the landscape of digital assets evolves, the application of NFTs has expanded beyond digital art and collectibles to include uses in sectors such as healthcare, supply chain management, and intellectual property rights management (Jaribion *et al.*, 2022; Yaghy *et al.*, 2023).

NFTs introduce a novel paradigm in digital asset management by ensuring traceability, reducing fraud, and enhancing the transparency of transactions (Chen *et al.*, 2023). They are essential in digitalization strategies, particularly within Product Lifecycle Management (PLM) and Supply Chain Management (SCM). In PLM, NFTs can be utilized to create digital twins of physical products, enabling real-time tracking, verification, and management of changes throughout a product's lifecycle(Wang and Lau, 2023). In SCM, NFTs enhance the authenticity and traceability of products. By tokenizing physical goods, NFTs allow for the secure and transparent tracking of the product journey from production to end consumer, mitigating risks associated with counterfeit goods and enhancing supply chain efficiency (Seol *et al.*, 2023). Furthermore, integrating NFTs with digital twins technology provides a robust mechanism for managing digital representations of physical assets in industries like shipping, where traceability and compliance are paramount (Elmay *et al.*, 2023).

The use of NFTs in digital rights management (DRM) exemplifies their potential to innovate beyond typical blockchain applications. Through DRM, creators can retain control over their digital content, offering new methods for monetization while protecting intellectual property (Jaribion *et al.*, 2022). Adopting NFTs in healthcare for managing medical device life cycles illustrates NFTs' broad applicability and potential to ensure compliance with safety standards and regulatory requirements (Gebreab *et al.*, 2022).

However, the deployment of NFTs faces several challenges, including scalability, the environmental impact of blockchain technology, and the legal complexities involved in asset tokenization (Guidi and Michienzi, 2023). These challenges impose further research and development to optimize the architecture of NFT-based systems for broader adoption and regulatory compliance.

NFTs offer a transformative potential that extends across various sectors, enabling more secure, transparent, and efficient management of digital and physical assets. As this technology matures, further exploration and integration into existing digital frameworks will be critical for realizing its full potential in SCM and PLM (Chen *et al.*, 2023; Wang and Lau, 2023). The evolution from static NFT (v1.0) to interactive and dynamic NFT (v2.0) marks a significant step in this direction, promising enhanced functionalities and broader applications in a rapidly digitizing world (Guidi and Michienzi, 2023).

2.3 Blockchain in Supply Chain Management (SCM)

Blockchain technology has revolutionized Supply Chain Management (SCM) by providing increased transparency, accountability, and efficiency. This section analyzes the relationship between blockchain and SCM to provide a comprehensive understanding of this innovative technology.

2.3.1 Current State of Blockchain in SCM

Integrating blockchain technology into SCM represents a significant advancement towards sustaining transparency and fostering trust across various industries. The inherent capability of blockchain to ensure a secure and immutable ledger is pivotal in building trust among supply chain participants, an aspect thoughtfully analyzed by Kshetri (2018). The harmonious fusion of blockchain with the Internet of Things (IoT) paves the way for remarkable progress in SCM, enabling detailed tracking and authentication of goods. This is particularly notable in the food sector, where blockchain's implementation has been crucial in tackling significant issues such as traceability and safety, as thoroughly discussed by Kshetri (2018) and Treiblmaier (2018).

While the trajectory of blockchain's incorporation within SCM is promising, there is a growing recognition of its transformative capacity. Beyond its initial use in cryptocurrencies, blockchain's utility in SCM extends to streamlined operations and improved product traceability (Dursun *et al.*, 2022; Rejeb *et al.*, 2021). The evolution of blockchain in SCM highlights the technology's ability to overcome traditional supply chain challenges, with its potential increasingly acknowledged across sectors such as Pharmaceuticals, IoT, Energy creation and trading, Anti Counterfeiting, and essential for the SCM environment, product traceability (Queiroz *et al.*, 2019; Surjandy *et al.*, 2019).

2.3.2 Benefits of Blockchain in SCM

Blockchain technology endows SCM with several advantages, most notably the enhancement of transparency and the cultivation of trust. Its decentralized nature ensures that all transactions and product origins are immutably documented, thereby creating a trustworthy environment and diminishing fraud across the supply chain (Sanyal and Khan, 2021; Surjandy *et al.*, 2019). Such technological innovation is instrumental in combating counterfeiting and preserving supply chain integrity, as Surjandy *et al.* (2019) and Rajput *et al.* (2022) emphasize.

Surjandy *et al.* (2019) and Rajput *et al.* (2022) provide a detailed analysis of the numerous benefits of blockchain technology in Supply Chain Management (SCM), highlighting its transformative impact across a variety of SCM areas through rigorous scholarly inquiry.

In their study, Surjandy *et al.* (2019) emphasize the crucial role of blockchain technology in improving traceability and transparency in the pharmaceutical supply chain. Their research notably documents how blockchain can trace product origins, prevent the spread of counterfeit products, and certify the authenticity and safety of pharmaceuticals. In their research, Surjandy *et al.* (2019) demonstrate the effectiveness of blockchain in tracking pharmaceutical products throughout the supply chain, ensuring consumer safety and promoting drug authenticity. Their analysis suggests that adopting blockchain technology in the pharmaceutical industry can be a strategic response to the risks of drug counterfeiting, ultimately enhancing the overall integrity of the supply chain.

In Addition, Rajput *et al.* (2022) have extensively researched the use of blockchain-based smart contracts in supply chain management (SCM), highlighting the technology's ability to foster trust among stakeholders, simplify transactions, and drive operational improvements. Their findings explain how smart contracts build trust by recording immutable and transparent transactions within them, ensuring all stakeholders have access to and can authenticate all transactions. This transparency boosts confidence and eliminates the need for intermediaries. Furthermore, Rajput *et al.* (2022) explore how smart contracts can enhance operations through precise and secure data collection, such as efficient inventory management and tailored product offerings. This approach leads to increased efficiency and supply chain responsiveness, showcasing the vast benefits that blockchain technology can bring to SCM.

Synthesizing the insights from both studies reveals that blockchain and smart contracts establish a novel SCM paradigm characterized by enhanced transparency, bolstered trust, and streamlined operations. While Surjandy *et al.* (2019) offer an in-depth investigation into blockchain's influence on the pharmaceutical industry, Rajput *et al.* (2022) provide an expansive analysis of smart contracts' utility across various SCM sectors. Collectively, these scholarly contributions articulate a persuasive argument regarding blockchain technology's revolutionary potential in redefining SCM practices, highlighting its pivotal role in fostering secure, transparent, and efficient supply chains.

Alongside transparency, blockchain significantly refines operational efficiencies—the technology's capacity to bypass intermediaries results in faster and more economical transactions. Integrating blockchain with IoT and artificial intelligence (AI) further enhances its efficacy for real-time product tracking, thus optimizing supply chain procedures and improving visibility (Dwivedi *et al.*, 2020; Hirata *et al.*, 2020; Sanyal and Khan, 2021).

Dwivedi *et al.* (2020) argue that blockchain technology can eliminate intermediaries, streamline supply chain operations, and promote cost-effectiveness and efficiency. They assert that blockchain technology facilitates direct interactions within supply chains, leading to a more agile and responsive supply chain landscape.

Similarly, Hirata *et al.* (2020) examine the nuanced roles that blockchain technology plays in redefining intermediation within supply chains. They hypothesize that blockchain technology can complement traditional intermediaries, presenting a balanced view of its transformative potential in traditional supply chain models. By facilitating novel forms of intermediation, blockchain technology can enhance supply chain structures, fostering innovation and sustainability.

Sanyal and Khan (2021) provide further insights into blockchain technology's economic and social benefits in supply chain management. They illustrate how blockchain technology can reduce transaction costs and enhance transparency, leading to significant economic and social benefits within supply chains. They also emphasize the social implications of blockchain technology in supply chain management, including enhancing labor standards and preventing fraud, contributing to a more sustainable and ethical global supply chain ecosystem.

These scholarly contributions collectively highlight blockchain technology's multifaceted benefits in supply chain management. By bypassing intermediaries, blockchain technology can accelerate transactions, reduce costs, and introduce a new paradigm of efficiency and transparency. With the integration of IoT and AI, blockchain technology is prepared to revolutionize supply chain operations, ensuring more robust, secure, and efficient supply chains. These scholarly contributions underscore the transformative potential of blockchain technology in redefining SCM practices, contributing to a more secure, transparent, and efficient supply chain network.

2.3.3 Challenges and Limitations

Integrating blockchain technology within Supply Chain Management (SCM) represents a paradigm shift towards enhancing transparency, efficiency, and traceability (Dwivedi *et al.*, 2020). However, its adoption is not without challenges and limitations. This section summarizes insights from scholarly papers articulating blockchain technology's primary hurdles in SCM.

One of the most mentioned challenges is scalability. Blockchain's capability to manage the extensive transaction volumes characteristic of global supply chains is crucial. However, as Chang *et al.* (2022), Cui *et al.* (2019), and Dwivedi *et al.* (2020) emphasize that an increase in transactional demands can strain blockchain networks, potentially degrading their performance and, by extension, their effectiveness within SCM.

Integrating blockchain into SCM systems also raises questions regarding technological and organizational readiness (Hirata *et al.*, 2020). The absence of standardization and interoperability across different blockchain platforms hampers seamless information exchange among supply chain participants. The fragmentation of blockchain applications complicates its adoption and limits the potential for widespread integration (Hirata *et al.*, 2020).

Blockchain technology requires substantial initial investments and ongoing operational costs (Sanyal and Khan, 2021). For small and medium-sized enterprises (SMEs), the cost implications of blockchain technology could be a constraint, limiting its adoption across the broader SCM landscape. The financial burden associated with blockchain implementation can restrict its accessibility and utilization, particularly among smaller enterprises (Sanyal and Khan, 2021).

The regulatory and legal environment surrounding blockchain technology remains uncertain, posing additional challenges to its adoption in SCM. Clear regulatory guidelines and legal standards are needed to mitigate risks and foster a conducive environment for blockchain integration in supply chains (Surjandy *et al.*, 2019).

The deployment of blockchain technology in SCM necessitates specialized knowledge and expertise (Rajput *et al.*, 2022). The technical complexities involved in blockchain implementation require significant training and capacity-building efforts. The lack of blockchain expertise among SCM stakeholders can impede its effective utilization (Rajput *et al.*, 2022).

While blockchain is renowned for its security features, the technology raises concerns regarding data privacy (Al Amin *et al.*, 2023). Ensuring data privacy while maintaining the integrity and transparency of blockchain transactions remains a critical concern (Al Amin *et al.*, 2023).

Transformational change driven by blockchain adoption in SCM can encounter organizational resistance (Yadlapalli *et al.*, 2022). Resistance to change and cultural challenges are significant barriers to blockchain integration, emphasizing the need for a shift in mindset and operational practices among SCM stakeholders (Yadlapalli *et al.*, 2022).

Lastly, the technological maturity of blockchain and its readiness for large-scale applications in SCM is under scrutiny (Haque *et al.*, 2021; Menon and Jain, 2021; Queiroz *et al.*, 2019). The absence of comprehensive, proven applications in SCM presents a hurdle to its widespread adoption and effectiveness within supply chains (Haque *et al.*, 2021; Menon and Jain, 2021; Queiroz *et al.*, 2019).

While blockchain technology holds promise for revolutionizing SCM practices, it faces several challenges spanning scalability, readiness, financial implications, regulatory uncertainties, technical complexity, data privacy concerns, cultural resistance, and technological maturity. Addressing these challenges necessitates a collaborative effort among academia, industry stakeholders, and regulatory bodies to foster the development and adoption of blockchain technology within SCM.

Despite its myriad benefits, implementing blockchain within SCM is challenging. The technology's complexity and the requirement for advanced digital infrastructure pose substantial obstacles, especially for stakeholders in developing regions (Al Amin *et al.*, 2023; Yadlapalli *et al.*, 2022). Privacy, scalability, and regulation compliance complicate blockchain adoption in supply chains (Haque *et al.*, 2021; Menon and Jain, 2021).

The success of blockchain-based SCM systems depends on all stakeholders' cooperative involvement. However, achieving consensus among diverse and often competing parties presents a formidable challenge. Several academic papers highlight the need for standardization, governance, and technological interoperability, indicating the complex hurdles faced in implementing blockchain solutions within SCM (Al Amin *et al.*, 2023; Queiroz *et al.*, 2019; Rejeb *et al.*, 2021).

2.4 Blockchain in Product Lifecycle Management (PLM)

Inherently, blockchain technology offers a decentralized framework that significantly enhances data security, accountability, and traceability across various stakeholders throughout the product lifecycle—from conception to design, manufacturing, service, and disposal. This shift not only aims to alleviate the complexities associated with traditional PLM systems but also introduces novel paradigms of operation and collaboration across the industry spectrum. The forthcoming sections will explore the transformative potential of blockchain in PLM, spotlighting case studies, analyzing benefits, and addressing the inherent challenges and future directions of this integration.

For a comprehensive understanding, Leng *et al.* (2020) discuss how blockchain empowers sustainable manufacturing and PLM, signaling a shift towards consumer-centric models facilitated by blockchain architectures. Similarly, Belhi *et al.* (2020) provide a conceptual assessment, elucidating the added value and challenges of integrating blockchain with PLM systems, thereby setting the stage for the subsequent detailed exploration.

2.4.1 Role of Blockchain in PLM

Recognized for its foundational role in cryptocurrency systems, blockchain technology is rapidly being acknowledged as a transformative tool in Product Lifecycle Management (PLM). This section exposes the inherent relevance of blockchain to PLM, particularly its capacity to enhance the phases of product lifecycle management through its decentralized, immutable, and transparent nature (Leng *et al.*, 2020). By facilitating a decentralized network, blockchain technology enables stakeholders—from designers to consumers—to actively participate in the lifecycle of products, thereby challenging traditional centralized models of manufacturing and management (Leng *et al.*, 2020).

Integrating blockchain into PLM systems revolutionizes traditional practices by enhancing transparency, traceability, and data integrity across the product lifecycle. This is particularly vital in scenarios where multiple stakeholders are involved in the product development process across geographical and organizational boundaries. For instance, Belhi *et al.* (2020) underscore the capability of blockchain to streamline operations by creating a trustless environment where all transactions and data exchanges are recorded immutably and transparently. This feature minimizes fraud opportunities and facilitates compliance and auditing processes (Belhi *et al.*, 2020).

The transformative role of blockchain in PLM extends beyond mere data management to foster a shift in manufacturing paradigms—from linear, sequential processes to interconnected, transparent networks that utilize distributed ledger technology for enhanced collaboration and efficiency.

Several case studies exemplify the successful integration of blockchain in PLM processes. For instance, in the automotive industry, blockchain has been employed to ensure the traceability of components across the entire supply chain, thereby enhancing the security and transparency of data exchanges among manufacturers, suppliers, and consumers (Chen *et al.*, 2022; Holler *et al.*, 2019). This application has profound implications for areas such as warranty management, recall operations, and customer trust, as each transaction related to a product's lifecycle is verifiable and immutable.

Another notable application is observed in the aerospace industry, where blockchain supports the lifecycle management of aircraft parts, ensuring that every component used in the construction and maintenance of aircraft is meticulously documented. This provides a reliable and immutable record that enhances safety, compliance, and maintenance scheduling (Holler *et al.*, 2019).

2.4.2 Benefits of Blockchain for PLM

Integrating blockchain technology into Product Lifecycle Management (PLM) systems substantially elevates efficiency, transparency, security, and compliance capabilities. This section explores the significant advantages of blockchain for PLM, supported by scholarly research and empirical case studies.

A fundamental benefit of blockchain in PLM is the enhanced transparency and traceability throughout the product lifecycle. Belhi *et al.* (2020) highlight that blockchain's decentralized nature obviates the need for intermediaries, thereby streamlining processes and improving the visibility of transactions. This transparency proves indispensable in sectors such as pharmaceuticals and aerospace, where the provenance and history of parts and ingredients are beneficial and often mandated by regulatory standards.

The application of blockchain in PLM significantly bolsters security and data integrity. The immutable nature of blockchain ensures that once product data is recorded, it cannot be altered without consensus from all involved parties. Chen *et al.* (2022) note that blockchain's robust security features safeguard against unauthorized changes and access to sensitive product information.

Blockchain technology enhances operational efficiency within PLM by automating numerous routine tasks through smart contracts. These contracts are executed automatically based on predefined conditions, thus reducing delays and eliminating potential human errors. Li *et al.* (2022) underscore how blockchain optimizes operations and curtails costs by enabling quicker and more precise information flow throughout the product lifecycle.

Blockchain facilitates compliance with regulatory requirements by providing a transparent and immutable record of all transactions. As demonstrated by Holler *et al.* (2019), blockchain assists automotive manufacturers in adhering to safety and environmental regulations by maintaining an unalterable record of manufacturing data.

While the benefits are substantial, integrating blockchain into existing PLM systems presents challenges. Addressing scalability issues stemming from the extensive data managed within blockchain networks and the interoperability challenges with existing legacy systems (Liu, Wang, *et al.*, 2020; Liu, Zhang, *et al.*, 2020).

Blockchain technology redefines traditional paradigms of product lifecycle management by enhancing traceability, increased security, improved operational efficiency, and streamlined compliance. These capabilities render blockchain an invaluable asset within the intricate ecosystems of modern manufacturing and product management.

2.4.3 Challenges in Integrating Blockchain with PLM

Though replete with promise, integrating blockchain technology into Product Lifecycle Management (PLM) systems introduces a spectrum of significant challenges that must be navigated to leverage its potential fully. These challenges span technical, organizational, and regulatory domains.

A primary hurdle is the inherent complexity of blockchain technology. Transitioning from traditional centralized data management to a distributed ledger approach necessitates profound alterations in existing IT infrastructure. It demands a comprehensive understanding of blockchain's functionality, including consensus mechanisms and smart contracts. Liu *et al.* (2020) stress the importance of developing blockchain frameworks that seamlessly integrate with current PLM systems without disrupting their operations.

As Chen *et al.* (2022) highlighted, blockchain applications in PLM must manage the substantial data volumes generated throughout various product lifecycle stages. The scalability of blockchain technology in processing such extensive data while maintaining performance and speed presents a formidable challenge. This issue is exacerbated by the need for blockchain networks to handle increasing transactions as PLM systems expand (Chen, Cai, *et al.*, 2022)

Effective blockchain integration into PLM systems also necessitates high interoperability with existing enterprise systems, which may employ diverse standards and technologies. Hayat and Winkler (2022) underscore the difficulties in achieving this interoperability, noting that current PLM systems often operate in silos and may not be configu red to interact with blockchain-based platforms.

Implementing blockchain technology incurs significant costs, encompassing initial setup and integration expenses and ongoing operational costs. These expenditures arise from the necessity for continual maintenance, updates, and security measures to safeguard the blockchain network. Belhi *et al.* (2020) accentuate the financial commitment required to transition to blockchain-based PLM systems, which may constitute a barrier for many organizations.

Additionally, the adoption of blockchain in PLM must compete with a complex array of regulatory and legal considerations. These include issues on data privacy, cross-border data transfers, and compliance with industry-specific regulations. The decentralized nature of blockchain complicates jurisdiction and compliance determination, particularly in global supply chains.

Despite these challenges, the potential benefits of integrating blockchain into PLM systems—such as enhanced traceability, increased security, and improved collaboration—render it worthwhile. Addressing these challenges necessitates a concerted effort from technology providers, industry stakeholders, and regulatory bodies to develop standards, provide education, and foster an ecosystem conducive to blockchain adoption in PLM.

2.4.4 Future Directions and Research Opportunities

The convergence of blockchain with Product Lifecycle Management (PLM) opens a horizon rich with novel research opportunities and potential advancements. This section explores prospective directions that future research might pursue to integrate blockchain into PLM further, emphasizing the symbiosis with emerging technologies, the development of standards, and the exploration of innovative applications.

The unique properties of blockchain, such as immutability and transparency, could be harnessed to introduce groundbreaking applications within PLM. For example, employing blockchain to create digital twins of physical assets can provide a real-time, incorruptible record of product changes throughout its lifecycle (Belhi *et al.*, 2020). Additionally, using Non-Fungible Tokens (NFTs) for unique product identification could revolutionize product tracking, offering detailed provenance and authenticity verification (Hayat and Winkler, 2022).

Integrating blockchain with other cutting-edge technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) presents exciting prospects. AI can augment blockchain's capabilities within PLM by optimizing supply chain decisions and predictive maintenance based on real-time data from IoT devices. Such integrations can promote smarter manufacturing practices and enhanced data-driven decision-making (Chen, Cai, *et al.*, 2022; Kulkarni *et al.*, 2020).

There is an urgent need to develop global standards and protocols that facilitate blockchain integration into existing PLM systems. These standards would ensure interoperability among diverse systems and industries, promoting a more seamless adoption of blockchain technology (Leng *et al.*, 2020). Standards could also help address security concerns by defining robust protocols for data encryption and transaction validation in a PLM context.

Future research can explore the concept of DAOs to manage PLM activities, where blockchain supports the data integrity of product records and automates governance processes. This approach could include smart contracts that execute based on predefined criteria without human intervention, potentially reducing the time and costs associated with manual oversight (Li *et al.*, 2022).

Future investigations should also consider blockchain applications' ethical implications and sustainability in PLM. This involves assessing the environmental impact of blockchain operations and exploring sustainable blockchain solutions that reduce energy consumption. Additionally, ethical considerations regarding data privacy and the potential displacement of jobs due to automation should be rigorously examined (Hayat and Winkler, 2022).

These avenues underscore the transformative potential of blockchain in revolutionizing PLM and highlight the multidisciplinary approach required to leverage this technology fully. As blockchain continues to evolve, so do its applications in PLM, promising significant advancements in how products are managed from conception to end-of-life.

2.5 Digital Twins and Blockchain Integration

Integrating Digital Twins with Blockchain technology has emerged as a promising approach to enhance security, transparency, and trust in supply chain management (SCM) and product lifecycle management (PLM) processes. This section provides an in-depth exploration of the concepts and applications of Digital Twins within various domains, followed by a detailed analysis of the integration of Blockchain technology with Digital Twins.

2.5.1 Digital Twins: Concepts and Applications

Digital Twins have emerged as a significant area of academic and industrial interest, as they represent the entanglement of the real and virtual worlds by creating virtual duplicates of physical entities or systems (Grieves, 2005; Singh *et al.*, 2021). The concept of Digital Twins originated from the "Mirror Worlds" in 1991 and was formally established by John Vickers at NASA in 2010 (Shafto *et al.*, 2010), since which time, Digital Twins have undergone significant evolution (Grieves, 2005; Shafto *et al.*, 2010; Singh *et al.*, 2021).

The digital replicas of physical entities facilitate real-time monitoring, analysis, and simulation of their physical counterparts (*Figure 2.*), allowing for a comprehensive understanding of intricate systems. The fundamental aspect of Digital Twins lies in achieving and maintaining a dynamic alignment between the virtual model and the physical entity's characteristics, ensuring an unparalleled level of accuracy (*Digital Twin Conversation*, 2023; Minerva *et al.*, 2020).

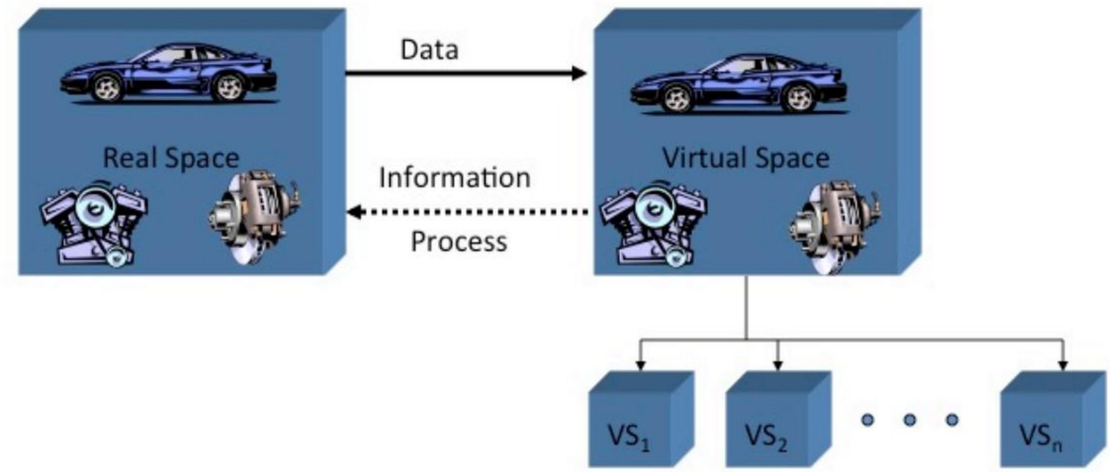

Figure 2.
Mirrored Spaces Model (MSM) (Source: Grieves, 2005)

In *Figure 2*, the boxes represent the physical (real-world) environment at the left and the digital (virtual) environment at the right. The connecting arrows indicate the continuous flow of data and information between the physical product and its digital counterpart. By visually illustrating these mirrored spaces, the figure clarifies how real-time sensor data, operational parameters, and feedback loops enable the digital twin to reflect, predict, and improve the physical system’s performance.

Advancements in technology, such as Radio-Frequency Identification (RFID) and the Internet of Things (IoT), have revolutionized data acquisition processes for Digital Twins (Tao *et al.*, 2018), enabling the seamless integration of real-world data into digital models, which enhances the capability to capture and analyze real-time information from the physical environment through sensor data and IoT devices (Jacoby and Usländer, 2020; Tao *et al.*, 2018).

Digital Twins extend beyond mere replication to encompass the entire lifecycle of an entity, allowing organizations to monitor the evolution of physical assets from creation to disposal. This holistic approach facilitates predictive maintenance and performance optimization, driving innovation and efficiency across various domains such as manufacturing processes, infrastructure systems, and healthcare facilities (Grieves and Vickers, 2016; Grieves, 2005; Mayer, 2022).

In the domain of Supply Chain Management (SCM) and Product Lifecycle Management (PLM), Digital Twins enhance visibility and efficiency across the value chain (Wilking *et al.*, 2022). By creating digital replicas of products, supply chain networks, and manufacturing processes, organizations are empowered to optimize operations, mitigate risks, and improve decision-making. Integrating Digital Twins in SCM and PLM processes fosters a comprehensive understanding of operations, enhancing agility and competitiveness (Minerva *et al.*, 2020; Shafto *et al.*, 2010; Wilking *et al.*, 2022).

Moreover, the RWTH Aachen University (Rheinisch-Westfälische Technische Hochschule Aachen) Cluster of Excellence "Internet of Production" expands the Digital Twin model by incorporating a system model with digital shadows and services, facilitating a purposeful connection between components and the original system (Dalibor *et al.*, 2020; Gray and Rumpe, 2022). This marks a significant milestone in closing the gap between the physical and digital worlds, unlocking unprecedented insights and capabilities for organizations across various sectors (Liu *et al.*, 2021).

The transformative paradigm of Digital Twins, underpinned by the integration with cutting-edge technologies like Blockchain, bridges the physical and digital worlds, promising to revolutionize traditional business processes. This integration enhances security, traceability, and collaboration in SCM and PLM domains, paving the way for a new era of efficiency and innovation across industries (Akash and Ferdous, 2022).

2.5.2 Integrating Blockchain and Digital Twins

The synergy between blockchain technology and digital twins promises a new era in various industries. It combines the virtual replication of assets with the blockchain's secure, immutable nature. This integration enhances digital twins' accuracy and real-time functionality, significantly supporting their security and reliability. Investigating the integration within Industry 4.0, supply chain management, and areas like healthcare illustrates a pivotal innovation across these sectors.

In Industry 4.0, the combination of blockchain with digital twins is seen as a key innovation, particularly in manufacturing. Yaqoob *et al.* (2020) describe a blockchain-based architecture that supports digital twins in industrial settings, ensuring data integrity and robust cybersecurity measures. This architecture is effectively illustrated in *Figure 3*, which shows the extensive role of blockchain in reinforcing digital twins within Industry 4.0.

Tao *et al.* (2018) further discuss how blockchain facilitates real-time updates and transparency in digital twin-driven product design, enhancing decision-making and improving operational efficiencies across manufacturing processes by exploring the integration of blockchain with digital twins in manufacturing, highlighting how blockchain's real-time updates, decentralization, and immutability enhance transparency and data integrity across all stakeholders. Increasing transparency and traceability improves decision-making and operational efficiencies by enabling proactive management of product lifecycle stages and reducing response times (Tao *et al.*, 2018). Additionally, blockchain facilitates automation via smart contracts, streamlining processes, reducing operational costs, and improving collaboration across organizational boundaries (Khan *et al.*, 2021; Tao *et al.*, 2018).

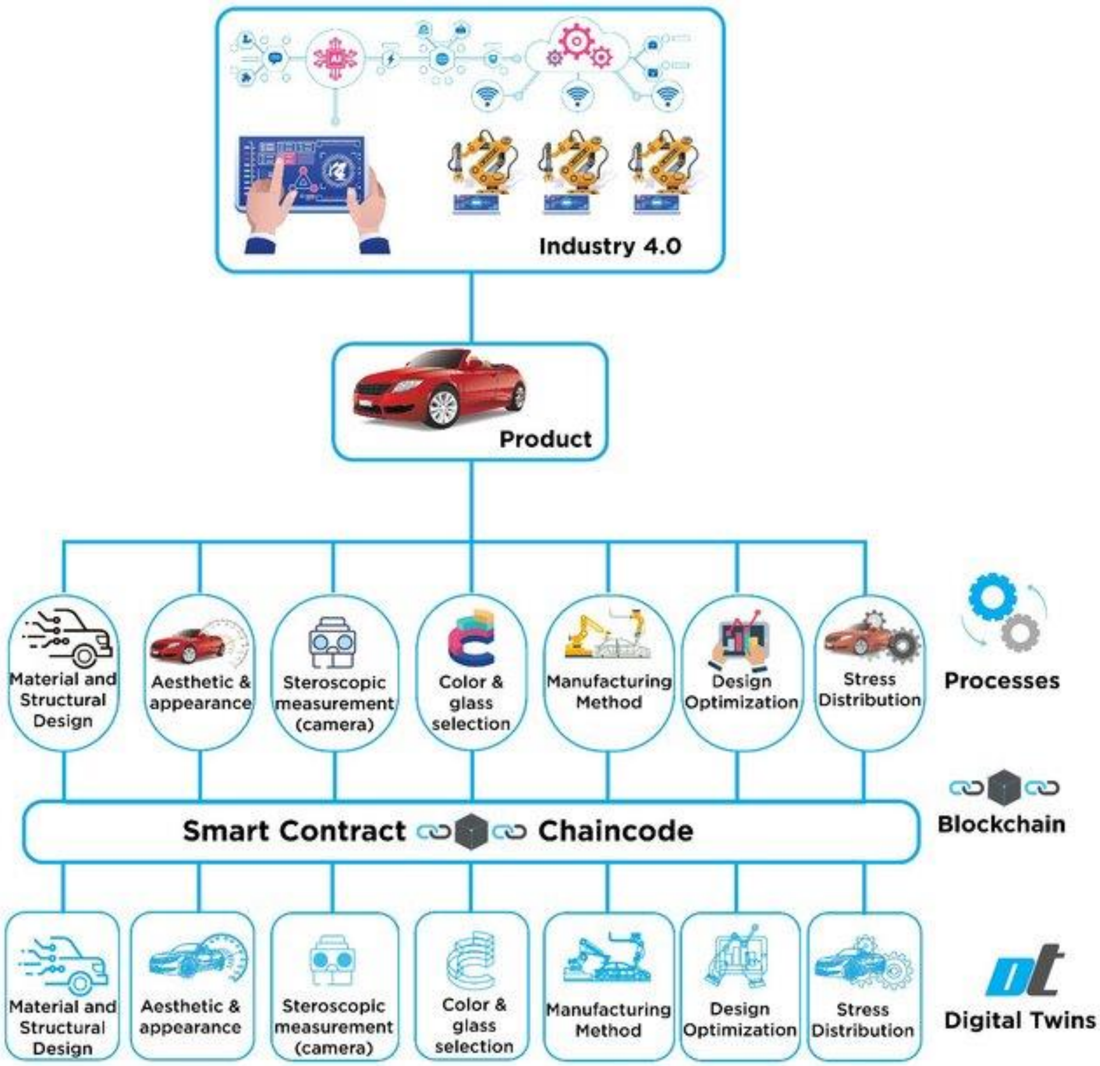

Figure 3.
Blockchain-based Digital Twins in Industry 4.0 (Source: Yaqoob et al., 2020)

The integration also transforms supply chain management and enhances traceability and transparency. Wang *et al.* (2020) describe a blockchain-based framework that improves information sharing in precast construction, optimizing the supply chain from manufacturing to onsite assembly. Moreover, Wang *et al.* (2018) highlight blockchain's potential to become a standard component in supply chains thanks to its secure information storage and sharing capabilities.

In healthcare, blockchain-enabled digital twins offer significant advancements in patient care management. Akash and Ferdous (2022) outline a blockchain framework to secure sensitive health data, enhancing patient trust and system reliability while supporting real-time health monitoring and predictive analytics. This integration enables personalized medical interventions that are timely and based on accurate health data analytics.

Despite these benefits, integrating blockchain with digital twins presents challenges such as the scalability of blockchain networks, data privacy concerns, and the computational demands of maintaining blockchain operations. Future research should address these challenges by developing more efficient blockchain algorithms and frameworks that can effectively scale with the increasing complexity of digital twins, as Gonserkewitz *et al.* (2022) suggested.

Integrating blockchain with digital twins provides a robust infrastructure for enhancing digital replication across various sectors, supporting real-time data exchange and analytics. As this technology pairing evolves, it promises to expand digital twin capabilities further, broadening their application across more industries and enhancing their real-world effectiveness.

2.6 Frameworks and Models for Blockchain Integration

In the ever-evolving domain of supply chain management and product lifecycle management (PLM), the advent of blockchain technology stands as a pivotal transformational force, redefining conventional operational frameworks. The critical role of frameworks and models in facilitating this transformation cannot be overstated, as they offer structured methodologies for navigating the intricacies of blockchain's implementation within these essential realms. Insight is drawn from seminal contributions to the literature, notably the blockchain-based framework for supply chain traceability utilizing the Internet of Things (IoT) as proposed by Agrawal *et al.* (2021; 2023), the IoT and blockchain-based supply chain system framework by Song *et al.* (2021), and the examination of blockchain security within supply chain management delineated by Al-Farsi *et al.* (2021). This discourse undertakes a thorough review of existing frameworks, further enriched by the smart contract architecture framework for supply chain management introduced by Bruel and Godina (2023), which highlights the paramount importance of suggested solutions in augmenting transparency and operational efficacy across supply chains.

Paliwal *et al.* (2020) execute a systematic literature review, subsequently proposing a classification schema known as the Emerging Technology Literature Classification Level (ETLCL) for scrutinizing research on blockchain technology within sustainable supply chain management (SSCM). The ETLCL schema categorizes literature according to the maturity degree of blockchain technology in SSCM contexts (Paliwal *et al.*, 2020).

Through a critical analysis of these foundational contributions, the present review seeks to explain the multifaceted frameworks and models that are instrumental in shaping the integration of blockchain technology within the supply chain and product lifecycle spheres, thus offering a nuanced comprehension of their transformative potential (Agrawal *et al.*, 2021; 2023; Al-Farsi *et al.*, 2021; Bruel and Godina, 2023; Song *et al.*, 2021).

2.6.1 Review of Existing Frameworks

Blockchain technology integration in supply chain management (SCM) and product lifecycle management (PLM) has witnessed a surge in scholarly interest, leading to diverse frameworks to enhance operational efficiency and transparency. This section critically evaluates the existing frameworks in this domain, categorizing them based on their technological underpinnings and explaining their advantages and challenges.

2.6.1.1 Blockchain-Based Supply Chain Management Frameworks

The incorporation of blockchain technology into supply chain management has garnered substantial attention in recent periods, primarily due to its capacity to surmount prevalent obstacles, including the absence of transparency, traceability, and instantaneous information exchange (Toyoda *et al.*, 2017; Wang *et al.*, 2021). Various blockchain-oriented frameworks have emerged, aiming to refine supply chain management across diverse sectors such as construction (Wang *et al.*, 2021), electronics (Cui *et al.*, 2019), and textiles and apparel (Agrawal *et al.*, 2021).

Wang *et al.* (2021) advocate for a blockchain-informed information management framework dedicated to precast supply chains (BIMF-PSC), which consolidates all discrete processes within a supply chain, diverging from prior investigations that concentrated on individual stages. This BIMF-PSC framework identifies four principal entities: owners, construction contractors, off-site factories, and logistics enterprises, each granted access to a mutual ledger (Wang *et al.*, 2021). Correspondingly, Agrawal *et al.* (2021) introduce a blockchain-supported framework tailored for the textile and garment supply chain, facilitating traceability and information dissemination amongst numerous stakeholders. Both models employ consortium blockchains and smart contracts to enable real-time data sharing, traceability, and transparency (Agrawal *et al.*, 2021; Wang *et al.*, 2021).

Toyoda *et al.* (2017) present an innovative blockchain-based product ownership management system (POMS) designed for anti-counterfeiting in the post-supply chain phase, employing the "proof of product possession" notion. This POMS permits supply chain affiliates and consumers to exchange and validate the ownership of RFID-tagged items, thereby rendering counterfeiting endeavors futile (Toyoda *et al.*, 2017). Similarly, Al-Farsi *et al.* (2021) explore the security aspects of blockchain-oriented supply chain management systems, underscoring blockchain's capability to mitigate fraud, compliance, and inventory management issues.

Cui *et al.* (2019) outline a blockchain-based framework to augment supply chain provenance using unique device identification and a five-step transaction process (proposing transactions, executing proposals, ordering transactions, validating transactions, and notifying transactions) alongside smart contracts. This framework encompasses two smart contracts: Manufacturers Manager (MM) and Products Manager (PM), which oversee manufacturers' data and product specifics to protect against counterfeiting of products and product tags. (Cui *et al.*, 2019). Zhou (2024) further elaborates on the application of blockchain technology within product supply chains, highlighting its benefits in traceability, simplified supervision, and efficient inventory management.

These frameworks collectively underscore the prospective advantages of blockchain-based supply chain management technology in enhancing supply chain management efficiency, diminishing costs, and bolstering trust amongst participants (Agrawal *et al.*, 2021; Al-Farsi *et al.*, 2021; Cui *et al.*, 2019; Paliwal *et al.*, 2020; Toyoda *et al.*, 2017; Wang *et al.*, 2021; Zhou, 2024). The utilization of smart contracts and distributed ledgers ensures the dependability and security of supply chain data (Cui *et al.*, 2019; Wang *et al.*, 2021).

Nevertheless, the deployment of blockchain-based frameworks within supply chain management encounters challenges, encompassing technical dilemmas such as throughput and latency, a lack of awareness and comprehension among stakeholders, considerable initial investment outlays, and the requisite for comprehensive collaboration from all involved parties (Al-Farsi *et al.*, 2021; Wang *et al.*, 2021). Zhou (2024) also acknowledges challenges like heightened energy consumption, substantial capital investments, and legal and regulatory hurdles. Furthermore, integrating blockchain with extant systems and procedures may necessitate extensive modifications and adaptations (Cui *et al.*, 2019).

Despite these challenges, the advantages of blockchain-oriented frameworks in supply chain management render them a promising solution for forthcoming endeavors (Paliwal *et al.*, 2020). With the continuous evolution and maturation of blockchain technology, it is anticipated that an increasing number of industries will embrace blockchain-based frameworks to optimize their supply chain operations and tackle the challenges related to transparency, traceability, and information dissemination (Agrawal *et al.*, 2021; Al-Farsi *et al.*, 2021; Zhou, 2024).

2.6.1.2 Blockchain-Based Product Lifecycle Management Frameworks

The adoption of blockchain technology within product lifecycle management (PLM) frameworks signifies a groundbreaking shift, poised to augment traceability, transparency, and operational efficiency across a product's lifecycle. PLM, encompassing a comprehensive range from the inception and design through to manufacturing, distribution, and the final stage of end-of-life management, derives substantial benefits from blockchain's core attributes—immutability, decentralization, and enhanced security measures (Bahga and Madisetti, 2016; Stark, 2015). These inherent qualities of blockchain address and overcome the constraints faced by traditional PLM systems, presenting a robust alternative to conventional methodologies.

Innovative blockchain-based PLM frameworks proposed by researchers aim to refine product data management, bolster data integrity, and catalyze stakeholder collaboration. Utilizing smart contracts coupled with decentralized data storage solutions, these frameworks provide a structured approach to managing product data throughout its lifecycle. This innovative integration facilitates secure, transparent data sharing, meticulous version control, and stringent access management, mitigating risks associated with data tampering and unauthorized access (Bahga and Madisetti, 2016).

The merits of employing blockchain-based PLM frameworks are extensive. Primarily, they establish an immutable, tamper-evident product data record, fortifying data integrity and fostering stakeholder trust. Additionally, blockchain's decentralized architecture promotes secure, transparent data exchanges, eliminating the necessity for intermediaries and minimizing the emergence of data silos (Aljuhani *et al.*, 2024; Bahga and Madisetti, 2016). Furthermore, the automation capabilities of smart contracts streamline various PLM processes—including data validation, access control, and compliance verification—thus enhancing operational efficiency and diminishing the likelihood of manual inaccuracies.

The deployment of blockchain-based PLM frameworks encounters several impediments. A critical challenge is ensuring interoperability between blockchain networks and existing PLM systems, which may necessitate comprehensive modifications and adaptations (Cui *et al.*, 2019). Moreover, the scalability of blockchain networks could be hindered by the growing volume of product data and the intricacies of PLM processes (Song *et al.*, 2021). Maintaining data privacy and confidentiality within a decentralized network poses a significant challenge, especially concerning sensitive product information (Al-Farsi *et al.*, 2021).

In response to these challenges, scholars have articulated various strategies for mitigation. Cui *et al.* (2019) advocate for implementing a multi-chain architecture and a refined data management model to streamline the integration of blockchain technologies with prevailing PLM systems. Song *et al.* (2021) suggest adopting lightweight consensus mechanisms and off-chain storage alternatives to bolster the scalability of blockchain networks. Furthermore, establishing stringent access control measures and secure key management protocols and using a secured and authenticated blockchain network like the

Hyperledger fabric is pivotal for safeguarding sensitive product data within a decentralized framework (Al-Farsi *et al.*, 2021; Androulaki *et al.*, 2018).

Blockchain-based PLM frameworks are promising to revolutionize traceability, transparency, and efficiency in product lifecycle management. By harnessing the distinctive capabilities of blockchain technology, these frameworks are well-positioned to transcend the limitations inherent in traditional PLM systems, thereby enabling secure, transparent data interactions among stakeholders. However, the successful actualization of these frameworks is contingent upon effectively addressing interoperability, scalability, and data privacy concerns. As the research landscape in this domain continues to evolve, it is anticipated that forthcoming innovations will adeptly tackle these challenges, fully unlocking the transformative potential of blockchain technology within PLM.

2.6.1.3 Smart Contract and NFT Architecture Frameworks

The exploration of smart contract and non-fungible token (NFT) architecture frameworks by several researchers seeks to navigate the complexities inherent in supply chain management and virtual entrepreneurship. Agrawal *et al.* (2023) introduce a blockchain-oriented framework that leverages smart contracts to foster collaboration and resource allocation within supply chain networks. This framework is characterized by a multi-chain structure, a data management model, and a block structure model, alongside methodologies for information anchoring, key distribution, and encryption. The system efficiently orchestrates order distribution through smart contracts in line with supplier capacity and priority, additionally managing financial transactions through specified channels. The practicality and resilience of this framework against diverse security threats are evidenced through simulations and security analyses (Agrawal *et al.*, 2023).

Similarly, Bruel and Godina (2023) delineate a smart contract architecture framework employing Hyperledger Fabric to facilitate successful industrial symbiosis applications. This framework, grounded in a consortium blockchain architecture, addresses both the incentives and hindrances associated with adopting blockchain technology. It offers highly customizable smart contracts to cater to the varying requisites of distinct organizations, thereby facilitating waste exchange and administrative processes. Efforts to surmount barriers include conducting workshops, providing training, amalgamating existing platforms, and enhancing consumer consciousness (Bruel and Godina, 2023). These architectural frameworks underscore the transformative potential of smart contracts in augmenting collaboration, equity, and security across supply chain networks.

On virtual entrepreneurship, Chandra (2022) puts forward a conceptual framework for smart contract-based NFT-enabled entrepreneurship (NFTE), incorporating enablers, agencies, and mechanisms to decipher the burgeoning paradigm of NFTE. The framework identifies technological enablers, such as token standards, Web 3.0 infrastructure, and community enablers, like decentralization, gaming culture, and the sharing ethos. Entrepreneurial agency in this context is defined by the distinctive incorporation of resources and motivations propelled by interactive ritual chains. The NFTE framework elucidates mechanisms of generation, compression, substitution, expansion, and elimination, significantly influencing the creation of artifacts, ventures, and institutions (Chandra, 2022). This offers a pioneering perspective on NFTs' capacity to catalyze novel forms of virtual entrepreneurship.

Liu and Li (2020) propose a blockchain-based framework tailored for cross-border e-commerce supply chain management, emphasizing product and data traceability by accessing smart contracts. This framework employs a multi-chain architecture for segregating data according to characteristics alongside a detailed data management model encompassing structures for account, transaction, and IoT chains. It devises methods for information anchoring, key distribution, and encryption to guarantee data integrity and protection. Furthermore, an anti-counterfeiting traceability tag scheme is devised in Rivest–Shamir–Adleman (RSA) and Ellipse Curve Cryptography (ECC), linking products with their corresponding information on the blockchain (Liu and Li, 2020).

Toyoda *et al.* (2017) present a smart contract-based Product Ownership Management System (POMS) to combat counterfeiting in post-supply chain phases. This system, drawing on the "proof of possession of products" principle, incorporates two smart contracts: the ManufacturersManager (MM) and the ProductsManager (PM), which are responsible for overseeing manufacturer and product information. The algorithmic procedures explicate the interactions amongst supply chain entities via the smart contract functionalities. Protocol validation affirms POMS's competency in identifying and mitigating counterfeits by authenticating the seller's product ownership on the blockchain (Toyoda *et al.*, 2017).

These frameworks collectively highlight the efficacy of smart contracts and NFTs in fostering collaboration, traceability, and security across varied sectors. Nonetheless, the implementation phase encounters obstacles, such as incentivizing participation, safeguarding data privacy, and synchronizing with extant systems (Agrawal *et al.*, 2023; Bruel and Godina, 2023). To navigate these challenges, carefully crafting smart contract architectures, governance models, and barrier mitigation strategies is imperative (Bruel and Godina, 2023; Toyoda *et al.*, 2017).

The frameworks reviewed here manifest the transformative potential of smart contracts and NFTs in redefining supply chain management and pioneering new vistas in virtual entrepreneurship. Capitalizing on the unique attributes of blockchain technology, these frameworks offer groundbreaking approaches for enhancing collaborative efforts, traceability, and security measures. Nevertheless, the maturity of these innovations necessitates addressing the outlined challenges and tailoring the frameworks to align with specific industry demands.

2.6.1.4 IoT and Blockchain Integration Frameworks

The convergence of Internet of Things (IoT) devices with blockchain technology represents a formidable alliance, poised to significantly enhance supply chain management (SCM) and product lifecycle management (PLM) frameworks. IoT devices facilitate the acquisition of immediate data across various junctures of the supply chain. In contrast, blockchain delivers a secure, transparent, and immutable ledger for recording and disseminating this data among involved parties (Agrawal *et al.*, 2021; Song *et al.*, 2021). This discourse delineates the pivotal attributes of IoT and blockchain-integrated frameworks, elucidating their merits and the hurdles encountered in their deployment.

Agrawal *et al.* (2021; 2023) outline a blockchain-anchored framework that enhances supply chain traceability, capitalizing on IoT devices to accumulate data throughout the supply chain continuum. This architecture employs a multi-chain structure, a data management model, and a block structure model to secure and share data harvested by IoT devices. Additionally, the framework integrates smart contracts to streamline order allocation and financial transactions (Agrawal *et al.*, 2023). In parallel, Song *et al.* (2021) unveil an IoT and blockchain-integrated supply chain system framework that merges IoT devices for data gathering with blockchain for safeguarded data storage and dissemination. This framework aims to bolster supply chain mechanisms' transparency, traceability, and operational efficiency.

Liu and Li (2020) propose a blockchain-centric framework for cross-border e-commerce supply chain management, incorporating IoT devices to facilitate product and data traceability. This framework adopts a multi-chain architecture and a data management model incorporating structures for IoT chains, thereby enabling the synthesis of data collected by IoT devices with the blockchain network. The framework also articulates information anchoring, key distribution, and encryption methods to guarantee data authenticity and security (Liu and Li, 2020).

Integrating IoT with blockchain in SCM and PLM frameworks offers numerous advantages. Primarily, it permits gathering instantaneous data from diverse supply chain loci, presenting a holistic overview of the entire supply chain operation (Agrawal *et al.*, 2021; Song *et al.*, 2021). This live data facilitates the identification of potential discrepancies, the optimization of procedures, and the enhancement of decision-making processes. Furthermore, blockchain's incorporation ensures that the data collected by IoT devices is secure, transparent, and unalterable (Liu and Li, 2020), cultivating trust among stakeholders and diminishing the risks associated with data tampering or manipulation.

Nevertheless, deploying IoT and blockchain integration frameworks is not without challenges. One significant issue is the interoperability between IoT devices and blockchain networks (Agrawal *et al.*, 2023), given that IoT devices may utilize different communication protocols and data formats, complicating their seamless integration with blockchain networks. Another concern is the scalability of blockchain networks, as the increasing number of IoT devices and the voluminous data they generate can lead to network congestion (Song *et al.*, 2021).

To overcome these obstacles, researchers propose various strategies. Agrawal *et al.* (2023) recommend adopting a multi-chain structure and a data management model to ease the integration of IoT devices with blockchain networks. Similarly, Liu and Li (2020) advocate for a multi-chain architecture and a data management model that includes structures for IoT chains to facilitate the amalgamation of IoT-generated data with the blockchain network. Moreover, deploying lightweight consensus mechanisms and off-chain storage solutions could ameliorate the scalability concerns of blockchain networks (Song *et al.*, 2021).

The symbiosis of IoT and blockchain within SCM and PLM frameworks harbors immense potential to revolutionize transparency, traceability, and efficiency. However, the actualization of these frameworks is impeded by several challenges, notably interoperability and scalability. As the domain of research in this field continues to progress, it is anticipated that novel resolutions will materialize to navigate these challenges, thereby unleashing the full capabilities of IoT and blockchain integration in SCM and PLM arenas.

2.6.1.5 Blockchain Integration Challenges and Mitigation Strategies

The integration of blockchain technology within supply chain management (SCM) and product lifecycle management (PLM) paradigms heralds substantial improvements in transparency, traceability, and operational efficiency (Agrawal *et al.*, 2021; Song *et al.*, 2021). Despite these promising benefits, successfully adopting blockchain-infused frameworks is challenging.

A paramount challenge lies in achieving interoperability between blockchain networks and pre-existing systems (Cui *et al.*, 2019; Wang *et al.*, 2021). The involvement of numerous stakeholders characterizes SCM and PLM ecosystems, each operating its distinct systems and procedures. Integrating blockchain technology with these heterogeneous systems necessitates extensive modifications and adjustments, which may prove both time-intensive and financially burdensome (Al-Farsi *et al.*, 2021; Paliwal *et al.*, 2020). To navigate this complexity, scholars advocate for adopting multi-chain architectures and data management models that promise streamlined integration (Agrawal *et al.*, 2023; Liu and Li, 2020). Moreover, the formulation of standardized protocols and application programming interfaces (APIs) could serve as a connector between blockchain networks and present systems (Wang *et al.*, 2021).

Scalability is another interesting challenge in blockchain integration (Song *et al.*, 2021; Zhou, 2024). The expansion in the volume of transactions and network participants may limit the network's capability to process transactions efficiently. This issue gains prominence within SCM and PLM frameworks, where the copious data generated by IoT devices and intricate process complexities can strain network capacity (Agrawal *et al.*, 2023). As mitigation, the deployment of lightweight consensus mechanisms, such as Proof of Authority (PoA) or Delegated Proof of Stake (DPoS), is proposed to enhance transaction throughput and minimize latency (Bruel and Godina, 2023; Song *et al.*, 2021). Additionally, off-chain storage modalities, including sidechains or state channels, can relieve pressures on the primary blockchain network (Liu and Li, 2020).

The assurance of data privacy and confidentiality within a decentralized schema poses a critical challenge (Al-Farsi *et al.*, 2021; Paliwal *et al.*, 2020). Although blockchain technology ensures a secure and immutable transaction ledger, the ledger's transparency could inadvertently reveal sensitive information to unauthorized entities. This concern is particularly acute in SCM and PLM frameworks, where safeguarding confidential product information and business affiliations is paramount (Agrawal *et al.*, 2021; Stark, 2015; Toyoda *et al.*, 2017). Access control measures and robust key management systems are suggested to counteract this issue by limiting access to sensitive data or the entire Network, for example, the Hyperledger fabric (Al-Farsi *et al.*, 2021; Androulaki *et al.*, 2018; Cui *et al.*, 2019). Furthermore, applying privacy-preserving mechanisms, such as zero-knowledge proofs or homomorphic encryption, can facilitate secure data sharing while upholding confidentiality (Liu and Li, 2020; Lund, 2024; Rouhani and Deters, 2019; Teisserenc and Sepasgozar, 2022; Zhou, 2024).

Legal and regulatory compliance also presents a significant hurdle (Paliwal *et al.*, 2020; Zhou, 2024). Blockchain technology's inherently decentralized and borderless nature may clash with established legal frameworks and regulatory mandates. This challenge is especially pertinent in cross-border SCM and PLM frameworks, where jurisdictions may vary in their stipulations regarding data protection, intellectual property rights, and contractual obligations (Agrawal *et al.*, 2021; Duy *et al.*, 2018; Liu and Li, 2020; Toufaily *et al.*, 2021). To navigate this landscape, it is imperative for organizations to actively consult with regulators and legal specialists to ensure adherence to all relevant laws and regulations (Paliwal *et al.*, 2020). Additionally, crafting smart contracts that encapsulate legal requisites and automate compliance verifications can further assist organizations in managing the regulatory environment (Bruel and Godina, 2023; Toyoda *et al.*, 2017).

While the fusion of blockchain technology with SCM and PLM frameworks promises numerous advantages, it concurrently introduces challenges that span interoperability, scalability, data privacy, and legal compliance. For blockchain-based frameworks to flourish, organizations must adopt a comprehensive strategy that addresses these challenges through technical innovations, governance frameworks, and collaborative endeavors. As the blockchain ecosystem evolves, it is anticipated that novel instruments and methodologies will materialize, streamlining integration and unlocking the full potential of this disruptive technology.

2.6.2 Research Gaps in Existing Frameworks

The last section's overview unveils substantial gaps in blockchain-based supply chain management, highlighting an imperative need for augmented scholarly inquiry and the cultivation of future frameworks. Detailed scrutiny of the existing literature uncovers numerous pivotal areas ripe for exploration, presenting opportunities for substantial advancement and innovation within this vibrant field.

A prominent research void underscored the need for a broader investigation into integrating blockchain technology across various supply chain sectors (Al-Farsi *et al.*, 2021). Prior studies have explored blockchain's application within specific industries, such as textiles and clothing (Agrawal *et al.*, 2021), agriculture (Compagnucci *et al.*, 2022; Menon and Jain, 2021) or luxury and branded goods (de Boissieu *et al.*, 2021; Chen, Guo, *et al.*, 2022), an expansive array of sectors remains to be examined. Future research could aim to customize blockchain frameworks to the distinctive needs and demands of various supply chain domains or supply chains in general, thus broadening the technology's versatility and scalability.

Additionally, it draws attention to the critical importance of examining blockchain technology's operational models and practical implications within supply chain settings (Song *et al.*, 2021). Despite the proposition of numerous theoretical frameworks (Ahmed and MacCarthy, 2022; Bruel and Godina, 2023; Liu *et al.*, 2023; Lou *et al.*, 2021), there exists an urgent demand for empirical studies to affirm the efficacy and practicality of blockchain-based solutions in tangible supply chain contexts. Addressing this gap through empirical inquiry, future frameworks can be grounded in solid practical insights and operational precedents.

Moreover, the information hints at the yet-to-be-fully-exploited potential of smart contracts in transforming supply chain management practices (Bruel and Godina, 2023). With smart contracts at the forefront of enabling automation and enhancing transparency in supply chains, a compelling call for research emerges focused on the meticulous design, deployment, and refinement of smart contract architectures (Lou *et al.*, 2021). Investigating the complexities of smart contracts within supply chains could enable future frameworks to exploit this technology optimally, facilitating increased efficiency and trust within supply chain operations.

Overall, this highlights the progress made towards embedding blockchain technology into supply chain management and product lifecycle management and defines exciting paths for future research and framework evolution. By confronting these research gaps with academic diligence and creative thought, this research and future scholars can steer the field of blockchain-based supply chain management towards new frontiers of efficiency, transparency, and sustainability, thereby enriching the academic discourse.

2.7 Conclusion

The comprehensive literature review has illuminated the transformative potential of blockchain technology, smart contracts, and Non-Fungible Tokens (NFTs) in revolutionizing Supply Chain Management (SCM) and Product Lifecycle Management (PLM) practices. By delving into the core concepts, applications, benefits, and challenges of these technologies, this chapter has laid a solid foundation for understanding their impact on fostering trust, transparency, and efficiency in complex supply chain ecosystems (Centobelli *et al.*, 2021; Chang *et al.*, 2022).

Exploiting blockchain fundamentals has underscored the technology's inherent capabilities in enabling secure, decentralized, and immutable record-keeping, setting the stage for its integration into SCM and PLM domains (Puthal *et al.*, 2018). The examination of smart contracts has revealed their pivotal role in automating and streamlining processes, reducing intermediaries, and enhancing operational efficiency (Khan *et al.*, 2021). The advent of NFTs has introduced new possibilities for representing unique assets, ensuring provenance, and combating counterfeiting (Anjum and Rehmani, 2022).

The in-depth analysis of blockchain applications in SCM has highlighted the technology's potential to enhance traceability, optimize operations, and mitigate risks associated with complex supply chain networks (Agrawal *et al.*, 2021; Lohmer *et al.*, 2022). Similarly, the blockchain investigation in PLM has shed light on its capacity to revolutionize product data management, foster collaboration, and enable granular tracking throughout the product lifecycle (Belhi *et al.*, 2020; Chen, Cai, *et al.*, 2022).

The convergence of blockchain and digital twins has emerged as a powerful paradigm, enabling the creation of secure, transparent, and dynamic virtual representations of physical assets and processes (Akash and Ferdous, 2022; Minerva *et al.*, 2020). This integration holds immense potential for optimizing supply chain operations, enhancing predictive maintenance, and driving innovation in product design and development (Tao *et al.*, 2018; Wang *et al.*, 2022).

Reviewing existing frameworks and models for blockchain integration has provided insights into the current state of research and practice in this domain (Agrawal *et al.*, 2023; Al-Farsi *et al.*, 2021; Bruel and Godina, 2023). The identification of research gaps and the proposal for developing a new framework have paved the way for advancing knowledge and practical applications of blockchain technology in SCM and PLM contexts.

As the digital landscape continues to evolve, integrating blockchain, smart contracts, and NFTs in SCM and PLM is poised to unlock new frontiers of efficiency, transparency, and value creation (Centobelli *et al.*, 2021). The insights garnered from this literature review serve as a springboard for further research and innovation, driving the development of robust, scalable, and adaptable solutions that harness the full potential of these technologies.

This literature review intends to provide a comprehensive understanding of the transformative impact of blockchain, smart contracts, and NFTs on SCM and PLM practices. This chapter has laid the groundwork for developing a novel framework that addresses the identified research gaps and propels the field forward by bridging the gap between theoretical foundations and practical applications. As organizations navigate the complexities of the digital era, embracing these technologies will be pivotal in fostering resilience, agility, and competitive advantage in the face of evolving market dynamics and customer expectations.

CHAPTER III:

METHODOLOGY

3.1 Overview of the Research Problem

Trust, transparency, and authenticity are increasingly recognized as critical in global markets, particularly within the realms of Supply Chain Management (SCM) and Product Lifecycle Management (PLM) (de Boissieu *et al.*, 2021). Blockchain Technology is acknowledged for its capability to address these challenges (Puthal *et al.*, 2018).

In 2018, the concept of smart contracts was further enriched with the definition of Non-fungible Tokens (NFTs) (Entriken *et al.*, 2018; Radomski *et al.*, 2018), expanding the range of possible use cases to include the Internet of Things (IoT), healthcare management, intellectual property management, and more (Centobelli *et al.*, 2021; Puthal *et al.*, 2018).

Gartner identified the Metaverse, a platform based on blockchain technology, as one of the top strategic technologies for 2023 (Groombridge, 2022). In the next two to three years, Gartner predicts use cases in avionics, banking, automotive, logistics and transportation, and brand awareness for businesses to protect and build brands and to grow revenue.

These innovative and complex technologies have the potential to either succeed or fail during the early implementation stages. In 2018, the success rate of projects based on blockchain technology was reported at 8% (James, 2018), highlighting the experimental nature of these innovations at large scales.

Design Science Research (DSR) offers a robust framework for exploring and addressing the challenges of integrating blockchain technologies in various industries. This methodology is particularly suited for developing and refining technology-based solutions through an iterative design, implementation, and evaluation. DSR focuses on creating innovative artifacts and generating new knowledge to advance theory and practice in technology-driven domains (Hevner *et al.*, 2004).

System theory provides a valuable lens for examining these developments and phenomena, focusing on isolated technologies and their interactions within larger ecosystems. This approach is crucial, given the interconnected nature of blockchain applications across different industries and processes (Hofkirchner, 2005).

Blockchain technology holds promise for many business and industrial applications, including supply chain management, product lifecycle management, healthcare management, intellectual property management, and integration with the Internet of Things (IoT). Including enhancing transparency and traceability in supply chains (Dursun *et al.*, 2022; Menon and Jain, 2021), securing digital rights through Non-Fungible Tokens (NFTs) (Anjum and Rehmani, 2022; Gonserkewitz *et al.*, 2022; Zanni *et al.*, 2019), and improving patient data management in healthcare (Akash and Ferdous, 2022; Gebreab *et al.*, 2022; Musamih *et al.*, 2022). However, translating theoretical uses into practical applications presents complexities. The novelty of the technology and the absence of established frameworks or best practices complicate the real-world integration of these technologies. This gap underscores the empirical research imperative to bridge theoretical potential with practical implementation, particularly concerning digital twins, smart contracts, and their broader implications for SCM and PLM.

This study aims to leverage Design Science Research (DSR) and System Theory to provide essential tools and insights to enhance the success rate of implementing Blockchain Technology-based projects, such as Smart Contract or NFT-backed Digital Twins (DT) in SCM or PLM. By analyzing the systemic interactions and feedback mechanisms, the research seeks to uncover underlying patterns that can predict system behaviors and guide successful implementations (Ramage and Shipp, 2020).

3.2 Research Design

3.2.1 Detailed Overview of Design Science Research (DSR) Methodology

This research follows the design science research method, or DSR, to design and evaluate the integration of blockchain technologies, such as smart contracts and NFTs, with Digital Twin environments within the SCM or PLM concepts. Historically originating from engineering, DSR, according to March and Smith (1995), involves creating an artifact that did not previously exist and served a meaningful human purpose. Focused on creating innovative solutions, new artifacts, models, methods, and systems, DSR is most suitable for fields like Computer Science, Information Systems, and Management. In conclusion, the development of blockchain technology and digitalization environments such as Digital Twins and DSR are a perfect match.

This research demonstrates the feasibility of the design process and the framework through artifact instantiation. It enables researchers to learn about the effects of the framework as an artifact on the natural world and its appropriate use (Hevner *et al.*, 2004).

The DSR Framework for Information System Research, as presented by Hevner *et al.* (2004) (*Figure 4.*), emphasizes understanding the appropriate environment or context and the relevance to the business needs of the research, in addition to its rigor and application in the knowledge base. In *Figure 4*, the environment (business needs, people, organizations) is illustrated on one side, and the knowledge base (theories, methods, expertise) on the other. The artifact-building and evaluation activities sit between these two elements. The arrows connecting the elements show the iterative nature of design science research. This visual highlights how real-world problems inform artifact creation and how evaluation refines the artifact and underlying theory—creating a continuous feedback loop that bridges practice and scholarship.

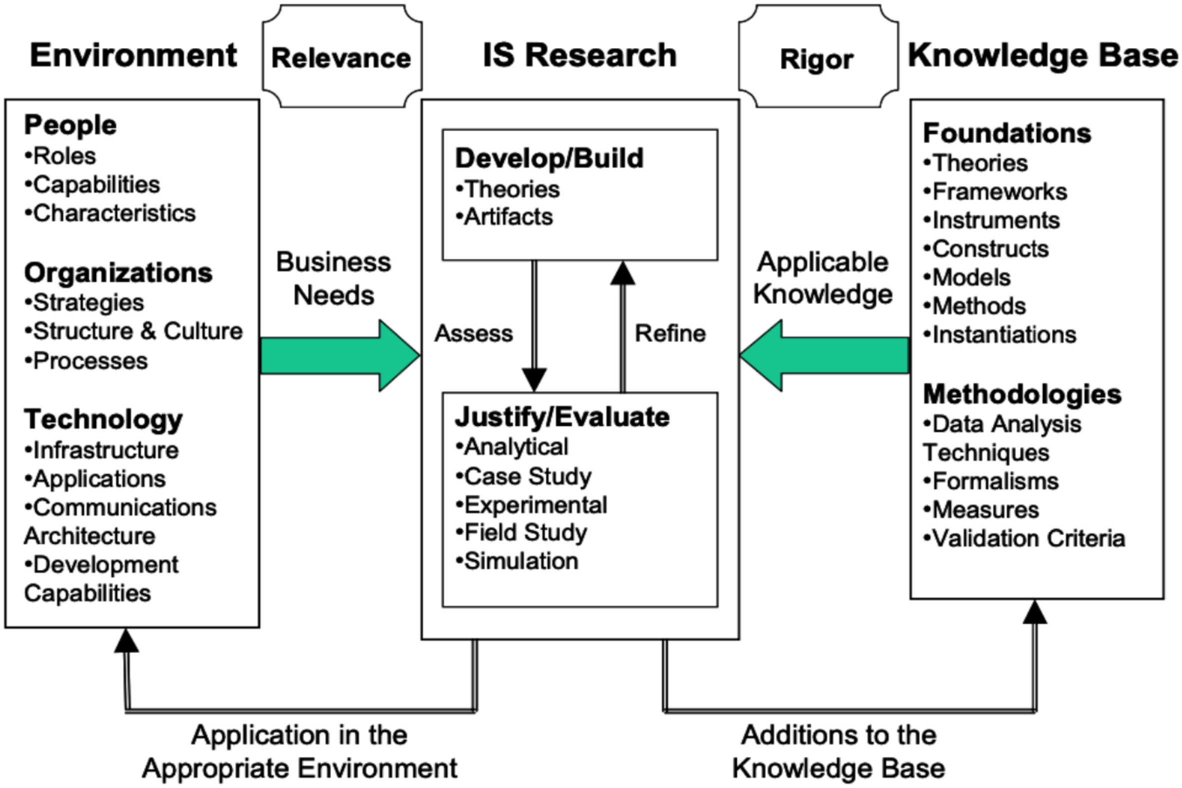

Figure 4.
Information Systems Research Framework (Source: Hevner et al., 2004)

Hevner *et al.* (2004) presented seven guidelines for creating a purposeful artifact.

- Guideline 1 – Design as an Artifact
  - → "Design-science research must produce a viable artifact in the form of a construct, a model, a method, or an instantiation."
- Guideline 2 – Problem Relevance
  - → "The design-science research aims to develop technology-based solutions to important and relevant business problems."
- Guideline 3 – Design Evaluation
  - → "The utility, quality, and efficiency of a design artifact must be rigorously demonstrated via well-executed evaluation methods."

- Guideline 4 – Research Contribution
    - → "Effective design-science research must provide clear and verifiable contributions in the areas of the design artifact, design foundations, and design methodologies."
- Guideline 5 – Research Rigor
    - → "Design-science research relies upon the application of rigorous methods in both the construction and evaluation of the design artifact."
- Guideline 6 – Design as a Search Process
    - → "The search for an effective artifact requires utilizing available means to reach desired ends while satisfying laws in the problem environment."
- Guideline 7 – Communication of Research
    - → "Design-science research must be presented effectively to both technology and management-oriented audiences."

Adding more clarity to DSR, Hevner *et al.* (2023) identified six forms of transparency: process, problem space, solution space, build, evaluation, and contribution, to foster a better appreciation of the full range of DSR and its transparency.

In the context of this research, DSR is selected for its capacity to align both theoretical requirements and practical demands. Unlike methodologies emphasizing observation or purely conceptual modeling, DSR orchestrates a systematic, iterative artifact creation, evaluation, and refinement process. This characteristic proves especially valuable for translating the theoretical potential of blockchain integration in SCM and PLM into tangible, rigorously validated solutions. By employing DSR, the study ensures that artifacts—such as those developed and presented in Chapter 4, the ProductNFT and ContainerNFT frameworks—are intellectually coherent, methodologically sound, and demonstrably effective in addressing identified industry challenges. The continuous feedback loops inherent to DSR enable the investigation to remain responsive to evolving organizational contexts, enhancing relevance and value. The decision to apply DSR empowers this research to produce academically rigorous, practically implementable contributions capable of advancing both scholarly discourse and real-world practice in SCM and PLM.

The methodology employed in this research adheres to the principles of the Design Science Research (DSR) algorithm as enhanced by Drescher *et al.* (2015) and further refined by Bronet Campos (2023) (*Figure 5*). Each box in *Figure 5* represents a distinct DSR step—identifying the problem, proposing a solution, designing and developing an artifact, evaluating it, and generating insights. The connections indicate iterative feedback loops that move the process forward, while the vertical arrangement of steps suggests how each stage builds upon the previous one. *Figure 5* visually mapping these phases clarifies the DSR process as a structured yet adaptive innovation, learning, and refinement cycle.

The initial phase of this research focuses extensively on delineating the problem scope and establishing its relevance within the field. This foundational phase is thoroughly explained in Chapter 1, encompassing steps one and two as delineated by the DSR framework, presented in *Figure 4*. Subsequently, Chapter 2 presents an exhaustive literature review, fulfilling the third step of the DSR process.

Upon completion of the initial DSR stages, the research progresses into the artifact creation phase. This involves the identification (4), proposal (5), design (6), development (7), and meticulous evaluation (8) of the artifacts in question. The culmination of this process leads to the generation of significant learnings (9) and conclusive insights (10), setting the stage for the subsequent phase, which involves generalizing the problem class (11) and disseminating the research findings (12).

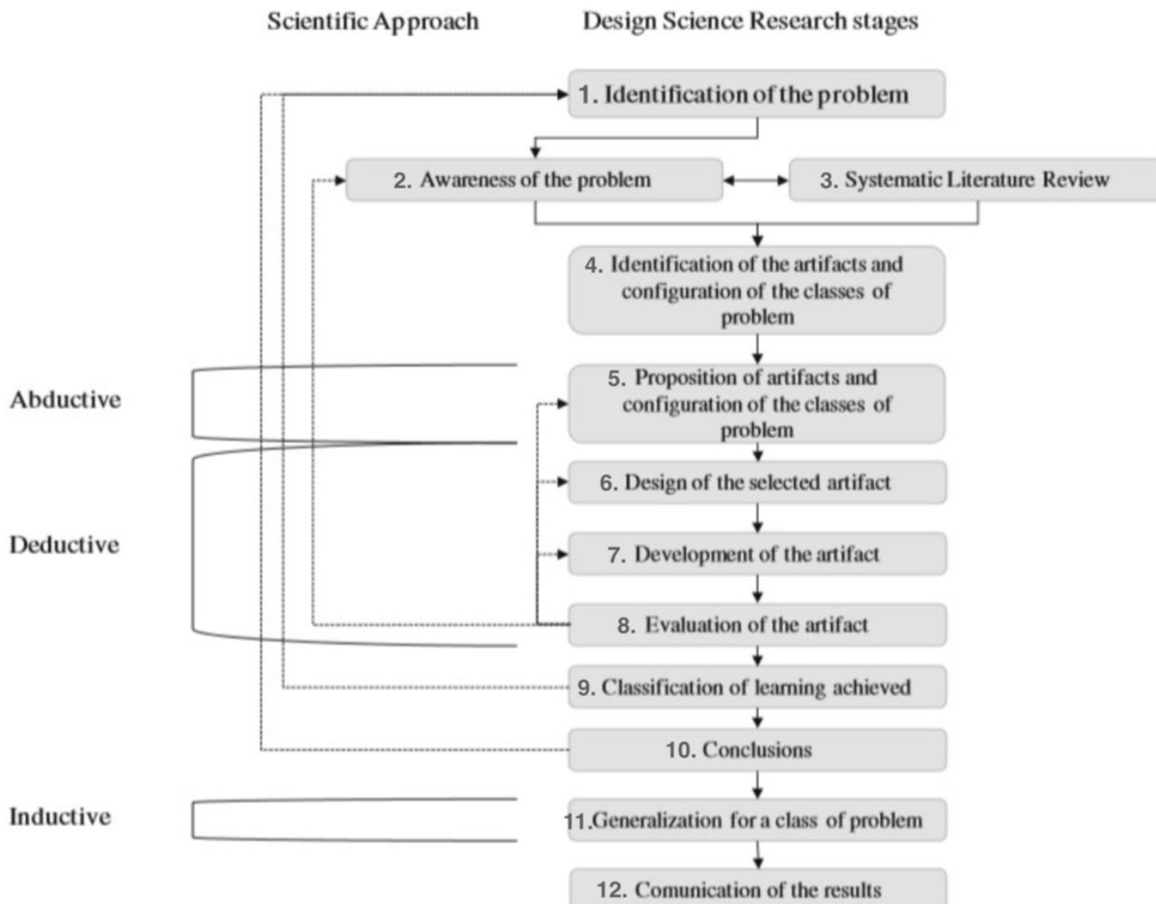

Figure 5.
Main steps to conduct design science research (Source: Bronet Campos, 2023)

3.2.2 Detailed Overview of System Theory

System Theory provides a critical framework for understanding the complexities and interconnectedness inherent in various scientific and practical disciplines. This theoretical approach emphasizes the holistic study of systems, where system components' interactions and collective behaviors are considered more significant than their individual actions. This perspective is instrumental for exploring and managing complex systems in biology, ecology, social sciences, and technology-driven industries like blockchain within supply chains (Ballandies *et al.*, 2023).

System Theory's roots can be traced back to the early 20th century, developed primarily by Ludwig von Bertalanffy. He was a pioneer who challenged the reductionist approach that dominated scientific thinking at the time. Bertalanffy introduced a model that considered systems as wholes, which could only be understood by analyzing their interrelations and total functioning rather than through their constituent parts alone. This paradigm shift heralded a new era of scientific inquiry, emphasizing connectivity and dynamic interactions across different systems (Hofkirchner, 2005).

At its core, the conceptual framework of System Theory revolves around several key concepts: interdependence, wholeness, feedback loops, and self-regulation. Each component within a system is seen as mutually dependent, contributing to the system's collective behavior and overall stability. Feedback loops within these systems are crucial in maintaining balance and facilitating adaptations to internal or external stimuli. Such dynamics are evident in the application of blockchain technologies, where systemic feedback can significantly influence operational efficiency and transparency (Ballandies *et al.*, 2023).

In contemporary research, System Theory is applied to understand and optimize complex systems. For instance, educational technology provides a framework to integrate various elements affecting learning environments, thereby enhancing educational outcomes (Kowch, 2023). Similarly, systems thinking in technology or process management helps design sustainable practices that account for technological, ecological, economic, and social factors. The adaptability of System Theory across different fields underscores its utility in addressing modern challenges, where systems are increasingly interconnected and influenced by many factors (Ballandies *et al.*, 2023; Kowch, 2023).

Applying System Theory to this research involving blockchain in supply chain management exemplifies its practical value. By analyzing the system as a whole, this research can identify leverage points where interventions could significantly improve efficiency and effectiveness. The theory aids in predicting the outcomes of such interventions, providing a reliable basis for decision-making and strategic planning in complex environments (Ramage and Shipp, 2020).

System Theory enriches academic understanding and enhances practical applications in complex system environments. It fosters a comprehensive approach to problem-solving and innovation, making it indispensable in studying and managing complex, dynamic systems. As such, System Theory remains a cornerstone of contemporary research methodologies, offering insights crucial for advancing knowledge and practice in an increasingly interconnected world.

3.2.3 Data Analysis and Framework Evaluation

The methodology for this latter phase consists primarily of methods deployed to evaluate the data gathered through the research design described previously, enriched with a dual framework of DSR and System Theory. This bifocal approach provides a comprehensive and robust structure for assessing the impacts and effectiveness of blockchain technology within the supply chain environment, considering both systemic and artifact-specific perspectives (Ballandies *et al.*, 2023; Tarpey and Mullarkey, 2019).

The research utilizes a mixed-method approach that combines qualitative and quantitative techniques to ensure a thorough evaluation of the blockchain framework under study. This covers statistical analyses to quantify relationships and impacts alongside systemic evaluations to understand the blockchain systems' dynamic interactions, as System Theory prescribes. Statistical tools are utilized for quantitative analysis, complemented by system dynamics modeling techniques to explore and elucidate the system's complex feedback loops and interdependencies.

Data handling processes are tailored to maintain the integrity of systemic relationships, ensuring that analysis captures the holistic nature of blockchain implementations. This involves advanced data analytics techniques where data cleaning, normalization, and transformation processes are guided by System Theory principles to reflect the interdependencies and feedback mechanisms accurately.

The framework's evaluation integrates traditional criteria such as system performance, user satisfaction, and cost-effectiveness with systemic evaluation metrics like system resilience, adaptability, and scalability. This comprehensive set of criteria, derived from both DSR and System Theory, allows for a nuanced assessment of the blockchain system's capacity to adapt to and influence the dynamics within the supply chain environment.

This evaluation integrates DSR and System Theory to measure the outputs of blockchain implementations and provide insights into the systemic properties that support successful technology integration in complex environments. This holistic approach ensures that the analysis aligns with the demands for efficient, adaptable technology and can enhance supply chain and product management systems' overall integrity and functionality.

3.3 Operationalization of Theoretical Constructs

In this thesis, key constructs are operationalized to assess the efficacy of Blockchain technology in Supply Chain Management (SCM) and Product Lifecycle Management (PLM). Exploring complex products through Smart Contracts and NFTs examines their integration and functionality within the SCM system. Another vital construct is the role of NFTs in enhancing lifecycle traceability and transparency in SCM. Additionally, methodologies for managing relationships between NFTs from various sources are developed and refined through iterative DSR processes, which are crucial for cohesive SCM and PLM processes. The analysis also extends to the tangible return on investment from integrating Digital Twin Blockchain Technology in SCM, focusing on financial and operational benefits and systemic impacts such as scalability and resilience. This operationalization framework, grounded in empirical research, aims to bridge the theoretical potential with practical application in Blockchain technology.

The operationalization of key constructs for evaluating Blockchain technology in Supply Chain Management (SCM) and Product Lifecycle Management (PLM) will proceed through structured Key Performance Indicators (KPIs) and system simulations, which will be elaborated upon in the subsequent sections:

1. Smart Contracts and NFTs in Complex Product Representation
    - KPI: Accuracy in depicting multifaceted product attributes.
    - Key Question: How effectively do Smart Contracts and NFTs represent complex product details?
    - System Simulation: Assess how Smart Contracts and NFTs integrate and function within the SCM system, examining the systemic effects of these technologies on the supply chain's efficiency and integrity.
2. NFTs in Product Lifecycle and SCM Traceability
    - KPI: Enhancement of transparency and traceability in product lifecycles.
    - Key Question: How do NFTs contribute to lifecycle transparency and traceability in SCM?
    - System Dynamics Modeling: Simulate and visualize how information flows through NFTs to enhance system-wide transparency and traceability, highlighting their impact on overall supply chain operations.
3. Inter-NFT Relationship Management

- KPI: Efficiency in managing relationships between NFTs of different origins.
- Key Question: What methodologies effectively manage inter-NFT relationships within SCM and PLM?
- System Dynamics Modeling: Simulate and visualize how information flows through NFTs to enhance system-wide transparency and traceability, highlighting their impact on overall supply chain operations.

4. ROI of Digital Twin Blockchain Technology in SCM
    - KPI: Financial and operational returns from Blockchain technology integration.
    - Key Question: What are the quantifiable benefits of implementing Digital Twin Blockchain technology in SCM?
    - System Dynamics Modeling: Simulate and visualize how information flows through NFTs to enhance system-wide transparency and traceability, highlighting their impact on overall supply chain operations.

Through those four structured Key Performance Indicators (KPIs) and targeted questions, this research establishes a clear pathway for evaluating Smart Contracts and NFTs and their roles in enhancing product representation, lifecycle traceability, and inter-NFT relationships. Additionally, it outlines the approach to assessing the Return on Investment (ROI) of Digital Twin Blockchain Technology in Supply Chain Management (SCM). This methodical approach bridges theoretical concepts with real-world applications and sets a robust foundation for empirical research in this evolving field.

3.4 Research Purpose and Questions

This section outlines the specific objectives and questions that guide this research, employing Design Science Research (DSR) and Systems Theory as foundational methodologies. These methodologies are frameworks for analysis and are instrumental in constructing and evaluating innovative solutions that address critical challenges in supply chain management (SCM) and product lifecycle management (PLM).

3.4.1 Integration of Design Science Research (DSR)

Design Science Research is pivotal in developing and applying new technologies within SCM and PLM. DSR is oriented toward creating and evaluating artifacts designed to solve identified problems (Hevner *et al.*, 2004). In this research, DSR facilitates the development of blockchain-based frameworks that enhance transparency, efficiency, and authenticity in SCM and PLM systems.

The objective is to construct and assess a blockchain framework that addresses the specific needs of SCM and PLM, focusing on improving operational efficiencies and data integrity across supply chains.

3.4.2 Application of Systems Theory

Systems Theory provides a holistic approach to understanding the complexities and interdependencies within SCM and PLM systems. This theory is essential for modeling the systemic impacts and interactions influenced by blockchain technology (Skyttner, 2005). Systems Theory aids in conceptualizing the entire ecosystem of SCM and PLM, ensuring that the blockchain solutions are robust, scalable, and integrated within existing infrastructures.

The objective is to model and analyze the interdependencies and feedback loops within SCM and PLM systems that affect the adoption and efficiency of blockchain technology.

3.4.3 Research Questions

The overarching research questions formulated through the lens of DSR and Systems Theory are designed to explore the transformative potential of blockchain technology in SCM and PLM. These questions are:

1. How can blockchain technology be integrated into SCM and PLM systems to enhance transparency, efficiency, and authenticity using DSR?
    - This question seeks to identify the specific attributes of blockchain that can be leveraged to address challenges within SCM and PLM. The use of DSR will facilitate the creation of artifacts that can be empirically tested and refined.
2. What systemic changes are required within SCM and PLM to support the integration of blockchain technology, as analyzed through Systems Theory?
    - This question explores the systemic and organizational transformations needed to incorporate blockchain effectively. Systems Theory provides a framework for understanding these changes holistically, considering all aspects of the systems involved.
3. What are the implications of blockchain technology for operational processes and strategic decision-making within SCM and PLM?
    - This question aims to assess the impact of blockchain implementations on the operational and strategic dimensions of SCM and PLM. It involves evaluating the artifacts developed through DSR and analyzing their efficacy and integration within systems per Systems Theory.

3.4.4 Theoretical and Practical Contributions

The study aims to bridge theoretical constructs with practical implementations, substantially contributing to academic knowledge and industry practices in SCM and PLM. By addressing these research questions, the study will deliver a comprehensive framework that enhances understanding and provides actionable solutions for leveraging blockchain technology in complex supply chains and product lifecycle systems.

3.5 Artifact Development

The process of artifact development is a cornerstone of the Design Science Research (DSR) methodology applied to this research (Hevner *et al.*, 2023; Hunziker and Blankenagel, 2024). This section outlines the detailed steps in designing and developing blockchain-based artifacts for Supply Chain Management (SCM) and Product Lifecycle Management (PLM) systems. The development of these artifacts adheres strictly to the principles of both DSR and Systems Theory, ensuring that each artifact addresses specific theoretical and practical challenges and contributes to the field's body of knowledge.

3.5.1 Design and Development Process

The design and development of artifacts within the scope of this thesis involve a structured, iterative process that integrates the foundational concepts of DSR (Hevner *et al.*, 2004) and the holistic insights of Systems Theory (Ramage and Shipp, 2020; Skyttner, 2005). This process begins with identifying the problem domain and the specification of requirements for the technological solutions originating from the research questions outlined in previous sections.

Requirement Specification: Initially, the requirements are gathered through a thorough analysis of existing systems within SCM and PLM, pinpointing deficiencies where blockchain could introduce enhancements in transparency, efficiency, or authenticity.

Artifact Design: Specific artifacts—from decentralized applications (dApps) for SCM to digital twins for PLM—are conceptualized. The design phase involves the architectural layout, including the choice of blockchain platforms (e.g., Ethereum or Polygon for its smart contract capabilities) and determining data structures and interfaces for user interaction.

Development: Following the design, the development phase involves the actual coding and implementation of the artifacts. This phase uses agile development practices for rapid prototyping and iterative testing. Tools and frameworks specific to blockchain development, such as Truffle and Solidity for Ethereum-based applications, are employed to construct robust and secure applications.

3.5.2 Role of Artifacts

The artifacts designed and developed in this research serve multiple roles, directly addressing the challenges identified in SCM and PLM:

Operational Efficiency: In SCM, blockchain-based dApps automate and streamline inventory management and provenance tracking processes, significantly reducing delays and human errors. The immutability and decentralization inherent in blockchain provide a trustworthy environment for sharing information across the supply chain network, thus enhancing operational transparency and efficiency.

Authenticity and Traceability: For PLM, integrating digital twins with blockchain technology ensures that every modification to a product, from design through to end-of-life, is recorded and traceable. This traceability is crucial for industries requiring high standards of compliance and authenticity, such as pharmaceuticals and high-value manufacturing.

Enhanced Security: The cryptographic nature of blockchain enhances the security of digital twins in PLM, protecting sensitive product data against tampering and unauthorized access. This is particularly important in sectors where intellectual property rights are a critical concern.

Feedback Mechanisms: SCM and PLM artifacts are designed with built-in feedback mechanisms that allow continuous data collection on usage and performance. This data is vital for the iterative modification of the artifacts, ensuring they remain effective and relevant as industry standards and technologies evolve.

The development of these blockchain-based artifacts is guided by the rigorous methodologies of DSR and Systems Theory, ensuring that each phase from design to deployment reflects academic rigor and practical relevance. The artifacts developed contribute to solving specific problems identified in SCM and PLM and also advance the theoretical understanding of integrating advanced digital technologies in these fields. The iterative development and refinement process ensures that the solutions are robust, scalable, and aligned with the current and future needs of the industry.

3.6 Evaluation Strategy

The evaluation of artifacts developed through Design Science Research (DSR) is pivotal for validating their effectiveness, efficiency, and applicability within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). This section outlines the systematic evaluation strategy employed to assess the blockchain-based artifacts, drawing on both DSR and Systems Theory principles. This dual-theoretical approach ensures a comprehensive assessment that addresses the artifacts' functionality and their impact on the systems within which they operate.

3.6.1 Evaluation Methods

The evaluation process is designed to be iterative, aligning with the DSR cycle (Dresch *et al.*, 2015; Hevner *et al.*, 2004; Hunziker and Blankenagel, 2024) and continuously incorporating feedback mechanisms to refine the artifacts. The qualitative and quantitative methods are tailored to measure the specific objectives defined for each artifact.

Functional Testing: Initially, the artifacts undergo rigorous functional testing to ensure they operate as intended. This includes testing for smart contract functionality, transaction integrity, and the correct execution of blockchain operations. Tools such as

Ganache and Truffle are used to deploy smart contracts in a simulated environment and verify their correct execution without real-world consequences.

Performance Evaluation: The performance of each artifact is assessed using metrics such as transaction throughput, latency, and resource utilization. These metrics are crucial for SCM and PLM contexts where real-time data processing and responsiveness are critical.

User Acceptance Testing: To gauge the practical utility and user interface adequacy, user acceptance tests are conducted with potential end-users from the SCM and PLM sectors. This involves workshops and pilot programs where users interact with the artifacts in controlled settings.

Systems Impact Assessment: Employing Systems Theory, this assessment evaluates the impact of artifacts on broader organizational and technological systems. This includes analyzing changes in system behaviors, interactions between system components, and overall system stability and resilience post-integration.

3.6.2 Feedback Integration

Feedback plays a critical role in the iterative development and refinement of the artifacts:

Continuous Improvement Loop: Feedback from each evaluation phase is fed back into the development cycle, allowing for the continuous improvement of the artifacts. This loop ensures that the artifacts meet the initial design specifications and adapt to evolving user needs and technological advancements.

Stakeholder Feedback: Feedback from a diverse range of stakeholders, including supply chain managers, product lifecycle specialists, and IT professionals, is integral. This feedback provides diverse perspectives on the artifacts' usability, effectiveness, and potential areas for enhancement.

The evaluation strategy detailed herein is robust, incorporating various methods to ensure the artifacts function as intended and contribute positively to the systems they are designed to enhance. By integrating feedback at every stage, the research ensures practical relevance and adaptability in rapidly evolving fields like SCM and PLM.

3.7 Documentation and Communication

The comprehensive documentation and effective communication of research findings are essential components of the Design Science Research (DSR) methodology, previously shown in Chapter 3.2.1, Guideline 7 (Hevner *et al.*, 2004) and Figure 5 Step 12 (Bronet Campos, 2023) - Communication of the research. This section outlines the strategies employed to document the development and evaluation processes of the blockchain-based artifacts and the mechanisms through which these findings are communicated to academic and industry audiences.

3.7.1 Documentation Process

Development Documentation: Throughout the artifact development phase, detailed records document the design choices, development stages, and iterations. This includes architectural diagrams and code repositories that capture the evolution of the artifacts.

Evaluation Records: The evaluation phase is documented thoroughly, including the setup, methodology, results, and analytical procedures. This involves capturing quantitative data outputs, such as performance metrics, and qualitative feedback from user acceptance testing. Data visualization tools and statistical software are used to analyze and present this data effectively, ensuring the findings are accessible and interpretable.

Systems Theory Integration: Reflecting the application of Systems Theory, the documentation also covers systemic impact assessments. This includes models and frameworks that show the interactions and feedback loops within the systems affected by the implementation of the blockchain artifacts. Systems modeling software aids in visualizing and understanding these complex interactions.

3.7.2 Knowledge Distribution

The distribution of knowledge generated from this research is carefully planned to align with the academic milestones and the practical application of findings in the industry. Given the focus on publishing the thesis as the primary output of this research, the distribution strategy emphasizes thorough engagement with industry practitioners and the broader academic community after this thesis's official completion and approval.

Industry Engagement: After publishing the thesis, findings will be shared with industry stakeholders through targeted presentations at industry-specific conferences and seminars. These presentations are designed to translate the research insights into actionable strategies that can be applied in Supply Chain Management (SCM) and Product Lifecycle Management (PLM). The engagement will also include roundtable discussions and panel sessions at industry forums where the practical implications of blockchain technologies can be debated and explored in depth.

Educational Outreach: Post-publication, the research will be adapted into case studies and modules for academic courses focusing on SCM, PLM, and blockchain technology. This adaptation educates future professionals about integrating DSR and Systems Theory in real-world applications, preparing them to effectively manage and implement similar technologies.

Public Access and Engagement: Once the thesis has been graded and published, a series of accessible articles summarizing the research findings will be prepared. These articles will be aimed at a general audience and distributed via technology and university blogs, newsletters, and social media platforms. The objective is to increase public awareness and understanding of the potential and challenges of implementing blockchain technologies in SCM and PLM.

Professional Development Workshops: Workshops and webinars will be conducted to provide hands-on experiences and deeper insights into the practical applications of the research findings. These sessions will be particularly beneficial for professionals in SCM and PLM sectors, providing them with the tools and knowledge to implement the innovations discussed in the thesis.

This structured approach to knowledge distribution ensures that the research findings are published academically and effectively translated into practical, actionable insights that can benefit industry and educational fields. The research is positioned to substantially impact theoretical and practical advancements in blockchain, SCM, and PLM by focusing on post-publication engagement.

3.7.3 Conclusion

The strategies for documentation and communication outlined in this section ensure that all aspects of the research are recorded comprehensively and communicated effectively, reaching both academic audiences and industry practitioners. The meticulous documentation facilitates future research and development, while diverse communication channels enhance the impact of the research by informing practice and contributing to academic discourse. This holistic approach to documentation and distribution ensures that the research achieves maximum reach and relevance, providing a foundation for future innovations in blockchain applications within SCM and PLM.

3.8 Research Design Limitations

Implementing Design Science Research (DSR) and Systems Theory methodology has proven to be a valuable tool in creating and examining groundbreaking solutions, such as blockchain technologies in supply chain management (SCM) and product lifecycle management (PLM). However, it is essential to acknowledge the limitations of this approach (Barata *et al.*, 2023; Jacob *et al.*, 2022), which must be recognized to understand the research scope and its outcomes. The following points illustrate the research design constraints of the DSR and Systems Theory method:

3.8.1 Limitations Related to Design Science Research (DSR)

Iterative Process Delays: DSR's iterative nature, while beneficial for refining artifacts, essentially introduces potential delays and resource overheads. The iterative cycles required for designing, testing, and refining artifacts can extend project timelines and increase costs, potentially limiting the scope of prototype development and evaluation (Hevner *et al.*, 2004). This limitation impacts the scalability of proposed solutions, suggesting areas for further investigation in optimizing the DSR methodology for time-sensitive research contexts.

Generalizability of Artifacts: DSR focuses on creating and evaluating artifacts that solve specific problems, which may limit the generalizability of findings. The specificity of artifacts designed for particular contexts in SCM and PLM might not readily apply to other domains or broader applications without significant adaptation (Gregor and Hevner, 2013). Future research should explore ways to enhance the versatility and applicability of DSR-developed artifacts across various settings.

3.8.2 Limitations Related to Systems Theory

Complexity in Systemic Integration: Systems Theory provides a comprehensive framework for analyzing the interdependencies within SCM and PLM systems. However, fully integrating Systems Theory into practical blockchain applications can be daunting, as it requires a deep understanding of the complex dynamics and feedback loops within and between systems (Skyttner, 2005). This complexity may obscure the clarity of research findings, particularly when translating theoretical models into practical implementations.

Adaptability Issues: While Systems Theory aids in understanding broad system interactions, its adaptability to rapidly evolving technological domains such as blockchain is sometimes limited. The static nature of some systemic models may not capture the dynamic changes typical of technology-driven environments, which could restrict the applicability of theoretical insights to practical scenarios (Jackson, 2003). Identifying and addressing these dynamic elements remain essential for future research to enhance the responsiveness of Systems Theory-based models.

3.8.3 Implications for Future Research

This study's limitations underscore the necessity for continuously adapting and refining DSR and Systems Theory in technology-driven research. Future studies should aim to develop methodologies that reduce the time and resources required by DSR's iterative processes, possibly integrating agile development practices to enhance efficiency and responsiveness. Additionally, expanding the scope of Systems Theory to incorporate elements that address the dynamic nature of technological advancements could improve the practical applicability of this theoretical framework.

Future research should also focus on enhancing the generalizability of DSR artifacts and exploring ways to simplify the integration of complex systemic theories into practical applications. By doing so, subsequent studies can build on the foundational work presented here, advancing the theoretical and practical understanding of blockchain in SCM and PLM.

Acknowledging and critically analyzing these limitations not only enhances the academic rigor of this study but also sets a clear agenda for future research to build upon. By delineating these constraints, this research contributes to a deeper understanding of the challenges inherent in employing DSR and Systems Theory in complex, technology-driven domains, paving the way for more effective and adaptable research methodologies in the future.

3.9 Conclusion

The conclusion of the methodologies outlined in this thesis signifies a comprehensive approach to addressing the complexities associated with integrating blockchain technology in Supply Chain Management (SCM) and Product Lifecycle Management (PLM). This chapter summarizes the methodologies employed, the expected outcomes of this research, and the potential impacts these may have on the academic community and industry practices.

3.9.1 Summary of Methodology

The methodology adopted for this research is rooted in Design Science Research (DSR) as outlined by Hevner *et al.* (2004) and Dresch *et al.* (2015), complemented by Systems Theory as described by Jackson (2003), Ramage and Shipp (2020) and Skyttner (2005), providing a robust framework for creating, testing, and refining innovative blockchain solutions. This approach facilitates the practical application of theoretical constructs and ensures that the solutions developed are rigorously evaluated and iteratively improved. The integration of these methodologies underpins the entire research process, from the conceptualization of blockchain artifacts to their systematic evaluation and iterative refinement, aligning with the insights provided by Centobelli *et al.* (2021) on shaping future distributed ledgers and decentralized technologies.

3.9.2 Anticipation of Outcomes

The research significantly contributes to knowledge of blockchain applications within SCM and PLM. The artifacts developed through this study demonstrate practical utility in enhancing transparency, efficiency, and security across SCM and PLM processes, echoing the challenges and opportunities highlighted by de Boissieu *et al.* (2021) in the luxury industry’s supply chains.

Moreover, evaluating these artifacts should provide valuable insights into their operational effectiveness and systemic impacts within organizational and technological frameworks, much in the spirit of the systematic review by Queiroz *et al.* (2019), which bridges blockchain's theoretical potential and practical application in SCM.

3.9.3 Potential Impact on the Field

The findings from this research are projected to have far-reaching implications for academia and industry. Academically, the research contributes to the literature on blockchain technology by providing a detailed account of how DSR and Systems Theory can be applied to solve real-world problems in SCM and PLM. This contributes to a deeper understanding of blockchain technologies' practical challenges and benefits, offering a foundation for future research in this rapidly evolving field as demonstrated through the frameworks and findings of Hevner *et al.* (2004; 2023), Centobelli *et al.* (2021), and Queiroz *et al.* (2019).

Implementing the developed blockchain framework and Best Practices in the industry will revolutionize SCM and PLM practices by providing more robust, transparent, and efficient systems. These technologies could significantly improve operational processes, data integrity, and overall supply chain and product lifecycle governance. This could further influence industry standards and practices, encouraging a shift towards more decentralized and secure management systems.

3.9.4 Future Research Directions

While this research provides substantial insights into the application of blockchain technology within SCM and PLM, it also opens avenues for further investigation. Future research could explore the scalability of the developed blockchain solutions across different industries or global supply chains. Additionally, the long-term sustainability and environmental impact of implementing blockchain technology at scale could be evaluated to balance efficiency gains with ecological considerations.

This research captures a comprehensive approach to exploring and harnessing the capabilities of blockchain technology in enhancing SCM and PLM systems. Through a methodical application of DSR and Systems Theory, it offers new perspectives and solutions that address existing challenges and pave the way for innovative practices. As the field continues to evolve, the insights and methodologies developed in this research will undoubtedly contribute to shaping the future of blockchain applications in various sectors, steering academic inquiry and industry practice toward more integrated and intelligent systems.

CHAPTER IV:

RESULTS

4.1 Research Question One - Integration of Blockchain Technologies in SCM and PLM

4.1.1 Overview of Implemented Solution

Integrating blockchain technology into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) systems significantly enhances transparency, traceability, and efficiency. This section provides a detailed overview of the implemented solutions, focusing on developing smart contracts and Non-Fungible Tokens (NFTs) within these domains. The solutions are designed to address critical challenges in SCM and PLM by leveraging the unique attributes of blockchain technology, such as immutability, decentralization, and automated compliance.

4.1.1.1 PLM Product Structure

Creating an effective Product Lifecycle Management (PLM) product structure is foundational for managing the complete lifecycle of a product efficiently. This structure ensures that all relevant product data is accessible and manageable from initial design through end-of-life. Below (*Table 1*), describes a comprehensive PLM product structure and expresses its suitability as a digital twin within a PLM system.

Table1 – PLM Product Structure

Category	Attribute	Description
1. General Information	Product ID	A unique identifier is essential for tracking the product through its lifecycle.
	Name	Identifies the product within internal and external communications.
	Description	Provides a brief overview, facilitating a quick understanding of the product’s purpose.

	Product Type	Categorize the product, useful for sorting and applying specific processes or regulations.
	Version	Tracks revisions, essential for managing updates and changes over the product's lifecycle.
2. Design Data	Design Files	Centralizes access to CAD files and schematics, supporting modifications and manufacturing.
	Designer	Records the creator for intellectual property rights and design traceability.
	Design Date	Marks the foundation of the design, crucial for version control.
	Bill of Materials (BOM)	Lists all integrated components. Critical for cost estimation, procurement, and manufacturing planning.
3. Manufacturing Info	Manufacturing Processes	Outlines steps to build the product, key for standardization and quality control.
	Manufacturing Locations	Ensures logistical efficiency and compliance with regional manufacturing regulations.
	Tools and Equipment	Specifies the tools required for product creation, integral for operational readiness.
	Quality Control Params	Standards the product must meet, crucial for maintaining consistency and safety.
4. Assembly Information	Assembly Instructions	Guides the assembly process, reducing errors and increasing efficiency.
	Component List	Ensures all parts are accounted for before assembly begins.
	Assembly Time	Helps in planning workforce and production schedules.
	Assembly Teams	Assigns responsibility, facilitating management and accountability.
5. Testing and QA	Test Procedures	Standardizes testing to ensure products meet required specifications.
	Test Results	Provides historical data for quality tracking and improvement.
	Quality Certifications	Demonstrates compliance with industry standards, enhancing marketability.
	Issues and Resolutions	Documents problems and solutions, vital for continuous improvement.
6. Logistics	Packaging	Specifies packaging requirements to ensure product safety during transport.
	Storage Requirements	Details conditions under which the product must be stored to maintain quality.

	Shipping Methods	Outlines preferred transportation means to optimize delivery and cost.
7. Regulatory Compliance	Regulations	Lists applicable laws and regulations, ensuring legal compliance.
	Compliance Status	Tracks the product's adherence to regulatory requirements.
8. End-of-Life Management	Disposal Instructions	Guides responsible product disposal to minimize environmental impact.
	Recycling Information	Identifies recyclable materials, supporting sustainability initiatives.
9. Historical Data and Versioning	Change Log	Records alterations for auditing and tracking purposes.
	Version History	Documents the evolution of the product, essential for managing iterations.
10. Digital Rights and Permissions	Access Control	Manages who can view or edit product data, protecting sensitive information.
	Rights Management	Outlines usage rights, protecting intellectual property and controlling product usage.

The product structure shown in *Table 1* is ideally suited as a digital twin within a PLM system because it integrates comprehensive, real-time data from every stage of the product lifecycle, enabling dynamic simulation and monitoring real-world conditions and behaviors. Digital twins require detailed and accurate representations to function effectively. This structure provides all the necessary data to mirror the physical product in a digital environment (Grieves, 2015; Tao *et al.*, 2018). Including components such as the Bill of Materials, assembly instructions, and quality control parameters ensures that the digital twin can simulate and analyze the product from conceptualization to disposal, enhancing decision-making and optimization throughout the product lifecycle (Kritzinger *et al.*, 2018).

This detailed PLM product structure supports efficient product management and aligns with the requirements for creating a robust digital twin in a PLM system. It encompasses all stages of the product lifecycle, ensuring comprehensive data collection and utilization, which is pivotal for successfully applying digital twin technology.

4.1.1.2 PLM Product Smart Contract

Implementing an NFT-based smart contract within Product Lifecycle Management (PLM) systems illustrates a transformative methodology that captures and systematically manages product data interactions through blockchain technology. This approach extends data integrity, traceability, and security and supports dynamic lifecycle management across various phases of a product's existence. The NFT-based smart contract 'ProductNFT' shown in *Appendix A* is an artifact that enhances the capabilities of traditional PLM systems. 'ProductNFT' considers the interconnected and interdependent components of the PLM ecosystem, thus ensuring comprehensive data integration and functionality.

Smart Contract Structure and Functions:

- Contract Details:
  - Base technology inherits from OpenZeppelin's ERC721 standard, ensuring compliance with established NFT protocols and providing foundational NFT functionalities.
  - Ownership and control utilizes the Ownable contract to manage access rights, ensuring only authorized entities, typically the product owner or designated administrators, can modify product data.
- Core Functionalities:
  - The mint function enables the creation of new NFTs representing unique product instances within the PLM system, each identified by a tokenId and linked with specific ProductMetadata.

- The update metadata function allows for updating the metadata of existing product NFTs, ensuring product information remains current and accurate throughout the product lifecycle.
- The get metadata function facilitates the retrieval of comprehensive product details by token ID, supporting transparency and accessibility in product management.
- The add/remove material item manages the dynamic aspects of the Bill of Materials (BOM), permitting additions or removals of material items, thus reflecting changes in product components or sourcing.

ProductMetadata Structure:

The ProductMetadata struct encapsulates essential data about a product, mapped in the contract to each NFT through a unique token ID. This structure includes comprehensive lifecycle data from general product identifiers to detailed assembly and compliance information, supporting the holistic systems view supported by Systems Theory (Ramage and Shipp, 2020).

Benefits of NFT-based Smart Contract Integration in PLM:

The integration of 'ProductNFT' smart contracts into PLM systems provides several advantages:

- Enhanced security and traceability offer a verifiable and tamper-proof product data record, aligning with the DSR goal of creating reliable and robust artifacts (Hevner *et al.*, 2004).
- Automated compliance and updates automatically enforce compliance and execute updates, reducing manual oversight and error and showcasing an effective use of Systems Theory in automating and optimizing system interactions (Ramage and Shipp, 2020).

- Real-time data management reflects changes in real-time across the blockchain network, ensuring that all stakeholders have access to the most current information, which enhances system responsiveness and efficiency (Puthal *et al.*, 2018).
- Interoperability and integration linking various product NFTs and material items offer a comprehensive view of product components and their origins, essential for an overview of the entire system (Kshetri, 2018).

Integrating ProductNFT smart contracts within a PLM system meets the digital transformation objectives and significantly enhances the data management capabilities across its lifecycle. By leveraging blockchain technology, this integration achieves greater efficiency, transparency, and security, improving product integrity and trust—evidence of the potential of combining DSR artifact design and Systems Theory in modern technological applications.

4.1.1.3 SCM Logistic Structure

Integrating blockchain technology into Supply Chain Management (SCM) requires a robust framework for managing unified or abstract containers, which are central in tracking the movement and status of goods. This section outlines the SCM Container Structure and SCM Container Index Structure, which are essential for ensuring transparency, traceability, and efficiency within the supply chain.

The unified SCM Container Structure (*Table 2*) is designed to capture comprehensive details about each abstract container used in the supply chain. This structure includes attributes such as container ID, name, capacity, contents, location, status, timestamps, and history. By integrating this structure into the SCM system, organizations achieve real-time visibility and traceability of containers and goods, ensuring efficient logistics management.

Table 2 – SCM Container Structure

Category	Attribute	Description
1. Container Details		
	containerId	Unique identifier for the container
	name	Name of the container
	capacity	Maximum capacity of the container (number of other containers or products)
2. Contents		
	type	Type of the content (e.g., "ProductNFT" or "ContainerNFT")
	id	Unique identifier for the content (either a product or another container)
	quantity	Quantity of the content within the container
3. Location and Status		
	location	Current location of the container
	isStatic	Boolean indicating whether the container is static or mobile
	status	Current status of the container (e.g., "in transit," "in storage")
4. Timestamps		
	created	Timestamp when the container was created
	lastMoved	Timestamp when the container was last moved
5. History		
	event	Description of the event (e.g., "moved," "added content," "removed content")
	timestamp	Timestamp when the event occurred

location	Location of the container during the event

The SCM Container Index Structure (*Table 3*) provides a comprehensive index of containers and goods within the supply chain, including company details, container details, contents, location, status, timestamps, and history. This index facilitates efficient container tracking and management, ensuring that all relevant data is efficiently accessible and up-to-date.

Table 3 – SCM Container Index Structure

Category	Attribute	Description
1. **Company Details**		
	companyId	Unique identifier for the company
2. Container Details		
	containerId	Unique identifier for the container
	name	Name of the container
	capacity	Maximum capacity of the container (number of other containers or products)
3. Contents		
	type	Type of the content (e.g., "ProductNFT" or "ContainerNFT")
	id	Unique identifier for the content (either a product or another container)
	quantity	Quantity of the content within the container
4. Location and Status		
	location	Current location of the container
	isStatic	Boolean indicating whether the container is static or mobile
	status	Current status of the container (e.g., "in transit," "in storage")
5. Timestamps		
	created	Timestamp when the container was created

	lastMoved	Timestamp when the container was last moved
6. History		
	event	Description of the event (e.g., "moved," "added content," "removed content")
	timestamp	Timestamp when the event occurred
	location	Location of the container during the event

Integrating the SCM Container Structure and SCM Container Index Structure into the SCM system offers several benefits:

Enhanced Traceability: By capturing detailed information about containers and their contents, organizations can achieve greater traceability of products throughout the supply chain (Kshetri, 2018; Rajput *et al.*, 2022).

Improved Efficiency: Real-time tracking of container locations and statuses enables more efficient logistics management, reducing delays and optimizing resource allocation (Dwivedi *et al.*, 2020; Hirata *et al.*, 2020).

Increased Transparency: Container data's transparent and immutable record enhances supply chain partners' accountability and trust (Chang *et al.*, 2022; Lohmer *et al.*, 2022).

Streamlined Operations: Automating the tracking and management of containers reduces manual intervention, minimizing errors and administrative overhead (Rajput *et al.*, 2022).

By leveraging these SCM container structures within the SCM framework, organizations can achieve a more integrated and efficient approach to managing products and their associated logistics, ultimately enhancing overall supply chain performance.

4.1.1.4 SCM Container Smart Contracts

Integrating blockchain technology into Supply Chain Management (SCM) requires a robust framework for managing containers, which are pivotal in tracking the movement and status of goods. This section outlines the design and functionality of the two smart contracts for ContainerNFT (*Appendix B*) and ContainerIndexNFT (*Appendix C*), which are essential for ensuring transparency, traceability, and efficiency within the supply chain.

Smart Contract Structure and Functions:

ContainerNFT Smart Contract:

The ContainerNFT smart contract is designed to manage individual containers within the supply chain. It includes the following key components and functionalities.

- Contract Details: The contract inherits from OpenZeppelin's ERC721 standard, ensuring compliance with established NFT protocols and providing foundational NFT functionalities. It also utilizes the Ownable contract to manage access rights, ensuring only authorized entities can modify container data.
- Core Functionalities:
    - The createContainer function creates a new container NFT with specified attributes such as name, capacity, location, and status. It emits an event upon creation, providing a transparent record of the container's inception.
    - The moveContainer function updates the container's location, ensuring real-time tracking of its movement. It emits an event each time the container is moved, enhancing traceability.
    - The loadContent function allows for adding contents (either products or other containers) to the container and updating the container's metadata accordingly.
    - The unloadContent function removes contents from the container, ensuring accurate and up-to-date records of the container's contents.

    - The getContainer function retrieves comprehensive details about a specific container, including its contents, location, status, and history.

ContainerIndexNFT Smart Contract:

The ContainerIndexNFT smart contract provides a comprehensive index of containers and goods within the supply chain. It includes the following key components and functionalities.

- Contract Details: Similar to ContainerNFT, this contract inherits from OpenZeppelin's ERC721 standard and Ownable contract, ensuring compliance and secure access control.
- Core Functionalities:
    - The createContainerIndex function creates a new container index NFT with specified attributes such as company details, container details, contents, location, and status. It ensures a transparent and immutable record of the container's metadata.
    - The moveContainerIndex function updates the container's location within the index, ensuring real-time tracking and traceability.
    - The loadContent function allows for the addition of contents into the container index, updating the metadata to reflect the current state of the container.
    - The unloadContent function removes contents from the container index, ensuring accurate records of the container's contents.
    - The getContainerIndex function retrieves detailed information about a specific container index, including company details, container details, contents, location, status, timestamps, and history.

Benefits of NFT-based Smart Contract Integration in SCM

The integration of ContainerNFT and ContainerIndexNFT smart contracts into SCM systems provides several advantages:

- Enhanced Security and Traceability offer a verifiable and tamper-proof record of container data, aligning with the DSR goal of creating reliable and robust artifacts (Hevner *et al.*, 2004).
- Automated Compliance and Updates enforce compliance and execute updates, reducing manual oversight and error and showcasing an effective use of Systems Theory in automating and optimizing system interactions (Ramage and Shipp, 2020).
- Real-time Data Management reflects changes in real-time across the blockchain network, ensuring that all stakeholders have access to the most current information, which enhances system responsiveness and efficiency (Puthal *et al.*, 2018).
- Interoperability and Integration are linking various container NFTs, and their contents offer a comprehensive view of container components and their origins, essential for an overview of the entire system (Kshetri, 2018).

Integrating ContainerNFT and ContainerIndexNFT smart contracts within an SCM system meets the digital transformation objectives and significantly enhances the data management capabilities across the supply chain. This integration achieves greater efficiency, transparency, and security by leveraging blockchain technology, improving container integrity and trust. This evidence demonstrates the potential of combining DSR artifact design and Systems Theory in modern technological applications.

4.1.2 Analysis of Integration Efficacy

The integration of blockchain technology, specifically using Non-Fungible Tokens (NFTs) and smart contracts, into Supply Chain Management (SCM) and Product Lifecycle

Management (PLM) systems represents a significant advancement in enhancing transparency, traceability, and efficiency. This section provides a comprehensive analysis of the efficacy of these integrations, drawing on the theoretical foundations and practical implementations discussed in previous chapters.

One of the primary benefits of integrating blockchain technology into SCM and PLM is its enhanced transparency and traceability. Blockchain's decentralized and immutable ledger ensures that all transactions and data entries are recorded tamper-proof, which is crucial for maintaining the integrity of supply chain and product lifecycle data (Kshetri, 2018). Using NFTs to represent unique product instances and containers further enhances this transparency by providing a verifiable and immutable record of each product's lifecycle and movement through the supply chain (Rajput *et al.*, 2022).

Implementing the 'ProductNFT' and 'ContainerNFT' smart contracts, as detailed in sections 4.1.1.2 and 4.1.1.4, respectively, ensures that all product and container data is unified, securely recorded and easily accessible. This transparency is particularly beneficial in industries where product authenticity and provenance are critical, such as pharmaceuticals and luxury goods(Rajput *et al.*, 2022; Surjandy *et al.*, 2019). By providing a transparent and immutable record of each product's lifecycle, these smart contracts help to combat counterfeiting and ensure compliance with regulatory standards.

Integrating blockchain technology into SCM and PLM systems significantly improves operational efficiency and automation. Smart contracts, which are self-executing contracts with the terms of the agreement directly written into code, automate many routine tasks and processes, reducing the need for manual oversight and minimizing the risk of human error (Khan *et al.*, 2021). For example, the 'ProductNFT' smart contract automates updating product metadata and managing the Bill of Materials (BOM), ensuring that all product information is current and accurate.

Similarly, the 'ContainerNFT' and 'ContainerIndexNFT' smart contracts automate the tracking and management of containers within the supply chain, providing real-time updates on container locations, statuses, and content. This automation improves logistics management efficiency and enhances supply chain responsiveness and agility.

Blockchain technology's inherent security features, such as cryptographic hashing and decentralized consensus mechanisms, provide a robust framework for ensuring the integrity and security of supply chain and product lifecycle data (Puthal *et al.*, 2018). NFTs and smart contracts enhance this security by providing a verifiable and tamper-proof record of all transactions and data entries (Chen, Cai, *et al.*, 2022).

For example, the 'ProductNFT' and 'ContainerNFT' smart contracts ensure that all product and container data is securely recorded on the blockchain, preventing unauthorized modifications and ensuring that all stakeholders have access to accurate and up-to-date information. This security is fundamental in industries where data integrity is critical, such as healthcare and pharmaceuticals (Gebreab *et al.*, 2022; Yaghy *et al.*, 2023).

Despite the significant benefits of integrating blockchain technology into SCM and PLM systems, several challenges and limitations must be addressed. One of the primary challenges is the scalability of blockchain networks, particularly in handling the large volumes of data generated by supply chain and product lifecycle processes (Chang *et al.*, 2022). The computational demands of maintaining a decentralized ledger and executing smart contracts can also be significant, potentially limiting the scalability and efficiency of blockchain-based systems (Chen *et al.*, 2023; Hirata *et al.*, 2020).

Another challenge is the interoperability of blockchain technology with existing SCM and PLM systems. Integrating blockchain with legacy systems can be complex and require significant modifications to existing infrastructure (Rajput *et al.*, 2022). Additionally, the regulatory and legal environment surrounding blockchain technology is still evolving, and organizations must navigate a complex landscape of data privacy and compliance requirements (Upadhyay *et al.*, 2021).

Integrating blockchain technology, NFTs, and smart contracts into SCM and PLM systems offers significant transparency, traceability, efficiency, and security benefits. However, addressing the challenges of scalability, interoperability, and regulatory compliance is crucial for realizing the full potential of these technologies. By leveraging the principles outlined in the unified Product and Container NFTs, organizations can develop robust and scalable blockchain-based solutions that enhance the integrity and efficiency of their supply chain and product lifecycle processes.

4.1.3 Case Study on the Assembly of a Hydraulic Pump

This case study illustrates the assembly process of a hydraulic pump according to the provided Bill of Materials (BoM). It demonstrates the integration of Product Non-Fungible Tokens (NFTs) and NFTs representing individual parts into the product assembly, utilizing the ProductNFT and ContainerNFT concepts described in section 4.1.1.

The hydraulic pump assembly begins with the procurement of raw materials and components as specified in the BoM (*Table 4*). Each component is assigned a unique NFT, including detailed metadata about its origin, specifications, and relevant certifications.

Table 4 – Bill of Materials for Hydraulic Pump

Pos.	Component	Article Number
1	Housing Assembly	HA-001
2	Pump Shaft	PS-002
3	Bearing Set	BS-003
4	Impeller	IM-004
5	Seals and O-Rings	SO-005

6	Valve Assembly	VA-006
7	Couplings and Adapters	CA-007
8	Filter	FL-008
9	Mounting Bracket	MB-009
10	Fasteners	FS-010
11	Hydraulics Fluid	HF-011
12	Electric Components	EC-012
13	Control Panel	CP-013
14	Safety Covers	SC-014
15	Documentation	DOC-015

Product NFT Assembly:

1. Material Integration:
    - NFT Creation for Components: Each component listed in the BoM is assigned a unique NFT. These NFTs contain metadata including part numbers, descriptions, materials, quantities, and certifications (e.g., hazardous certifications for materials requiring special handling).
    - Hazard Certification Integration: The NFT includes certification information for components like Seals and O-rings (SO-005) or Hydraulics Fluis (HF-011) that require specific hazard certifications to ensure compliance and safety.
2. Assembly of Product NFT:

- Component Verification: Each component's NFT is verified using smart contracts to ensure compliance with the BoM and certification requirements before assembly.
- Digital Record of Assembly: As each component is assembled into the hydraulic pump, its NFT is integrated into the ProductNFT, creating a comprehensive digital record of the entire product assembly process. This ProductNFT provides an immutable record of the components used and the assembly steps, ensuring traceability and accountability.

Packaging and Containerization

1. Individual Product Packaging:
   - Container NFT Creation: Once the hydraulic pump is fully assembled, it is packaged and assigned a ContainerNFT. This NFT contains metadata about the product, including its specifications, the components used, and compliance information.
2. Batching and Palletization:
   - Product Grouping: Several hydraulic pumps are grouped together, and their individual ContainerNFTs are aggregated into a larger pallet ContainerNFT. This pallet ContainerNFT includes detailed information about all the products it contains, enhancing visibility and management during transportation.
   - Shipping Container: Multiple pallets are consolidated into a shipping container, represented by a shipping ContainerNFT. This ContainerNFT encapsulates all previous NFTs, providing a complete and immutable record of the entire shipment.

Traceability and Indexing

1. Real-Time Tracking with Index Container:
    - Index Container NFT: Every move of the product containers, from the production line to the end consumer, is meticulously registered in the index container NFT. This index container acts as a ledger, maintaining real-time updates on the location and status of each product.
    - Blockchain Ledger: The blockchain ledger maintains an immutable record of all transactions, providing stakeholders with accurate and tamper-proof information regarding the product's journey through the supply chain.

Integrating ProductNFTs and ContainerNFTs in the assembly and distribution of Products, like the hydraulic pump used in the case study, significantly enhances transparency, traceability, and compliance within the supply chain. By leveraging blockchain technology, this case study demonstrates how digital records of components and products can transform traditional supply chain practices, ensuring that every part and product is accounted for and compliant with necessary certifications. The continuous tracking and indexing of containers provide an additional layer of security and transparency, fostering trust among all stakeholders in the supply chain.

4.1.4 Key Findings Related to Research Question One

Integrating ProductNFT and ContainerNFT provides a novel approach to enhancing transparency, efficiency, and authenticity in SCM and PLM systems. ProductNFT ensures authenticated lifecycle tracking of products, addressing the critical need for traceability. ContainerNFT automates logistics coordination, enhancing operational efficiency by reducing delays and errors. Together, these artifacts exemplify the potential of blockchain technology to overcome traditional SCM and PLM limitations.

4.2 Research Question Two - Challenges and Solutions in Adoption

This analysis directly addresses Research Question 2 by outlining key challenges and their corresponding solutions. As presented in the sections above, integrating blockchain technology within Supply Chain Management (SCM) and Product Lifecycle Management (PLM) represents a transformative shift towards enhanced transparency, traceability, and efficiency. Despite its potential, the adoption of blockchain faces significant challenges that delay its widespread implementation. This section addresses Research Question Two, as presented in section 1.5.1, by exploring the primary obstacles to blockchain adoption and proposing viable solutions and best practices to mitigate these challenges. The analysis leverages the Design Science Research (DSR) and Systems Theory methodologies, ensuring a comprehensive understanding of the systemic and practical barriers faced by industries adopting blockchain technologies such as Non-Fungible Tokens (NFTs) and smart contracts.

4.2.1 Identified Challenges

Adopting blockchain technology in SCM and PLM has several challenges, broadly categorized into technical, organizational, and regulatory hurdles.

4.2.1.1 Technical Challenges

Scalability and Performance: One of the foremost technical challenges is the scalability of blockchain networks. Blockchain systems, particularly public ones like Ethereum, often suffer from limited transaction throughput and high latency, hindering their performance in large-scale applications like supply chains. For instance, the average transaction speed on the Ethereum network can be too slow to meet the real-time demands of global supply chains (Li *et al.*, 2022).

Interoperability: Interoperability between different blockchain platforms and existing legacy systems is another significant challenge. Supply chains typically involve multiple stakeholders using various technological systems. The lack of standardization within the existing legacy systems and in blockchain protocols can lead to integration issues, complicating the seamless flow of information across the supply chain and to and from different stakeholders (Liu *et al.*, 2023).

Data Privacy and Security: While blockchain is renowned for its security features, data privacy and protection concerns remain. In SCM and PLM, sensitive information such as intellectual property, supplier contracts, and proprietary product details must be secured against unauthorized access. The immutable nature of blockchain can also pose a challenge in correcting inaccurate or outdated data (Kshetri, 2018).

4.2.1.2 Organizational Challenges

Resistance to Change: Adopting blockchain technology requires significant changes in business processes and organizational culture. Due to a lack of understanding or fear of the unknown, resistance from employees and management can impede adoption. The transition to a blockchain-based system necessitates comprehensive training and a shift in mindset, which can be challenging to achieve (Bruel and Godina, 2023; Karuppiah *et al.*, 2023).

High Initial Costs: Implementing blockchain technology involves substantial initial investments in infrastructure, development, and training. For many organizations, especially small and medium-sized enterprises (SMEs), these costs can be prohibitive, deterring them from adopting the technology despite its long-term benefits (Karuppiah *et al.*, 2023).

Skill Shortages: The successful deployment of blockchain technology requires specialized skills in blockchain development, cryptography, and data management. The current shortage of such expertise in the labor market can slow the adoption process and increase the dependency on external consultants, which adds to the cost and complexity (Karuppiah *et al.*, 2023; Toufaily *et al.*, 2021).

4.2.1.3 Regulatory Challenges

Regulatory Uncertainty: Blockchain technology operates in a regulatory grey area in many jurisdictions. The lack of clear regulations and guidelines creates uncertainty and risk for organizations considering blockchain adoption. Issues related to data sovereignty, cross-border data flows, and compliance with international standards, like the European GDPR, the many different US privacy laws (CCPA, CPRA, VCDPA, CPA, and more), or the general ban on Cryptocurrency transactions in China need to be addressed to foster a more conducive environment for blockchain deployment.

Legal Challenges with Smart Contracts: Smart contracts, a core feature of blockchain technology, are self-executing contracts with the terms of the agreement directly written into code. However, the legal recognition and enforceability of smart contracts are still evolving. Jurisdictions differ in their treatment of digital agreements, which can lead to legal complexities and uncertainties for businesses operating in multiple regions (Karuppiah *et al.*, 2023; Kõlvart *et al.*, 2016).

While blockchain technology holds immense potential for revolutionizing SCM and PLM, its adoption is stalled by several technical, organizational, and regulatory challenges. Addressing these challenges requires a multifaceted approach that includes technological advancements, organizational change management, and regulatory clarity.

4.2.1.4 Summary of Challenges to Research Question Two

The challenges identified in Section 4.2.1 align directly with Research Question Two, which focuses on understanding the hurdles to adopting blockchain technologies in SCM and PLM. These challenges include:

- Scalability Issues: Limited transaction processing capabilities of blockchain systems.
- Organizational Resistance: Resistance to change due to lack of understanding and fear of disruption.
- Regulatory and Compliance Uncertainty: Challenges in navigating privacy laws and international regulations.

Section 4.2.1

The solutions proposed in Section 4.2.2 address these challenges systematically, providing actionable recommendations for organizations seeking to adopt blockchain technologies.

4.2.2 Solutions and Best Practices

Addressing the challenges of adopting blockchain technology within Supply Chain Management (SCM) and Product Lifecycle Management (PLM) necessitates a multifaceted approach. This section comprehensively examines potential solutions and best practices, drawing on existing research and practical implementations. The proposed strategies aim to mitigate technical, organizational, and regulatory hurdles, facilitating the seamless integration of blockchain technologies such as Non-Fungible Tokens (NFTs) and smart contracts.

4.2.2.1 Technical Solutions

Enhancing Scalability and Performance: Implementing Layer 2 solutions and sidechains is recommended to address scalability and performance issues. Layer 2 solutions, such as the Lightning Network for Bitcoin (Poon and Dryja, 2016) or Plasma for Ethereum (Wackerow *et al.*, 2024), can significantly increase transaction throughput by processing transactions off the main blockchain. Additionally, sharding techniques can enhance scalability by partitioning the blockchain network into smaller, more manageable segments (Liu *et al.*, 2023). These methods collectively improve blockchain networks' overall efficiency and responsiveness in large-scale SCM applications.

Ensuring Interoperability: Adopting interoperability protocols like Polkadot and Cosmos can facilitate seamless communication between disparate blockchain networks and legacy systems (Dinesha and Patil, 2023). These protocols enable the creation of a unified blockchain ecosystem where different platforms can exchange information and assets without friction. Implementing standardized data formats and APIs further enhances compatibility and integration, reducing the complexity of integrating blockchain with existing SCM and PLM infrastructures (Rajput *et al.*, 2022).

Strengthening Data Privacy and Security: Incorporating advanced cryptographic techniques such as zero-knowledge proofs (ZKPs) and homomorphic encryption is crucial to address data privacy and security concerns. These technologies allow sensitive information to be verified and processed without exposing the actual data, thereby maintaining confidentiality and integrity. Adopting permissioned blockchain models like Hyperledger Fabric can provide enhanced control over data access and governance, ensuring that only authorized parties can access specific information (Rouhani and Deters, 2019).

4.2.2.2 Organizational Solutions

Facilitating Organizational Change: Effective change management strategies are essential to overcoming organizational resistance. These strategies include comprehensive training programs, awareness campaigns, and the involvement of key stakeholders in the decision-making process (Toufaily *et al.*, 2021). By fostering a culture of innovation and continuous learning, organizations can ease the transition to blockchain-based systems and ensure widespread acceptance and understanding of the technology (Kraft *et al.*, 2022).

Reducing Initial Costs: To mitigate the high initial costs associated with blockchain implementation, organizations can adopt a phased deployment approach. This involves starting with pilot or phased projects and gradually scaling up based on the success and learnings from these initial implementations. Leveraging local simulations Blockchains like the tool Ganache, available blockchain test networks like Rinkeby or Kovan, or cloud-based blockchain-as-a-service (BaaS) platforms (Whitfield and Liquin, 2022) can reduce upfront investment by providing scalable and cost-effective blockchain solutions (Karuppiah *et al.*, 2023; Yadlapalli *et al.*, 2022).

Addressing Skill Shortages: Collaborating with educational institutions and encouraging professional training to develop specialized blockchain knowledge can address the skill shortages in the industry. Continuous professional development and offering incentives for acquiring blockchain-related skills can help build a competent workforce capable of managing and innovating with blockchain technology.

4.2.2.3 Regulatory Solutions

Navigating Regulatory Uncertainty: Engaging with regulators and participating in blockchain consortia and industry groups like Enterprise Ethereum Alliance (EEA), Global Blockchain Business Council (GBBC), or others (*Appendix D*) can help organizations stay abreast of regulatory developments and contribute to shaping the regulatory landscape. Developing a robust compliance framework that aligns with existing regulations and anticipates future changes can mitigate risks associated with regulatory uncertainty (Li *et al.*, 2022).

Legal Recognition of Smart Contracts: To ensure the legal enforceability of smart contracts, organizations should collaborate with legal experts to develop standardized smart contract templates that comply with relevant laws and regulations. Advocacy for more straightforward legal frameworks and judicial recognition of smart contracts is also necessary to establish their validity and enforceability across different jurisdictions (Kõlvart *et al.*, 2016).

4.2.2.4 Best Practices

Adopting a Holistic Approach: A successful blockchain implementation requires a holistic approach that considers technical, organizational, and regulatory factors. This includes conducting thorough feasibility studies, developing a clear roadmap, and engaging all relevant stakeholders. Regularly reviewing and updating the implementation plan based on feedback and changing circumstances ensures that the project remains aligned with organizational goals and industry best practices.

Leveraging Consortium Blockchains: Consortium blockchains (*Appendix E*), which are semi-decentralized and governed by organizations, offer a balanced approach between public and private blockchains. These blockchains can provide the benefits of decentralization while allowing for greater control over participation and governance. Hyperledger Fabric is a notable example of a consortium blockchain successfully implemented in various SCM and PLM contexts (Androulaki *et al.*, 2018).

Continuous Monitoring and Evaluation: Implementing continuous monitoring and evaluation mechanisms is essential for the long-term success of blockchain projects. This involves regularly assessing the blockchain system's performance, security, and compliance and making necessary adjustments. Utilizing blockchain analytics tools can provide valuable insights into system performance and identify areas for improvement.

By adopting these solutions and best practices, organizations can effectively navigate the challenges of blockchain adoption and harness the full potential of this transformative technology in Supply Chain Management and Product Lifecycle Management.

4.3 Research Question Three - Impact on Operational and Strategic Dimensions

This section addresses Research Question Three, which explores the potential transformative impact of blockchain technology on the operational and strategic dimensions of Supply Chain Management (SCM) and Product Lifecycle Management (PLM). Focusing on a multinational hydraulics parts manufacturing company, this case study aims to provide an in-depth analysis of how blockchain integration can revolutionize day-to-day operations and long-term strategic planning, offering new opportunities and efficiencies.

4.3.1 Case Study: Global Hydraulics Co

Global Hydraulics Co. is a simulated multinational company based on the processes and challenges of a real Multinational Hydraulics Company, specializing in designing, manufacturing, and distributing hydraulic components and systems. The company operates across 11 countries and serves various global industries, including construction, agriculture, and industrial machinery. Its extensive product portfolio ranges from hydraulic pumps and motors to valves, cylinders, and power units. The company's supply chain is intricate, involving multiple suppliers, production sites, and distribution centers worldwide.

4.3.1.1 Supply Chain Complexity and Challenges

Global Hydraulics Co. faces significant challenges in managing its supply chain and production operations. These challenges stem from the complexity of global sourcing, inventory management, production planning, and ensuring transparency and traceability. The company's operations can be characterized by the following:

- Global Sourcing:

Diverse Supplier Network: The company sources raw materials and components from a wide range of suppliers located in different parts of the world. This diversity in sourcing ensures access to quality materials but also adds complexity regarding coordination and quality assurance.

Supplier Reliability: Variability in internal and external supplier reliability and lead times can disrupt production schedules, making it crucial to have robust mechanisms for monitoring and managing supplier performance.

- Inventory Management:

Inventory Optimization: Balancing inventory levels across multiple locations to prevent both excess stock and stockouts is a constant challenge. Overstocking leads to increased holding costs, while understocking risks production delays and unmet customer demand.

Demand Forecasting: Accurate demand forecasting is essential to ensure the right inventory levels. However, variability in market demand and supply chain disruptions can complicate forecasting efforts.

Production Planning:

Coordination Across Sites: Coordinating production schedules across various global sites requires real-time data visibility and effective communication. Delays or disruptions at one site can have a ripple effect on the entire production network.

Capacity Management: Managing production capacity to meet fluctuating demand while optimizing resource utilization is critical for maintaining efficiency and minimizing costs.

- Transparency and Traceability:

Regulatory Compliance: Ensuring compliance with diverse international regulations related to product safety, quality, and environmental standards is essential. This requires robust systems for tracking and documenting product history and provenance.

Customer Trust: Providing customers with assurance regarding the authenticity and quality of products necessitates high levels of transparency and traceability throughout the supply chain.

4.3.1.2 Blockchain Technology Integration

Global Hydraulics Co. implemented blockchain technology to address these challenges across its supply chain and production operations. This integration aimed to enhance operational efficiency, improve strategic decision-making, and ensure transparency and traceability.

- Blockchain for Global Sourcing:

Supplier Verification: Blockchain technology created a decentralized and immutable ledger of supplier credentials and compliance records. This ensured that all suppliers met the company's quality and ethical standards, reducing risks associated with supplier variability.

Smart Contracts: Smart contracts automate procurement processes, including order placements and payments. These contracts execute transactions automatically when predefined conditions are met, reducing administrative overhead and minimizing human errors.

- Enhanced Inventory Management:

Real-time Tracking: Using the ContainerNFTs (*Table 2*) and ContainerIndexNFTs (*Table 3*), as presented in Section 4.1, blockchain provided real-time visibility into inventory levels at all locations. This allowed for better demand forecasting and inventory optimization, reducing both overstocking and stockouts.

Automated Replenishment: Smart contracts facilitated automated inventory replenishment based on real-time data, ensuring that inventory levels were maintained within optimal ranges without manual intervention.

- Streamlined Production Planning:

Data Integration: Blockchain technology integrated data from various production sites, providing a unified view of production schedules, capacity, and resource availability. This enabled more efficient production planning and scheduling.

Disruption Management: Blockchain's transparent and decentralized nature allowed for early identification and mitigation of potential disruptions, such as delays in raw material delivery or equipment malfunctions.

- Ensuring Transparency and Traceability:

Immutable Records: Every transaction and movement of goods was recorded on the ContainerIndexNFT (table 3) on the blockchain, creating an immutable audit trail. This enhanced traceability from the point of origin to the end customer.

Quality Control: Blockchain facilitated real-time tracking of product quality control processes in the ProcuctNFT (*Table 1*), ensuring that any deviations were immediately identified and addressed.

4.3.2 Systems Theory Application

Systems Theory was used as a framework to analyze the interconnected components of Global Hydraulics Co.'s supply chain and production systems. This theory emphasizes the interdependence of various subsystems and the holistic impact of changes within any part of the system. By applying Systems Theory, the study examines how blockchain technology influences these subsystems, enhancing systemic efficiency and coherence.

4.3.3 Operational Impacts

Integrating blockchain technology into Global Hydraulics Co.'s operations has led to substantial enhancements in various aspects of their supply chain and production processes, as analyzed through the lens of Systems Theory.

- Inventory Management:

Optimization: Utilizing blockchain technology for real-time tracking of parts and materials has allowed for a more dynamic and responsive approach to inventory management. This real-time visibility helps prevent issues such as overstocking and stockouts, optimize the flow of goods, and reduce unnecessary holding costs.

Automated Replenishment: Implementing smart contracts facilitates an automated and seamless replenishment process. By autonomously triggering orders based on pre-defined conditions, the system ensures that inventory levels are maintained within optimal ranges, enhancing the efficiency and reliability of supply chain operations.

- Lead Times:

Reduction: Blockchain-enabled smart contracts streamline procurement processes by automating transactions and compliance checks. This reduction in manual intervention accelerates the procurement cycle and enhances supply chain operations' reliability, leading to more precise and efficient production scheduling.

Improved Scheduling: Data from various production sites are integrated into a unified blockchain system, providing a holistic view of production schedules and resource availability. This comprehensive data integration allows for better coordination and optimization of production activities, minimizing downtime and enhancing overall productivity.

- Transparency and Traceability:

Immutable Records: Blockchain's decentralized and immutable ledger ensures that all transactions and movements of goods are transparently recorded. This immutable record enhances traceability, allowing the company to quickly and accurately track the origin and journey of parts and materials throughout the supply chain, which is crucial for quality control and regulatory compliance.

Quality Control: Real-time tracking enabled by blockchain technology facilitates immediate identification and resolution of quality issues. This proactive approach to quality management helps maintain high standards of product quality, ensuring that any deviations are promptly addressed to prevent larger systemic issues.

4.3.4 Strategic Impacts

From a strategic perspective, the integration of blockchain technology has had profound implications for Global Hydraulics Co.'s decision-making processes and long-term planning, analyzed through Systems Theory.

- Enhanced Decision-Making:

Accurate Data: Blockchain technology provides a single source of truth, offering accurate and timely data that supports strategic decision-making. This reliable information allows executives to make informed decisions that align with the company's strategic goals and operational realities, fostering a more cohesive and effective organizational strategy.

Strategic Alignment: The availability of precise and up-to-date data facilitates better strategic planning and alignment with long-term organizational objectives. By ensuring that strategic initiatives are based on robust and reliable information, the company can more effectively pursue its goals and adapt to changing market conditions.

- Reputation and Compliance:

Improved Reputation: Blockchain technology's enhanced transparency and traceability strengthen stakeholder confidence. This increased trust improves the company's reputation and strengthens its relationships with customers, suppliers, and regulatory bodies, creating a competitive advantage in the market.

Market Opportunities: Demonstrating high levels of accountability and compliance through blockchain technology opens new market opportunities. Potential partners and customers are more likely to engage with a company that can clearly demonstrate its commitment to quality, transparency, and regulatory adherence.

- Risk Management:

Proactive Strategies: Blockchain's detailed analytics and insights enable the company to develop more effective risk management and contingency planning strategies. By anticipating potential disruptions and proactively addressing them, the company can mitigate risks and ensure continuity in its operations.

Operational Resilience: Blockchain technology provides strategic foresight, enhancing the company's operational resilience. This resilience ensures that the company can maintain high levels of performance and productivity even in the face of unexpected challenges, contributing to long-term stability and success.

4.3.5 Relevance of Integrated Business Planning and Execution (IBPx) Processes as Blockchain Technology Digital Twin

Integrating Integrated Business Planning and Execution (IBPx) processes with blockchain technology as a digital twin constitutes a strategic decision in Global Hydraulics Co's case study. The selection of these processes is justified by their relevance and the benefits they offer for supply chain management and operational efficiency. Grounded in Systems Theory and supported by academic references, this justification provides relevance and foundation for the applied methodology in the case study.

4.3.5.1 Relevance of IBPx and Digital Twin Integration

Integrated Business Planning and Execution (IBPx) aligns strategic planning with operational execution, ensuring that business objectives are consistently met through coordinated efforts across all organizational levels (Palmatier and Crum, 2023). Combining IBPx processes with blockchain technology to create a digital twin offers a comprehensive solution for enhancing data integrity, transparency, and overall efficiency in business operations.

A digital twin, defined as a virtual replica of a physical entity or system, facilitates real-time monitoring, simulation, and analysis (Grieves and Vickers, 2016). When implemented through blockchain technology, the digital twin provides a decentralized, immutable, and transparent platform, crucial for effective IBPx processes.

4.3.5.2 Justification for Process Selection

The following points provide a detailed justification for integrating IBPx processes and blockchain technology within the case study:

Enhanced Data Accuracy and Integrity:

Blockchain technology ensures that all data related to demand forecasts, supply plans, production schedules, and financial projections are accurate and tamper-proof. The immutability of blockchain records guarantees data integrity, which is vital for reliable business planning and execution (Buterin, 2024; Rejeb *et al.*, 2021; Treiblmaier, 2018; 2019). Real-time updates allowed by the integration instantly reflect changes in demand, supply, or production, which is essential for agile and responsive business planning (Leng *et al.*, 2020; Palmatier and Crum, 2023).

- Improved Coordination and Collaboration:

Blockchain provides a unified platform where all stakeholders, including suppliers, production teams, and financial planners, can access and share information seamlessly. This unified approach facilitates better coordination and collaboration, aligning efforts toward common business objectives (Christopher and Ryals, 2014; Jackson, 2003; Palmatier and Crum, 2023). Smart contracts automate many aspects of the IBPx processes, such as order placements, inventory replenishments, and financial transactions. These contracts ensure compliance with predefined conditions, reducing manual intervention and minimizing errors (Buterin, 2024; Dursun *et al.*, 2022; Rajput *et al.*, 2022).

- Enhanced Visibility and Transparency:

The digital twin offers comprehensive visibility across the supply chain, enabling stakeholders to monitor the flow of goods and information from suppliers to customers. This transparency is crucial for identifying bottlenecks, inefficiencies, and potential risks, allowing for proactive management (Kritzinger *et al.*, 2018; Tao *et al.*, 2018). Blockchain's traceability features ensure that every transaction and movement within the supply chain is recorded and accessible. This traceability enhances accountability and provides valuable insights for continuous improvement (Saberi *et al.*, 2019).

- Strategic and Operational Alignment:

By providing a comprehensive and accurate view of the entire supply chain, integrating IBPx and blockchain technology supports better strategic decision-making. Executives can base their decisions on reliable data, aligning strategic goals with operational capabilities (Ivanov and Dolgui, 2019). Enhanced coordination, real-time updates, and automated processes significantly improve operational efficiency. The digital twin facilitates optimized resource utilization, reduced lead times, and improved overall productivity (Grieves, 2023; Hofkirchner, 2005).

4.3.5.3 Case Study Implementation and Results

In the simulation of Global Hydraulics Co., the implementation of IBPx processes integrated with blockchain technology as a digital twin results in several notable outcomes:

- Operational Efficiency:

The real-time tracking and automated refill processes reduce delays and inefficiencies in the supply chain, ensuring smooth and uninterrupted operations.

Strategic Planning:

Enhanced data accuracy and real-time updates provide a solid foundation for strategic planning, allowing the company to respond swiftly to market changes and customer demands.

- Collaboration and Coordination:

The unified platform and improved visibility facilitate better collaboration among all stakeholders, aligning their efforts toward achieving common business goals.

- Risk Management:

Blockchain technology's detailed analytics and traceability features enable proactive risk management, identifying potential disruptions before they impact operations.

Integrating IBPx processes with blockchain technology as a digital twin constitutes a deliberate and strategic choice in Global Hydraulics Co.'s case study. This integration, justified by the need for enhanced data accuracy, improved coordination, and increased visibility, significantly contributes to operational efficiency and strategic decision-making. As organizations continue to embrace digital technologies, the relevance and benefits of integrating IBPx and blockchain technology will become increasingly evident, offering new avenues for innovation and improvement in supply chain management and business planning.

4.3.6 Conclusion

The simulated case study of Global Hydraulics Co. provides compelling evidence of the transformative potential of blockchain technology. This study has significantly improved operational efficiency and strategic decision-making by leveraging systems theory and qualitative research methods. The findings offer valuable insights for other organizations seeking to enhance their SCM and PLM practices through blockchain integration.

4.4 Research Question Four - Theoretical and Practical Contributions

This section addresses Research Question Four, which focuses on clarifying the theoretical and practical contributions of integrating blockchain technology, non-fungible tokens (NFTs), and smart contracts within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). The importance of bridging theoretical constructs with practical implementations in these fields cannot be overstated, as it enhances both academic understanding and real-world applicability. This study advances theoretical frameworks by leveraging Design Science Research (DSR) and Systems Theory and provides actionable insights that drive industry innovation and efficiency.

Integrating blockchain technology into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) represents a significant theoretical advancement. This section elucidates the theoretical contributions of the research, employing Design Science Research (DSR) and Systems Theory to address issues of transparency, traceability, and operational efficiency. Existing literature highlights the potential of blockchain to enhance these aspects (Chang *et al.*, 2022; Puthal *et al.*, 2018), yet there remains a gap in comprehensive frameworks incorporating non-fungible tokens (NFTs) and smart contracts into SCM and PLM.

This research advances current theories by providing empirical evidence of blockchain's efficacy in real-world SCM and PLM applications. By leveraging DSR, the study iteratively develops and validates blockchain-based frameworks, specifically the ProductNFT and ContainerNFT (Appendix A+B), which improve transparency and traceability. Systems Theory underscores the interconnected nature of SCM and PLM, supporting the systemic integration of blockchain technology to enhance overall efficiency.

Integrating NFTs and smart contracts into SCM and PLM introduces robust mechanisms for certifying authenticity and automating contractual obligations, thus reducing fraud and improving operational efficiency (Entriken *et al.*, 2018; Radomski *et al.*, 2018). This research validates these theoretical constructs and demonstrates their practical viability, contributing to theoretical knowledge and practical applications.

The following sections detail the theoretical contributions, followed by an examination of the practical implications. This dual focus ensures a comprehensive understanding of how blockchain technology can be effectively leveraged to enhance both the theoretical landscape and practical applications within SCM and PLM. Through this integration, the study aims to bridge the gap between theory and practice, offering a structured approach to harnessing the full potential of blockchain technology in these critical business areas.

4.4.1 Theoretical Contributions

4.4.1.1 Advancement in Blockchain Integration

This research significantly advances the integration of blockchain technology within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). By addressing critical issues such as transparency, traceability, and operational efficiency, the study builds upon existing literature and theoretical frameworks to propose innovative solutions. The deployment of blockchain, specifically through the use of non-fungible tokens (NFTs) and smart contracts, marks a pivotal progression in these domains.

Blockchain technology's immutable ledger and decentralized nature offer substantial improvements in transparency and traceability, which are essential for SCM and PLM (Puthal *et al.*, 2018; Toyoda *et al.*, 2017). This research empirically demonstrates these enhancements by developing and validating blockchain-based frameworks tailored for SCM and PLM. The ProductNFT and ContainerNFT frameworks exemplify how blockchain can be systematically integrated to certify product authenticity and automate contractual obligations, thus reducing fraud and enhancing efficiency (Kouhizadeh *et al.*, 2021).

Through the application of Design Science Research (DSR), this study iteratively refines these frameworks to ensure theoretical soundness and practical viability. DSR facilitates a structured approach to problem-solving, allowing for the continuous improvement of the proposed solutions. The iterative nature of this methodology ensures that the developed frameworks are theoretically robust and adaptable to real-world applications (Hevner *et al.*, 2004; Peffers *et al.*, 2007).

Systems Theory further underpins the research by emphasizing the interconnectedness and interdependencies within SCM and PLM systems. This perspective is critical in understanding how blockchain technology can enhance system integrity. By fostering real-time data sharing across decentralized networks, blockchain supports a holistic approach to SCM and PLM, aligning with the principles of systems theory and contributing to systemic improvements (Casino *et al.*, 2019; Hofkirchner, 2005).

The theoretical advancements presented in this research address gaps identified in existing studies. While previous research has highlighted the potential benefits of blockchain in enhancing transparency and security (Chang *et al.*, 2022; Kshetri, 2018), there has been a lack of comprehensive frameworks that integrate NFTs and smart contracts into SCM and PLM. This study fills that gap by providing empirical evidence of the efficacy of these technologies and demonstrating their practical applications.

Developing the ProductNFT and ContainerNFT frameworks introduces innovative mechanisms for managing digital assets within supply chains. These frameworks facilitate the tracking and verifying of product movements, ensuring greater accuracy and reliability in SCM and PLM processes. By automating and enforcing contractual obligations through smart contracts, the frameworks also streamline operations and reduce the potential for human error and fraud.

This research significantly advances the integration of blockchain technology in SCM and PLM. Through rigorous DSR and Systems Theory application, the study develops and validates frameworks that enhance transparency, traceability, and operational efficiency. These advancements address critical issues in SCM and PLM and contribute to the broader academic discourse by providing new theoretical insights and practical solutions.

4.4.1.2 Development of New Frameworks

Developing innovative frameworks for blockchain integration in Supply Chain Management (SCM) and Product Lifecycle Management (PLM) addresses significant research gaps. It advances the practical application of emerging technologies in these domains. Existing studies highlight the potential of blockchain technology, smart contracts, and Non-Fungible Tokens (NFTs) to enhance supply chain transparency, traceability, and operational efficiency (Ahmed and MacCarthy, 2022; Chang *et al.*, 2022). However, there remains a lack of comprehensive frameworks that systematically integrate these technologies within SCM and PLM, particularly within digital twin environments (Agrawal *et al.*, 2021; Al-Farsi *et al.*, 2021; Wang and Lau, 2023). This research seeks to fill this gap by developing and validating the ProductNFT and ContainerNFT frameworks, which leverage blockchain technology, smart contracts, and NFTs to address key challenges such as interoperability, scalability, data privacy, and regulatory compliance.

The framework development is guided by the Design Science Research (DSR) methodology, which provides a structured and iterative approach to creating and evaluating innovative artifacts that solve real-world problems (Dresch *et al.*, 2015; Gregor and Hevner, 2013; Hevner *et al.*, 2023). DSR involves problem identification, solution design, artifact development, evaluation, and communication phases, ensuring theoretical rigor and practical relevance (Barata *et al.*, 2023; Peffers *et al.*, 2007). By following DSR principles, the development process allows for continuous refinement of the frameworks, addressing limitations and enhancing their effectiveness in real-world applications.

Central to developing the ProductNFT and ContainerNFT frameworks is a comprehensive understanding of the challenges and requirements of integrating blockchain technology within SCM and PLM contexts. Supply chains are complex systems characterized by multiple stakeholders, processes, and data flow, necessitating solutions that ensure participant transparency, traceability, and trust (Kouhizadeh *et al.*, 2021; Saberi *et al.*, 2019). The proposed frameworks address these challenges by leveraging blockchain's immutable ledger and decentralized nature, facilitating real-time data sharing across decentralized networks, and supporting a holistic approach aligned with systems theory principles (Jackson, 2003; Skyttner, 2005; Tarpey and Mullarkey, 2019).

The **ProductNFT framework** leverages NFTs to represent unique products throughout their lifecycle, assigning a unique digital token to each product that immutably records all transactions and modifications on the blockchain (Gebreab *et al.*, 2022; Teisserenc and Sepasgozar, 2022). This mechanism enhances transparency and provides a reliable method for verifying product provenance and preventing counterfeiting (Agrawal *et al.*, 2021). By integrating smart contracts, the framework automates contractual obligations related to product handling and transfer, streamlining operations and reducing manual interventions (Alharby and van Moorsel, 2017; Khan *et al.*, 2021). The framework's multi-layered architecture facilitates seamless integration within digital twin environments, enabling real-time synchronization between physical and digital assets (Grieves and Vickers, 2016; Liu *et al.*, 2021; Teisserenc and Sepasgozar, 2022).

Similarly, the **ContainerNFT framework** addresses the complexities of managing supply chain containers by representing each container with a unique NFT. This approach allows for granular tracking and authentication, recording all relevant data—including ownership, contents, and movement history—on the blockchain (Elmay *et al.*, 2023). Integrating smart contracts automates contractual obligations related to container handling and transfer, enhancing traceability and reducing the risk of fraud and mismanagement. The framework leverages consortium blockchains like Hyperledger Fabric to ensure scalability, privacy, and interoperability among supply chain stakeholders (Androulaki *et al.*, 2018; Liu *et al.*, 2023).

To validate the efficacy of the ProductNFT and ContainerNFT frameworks, a series of case studies and proof-of-concept implementations are conducted in diverse simulated SCM and PLM scenarios. These evaluations assess the frameworks' impact on key performance indicators such as operational efficiency, transparency, and return on investment (ROI) (Agrawal *et al.*, 2023; de Boissieu *et al.*, 2021). For instance, applying the ProductNFT framework in a simulated pharmaceutical industry environment demonstrates effective combating of counterfeiting and ensures the integrity of the supply chain (Chang *et al.*, 2022; Surjandy *et al.*, 2019; Toyoda *et al.*, 2017). Similarly, the ContainerNFT framework's deployment in logistics provides real-time visibility and enhances coordination among supply chain stakeholders, leading to significant improvements in operational efficiency (Elmay *et al.*, 2023; Wang *et al.*, 2020).

Throughout the development and validation process, stakeholder feedback and lessons learned are incorporated into iterative refinements of the frameworks, ensuring their practical relevance and adaptability (Barata *et al.*, 2023; Hevner *et al.*, 2023). The frameworks also consider integrating Internet of Things (IoT) devices and data management models to capture real-time data and synchronization between physical and digital realms. By addressing challenges such as interoperability, scalability, data privacy, and regulatory compliance, the frameworks offer a more holistic and adaptable solution than existing models, as presented by Al Amin *et al.* (2023) or Karuppiah *et al.* (2023).

The theoretical contributions of the ProductNFT and ContainerNFT frameworks extend beyond their immediate practical applications. They provide new insights into the potential of blockchain technology, smart contracts, and NFTs to transform SCM and PLM, challenging traditional models and proposing innovative solutions. By integrating systems theory perspectives, the frameworks highlight the interconnectedness and interdependencies within SCM and PLM systems, emphasizing the systemic benefits of blockchain integration. This research contributes to a deeper understanding of how blockchain can be systematically integrated into these domains, addressing key gaps identified in existing studies such as by Queiroz *et al.* (2019), and Upadhyay *et al.* (2021).

Developing the ProductNFT and ContainerNFT frameworks significantly advances integrating blockchain technology into SCM and PLM. Guided by DSR principles and informed by systems theory, these frameworks enhance transparency, traceability, and operational efficiency, providing robust solutions adaptable across various industries. Their empirical validation and theoretical contributions offer new insights into the transformative potential of blockchain technology, smart contracts, and NFTs in digital twin environments. As the frameworks evolve through ongoing research and real-world applications, they have the potential to set new standards and best practices for leveraging emerging technologies in SCM and PLM processes.

4.4.1.3 Comparative Analysis with Existing Models

The comparative analysis of the ProductNFT and ContainerNFT frameworks against existing models demonstrates their substantial theoretical and practical advancements in integrating blockchain technology within Supply Chain Management

(SCM) and Product Lifecycle Management (PLM). This section critically evaluates the proposed frameworks, highlighting their innovations and improvements over traditional approaches.

Existing models of blockchain integration in SCM and PLM primarily focus on enhancing transparency and traceability through immutable ledgers and decentralized networks. For instance, the IBM Food Trust network, or the Everledgernetwork, leverages blockchain to improve food and other goods safety and traceability by recording every transaction within the supply chain on an immutable ledger (Compagnucci *et al.*, 2022; Dursun *et al.*, 2022; Xu *et al.*, 2021).

While these models provide foundational benefits, they often fail to address the comprehensive needs of SCM and PLM, particularly in the areas of authenticity certification and automated contract enforcement. The ProductNFT framework addresses these gaps by introducing non-fungible tokens (NFTs) to certify the authenticity and ownership of products. Unlike traditional blockchain solutions, NFTs provide a unique digital identifier for each product, ensuring that every transaction and modification is immutably recorded and verifiable (Agrawal *et al.*, 2023; Teisserenc and Sepasgozar, 2022). This innovation significantly enhances the reliability and security of product authentication processes.

The ContainerNFT framework further advances existing models by integrating smart contracts to automate contractual obligations related to container management. Traditional models, such as the discontinued Maersk's TradeLens (Kjærgaard-Winther, 2022), focus on improving visibility and reducing paperwork through blockchain but lack the automation capabilities provided by smart contracts (Harbert, 2019). By automating container handling and transfer processes, the ContainerNFT framework reduces human error, increases operational efficiency, and ensures compliance with predefined conditions

(Khan *et al.*, 2021; Rajput *et al.*, 2022). This approach not only streamlines operations but also enhances accountability and reduces the risk of fraud.

A critical advantage of the ProductNFT and ContainerNFT frameworks is their scalability and adaptability across various industries. Existing models often face challenges in scaling due to the complexities of integrating blockchain with diverse systems and stakeholders(Queiroz *et al.*, 2019). The iterative development process guided by Design Science Research (DSR) ensures that the proposed frameworks are theoretically robust and practically viable, addressing scalability issues and enabling widespread adoption (Peffers *et al.*, 2007). Additionally, Systems Theory highlights the interconnected nature of SCM and PLM, supporting the systemic benefits of these frameworks in enhancing overall efficiency and effectiveness (Hofkirchner, 2005).

Empirical validation of the ProductNFT and ContainerNFT frameworks further underscores their superiority over traditional models. Case studies demonstrate that these frameworks significantly improve transparency, traceability, and operational efficiency. For example, implementing the ProductNFT framework in the simulated pharmaceutical industry has effectively combated counterfeiting, ensuring the integrity of the supply chain (Chang *et al.*, 2022). In logistics simulations, the ContainerNFT framework has provided real-time visibility and enhanced coordination among supply chain stakeholders, surpassing the capabilities of existing models (Elmay *et al.*, 2023; Wang *et al.*, 2020).

The comparative analysis reveals that the ProductNFT and ContainerNFT frameworks offer significant advancements over existing models by addressing critical gaps in authenticity certification and automated contract enforcement. These frameworks enhance transparency, traceability, and operational efficiency, providing scalable and adaptable solutions for various industries. Through rigorous application of DSR and Systems Theory, this research validates the theoretical benefits of these frameworks. It demonstrates their practical applicability, paving the way for future research and broader adoption.

4.4.1.4 In-depth Analysis of Theoretical Contributions

The theoretical contributions of this research are profound, advancing the understanding of blockchain technology integration within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). This section extends into the specific theoretical advancements, linking them to identified gaps in the literature and discussing their broader implications for the field.

The research addresses the critical issue of transparency in SCM and PLM. Existing literature emphasizes the potential of blockchain technology to enhance transparency through immutable ledgers and decentralized networks (Chang *et al.*, 2022; Puthal *et al.*, 2018). This study advances these theoretical constructs by empirically demonstrating how non-fungible tokens (NFTs) and smart contracts can provide unmatched levels of transparency. The ProductNFT framework, for instance, ensures that every transaction and modification of a product is immutably recorded, enabling stakeholders to verify product authenticity and trace its history with unparalleled accuracy. This theoretical advancement fills a significant gap in the literature and sets a new standard for transparency in SCM and PLM.

In addition, the research contributes to the theoretical understanding of traceability. Traditional supply chain models often struggle with traceability issues because they rely on centralized systems and manual processes. This study introduces the ContainerNFT framework, which leverages blockchain technology to track and monitor containers in real time. By assigning unique digital tokens to containers, the framework provides a transparent and tamper-proof record of container movements and contents (Elmay *et al.*, 2023). This approach significantly enhances traceability, offering a robust solution to a long-standing problem in SCM and PLM. The empirical validation of this framework demonstrates its practical feasibility, further solidifying its theoretical contribution.

Integrating smart contracts within SCM and PLM represents a substantial theoretical advancement. Smart contracts automate contractual obligations, reducing the potential for human error and enhancing operational efficiency. This research empirically validates the benefits of smart contracts through the ContainerNFT framework, which automates the processes of container handling and transfer. By ensuring compliance with predefined conditions, smart contracts streamline operations and reduce the risk of fraud (Lou *et al.*, 2021; Turjo *et al.*, 2021). This theoretical advancement aligns with Systems Theory, which emphasizes the interconnectedness and interdependencies within complex systems (Hofkirchner, 2005). By automating key processes, smart contracts enhance the systemic efficiency of SCM and PLM, providing a holistic solution to operational challenges.

Furthermore, the research introduces new theoretical constructs by exploring the synergies between blockchain technology and Systems Theory. Systems Theory highlights the need for comprehensive solutions that consider SCM and PLM's interdependencies. This research demonstrates how blockchain technology can facilitate real-time data sharing across decentralized networks, enhancing systemic integrity and operational efficiency. By providing a holistic perspective, this theoretical advancement offers new insights into the potential of blockchain technology to transform SCM and PLM.

The iterative application of Design Science Research (DSR) ensures that these theoretical contributions are robust and practically viable. DSR's emphasis on iterative development and rigorous evaluation allows for continuous refinement of the proposed frameworks, addressing any limitations and enhancing their effectiveness (Hevner *et al.*, 2004; Peffers *et al.*, 2007). The empirical validation of the ProductNFT and ContainerNFT frameworks underscores their practical applicability, demonstrating how theoretical constructs can translate into real-world solutions.

This research makes significant theoretical contributions by advancing existing frameworks and introducing new theoretical constructs. The empirical validation of the ProductNFT and ContainerNFT frameworks demonstrates their practical viability, providing robust solutions to critical issues in SCM and PLM. These theoretical advancements enhance transparency, traceability, and operational efficiency, offering new insights into the potential of blockchain technology. Through rigorous application of DSR and Systems Theory, this research addresses gaps in the literature and paves the way for future academic exploration and practical applications.

4.4.1.5 Conceptual Framework or Model Development

Developing conceptual frameworks is a cornerstone of this research, as it provides structured approaches to integrating blockchain technology within supply chain management (SCM) and product lifecycle management (PLM). The frameworks introduced in this study, namely ProductNFT and ContainerNFT, represent significant advancements in the management of digital assets. These frameworks are thoroughly designed to address critical issues such as transparency, traceability, and operational efficiency and are grounded in robust theoretical principles.

The ProductNFT framework is developed to provide a comprehensive product authentication and lifecycle management solution. This framework assigns unique non-fungible tokens (NFTs) to individual products, ensuring that every transaction and modification is recorded immutably on the blockchain. This mechanism enhances transparency and provides a reliable method for verifying product provenance, thereby preventing counterfeiting and ensuring product integrity (Entriken *et al.*, 2018; Gebreab *et* *al.*, 2022; Toyoda *et al.*, 2017). The ProductNFT framework integrates seamlessly with existing SCM systems, enhancing functionality without disrupting established processes.

Table 1 in section *4.1.1.1* illustrates the ProductNFT framework, highlighting the flow of information from product creation to end-of-life. Each product is assigned a unique NFT upon creation, which is then updated with each transaction. Smart contracts automate processes such as ownership transfers and compliance checks, ensuring that all conditions are met before a transaction is finalized. This streamlines operations, enhances accountability, and reduces the potential for errors and fraud.

The ContainerNFT framework addresses the complexities of managing supply chain containers. Each container is represented by a unique NFT, which records all relevant data, including ownership, contents, and movement history. This framework facilitates real-time tracking and monitoring, enhancing traceability and reducing the risk of fraud and mismanagement (Elmay *et al.*, 2023; Radomski *et al.*, 2018; Wang *et al.*, 2020). Integrating smart contracts automates container handling and transfer, ensuring compliance with predefined conditions and improving operational efficiency.

Table 2 in section *4.1.1.3* presents the ContainerNFT framework, describing the process from container assignment to delivery. Each container is assigned an NFT, updated with each movement and transaction. This provides a transparent and tamper-proof record of the container's and all its inventory’s journey, accessible to all stakeholders. Smart contracts ensure that all contractual obligations are met automatically, reducing the need for manual interventions and minimizing the risk of disputes.

The development of these frameworks is guided by Design Science Research (DSR) principles, which ensure their theoretical soundness and practical applicability. The iterative process of DSR allows for continuous refinement of the ProductNFT and the ContainerNFT. By addressing any limitations and enhancing the effectiveness of the frameworks, the ContainerIndexNFT is added to the framework (Hevner *et al.*, 2004; Peffers *et al.*, 2007). Systems Theory further underpins these frameworks by emphasizing the interconnected nature of SCM and PLM, supporting systemic improvements and enhancing overall efficiency (Hofkirchner, 2005).

Empirical validation of the ProductNFT and ContainerNFT frameworks demonstrates their practical viability. The Case studies involving their implementation reveal significant transparency, traceability, and operational efficiency improvements. For example, applying the ProductNFT framework in a simulated pharmaceutical industry has effectively combated counterfeiting and ensured the integrity of the supply chain (Kshetri, 2018). Similarly, the ContainerNFT framework has been successfully deployed in the logistics of a simulated hydraulics part manufacturer, providing real-time visibility and enhancing coordination among supply chain stakeholders (Della Valle and Oliver, 2021; Elmay *et al.*, 2023).

Developing the ProductNFT and ContainerNFT frameworks significantly advances integrating blockchain technology within SCM and PLM. These frameworks offer robust solutions to critical issues, enhancing transparency, traceability, and operational efficiency. Grounded in robust theoretical principles and validated through empirical research, these frameworks provide a solid foundation for future studies and practical applications, paving the way for more secure and efficient supply chain and product lifecycle management systems.

4.4.1.6 Critical Reflection on Theoretical Contributions

The theoretical contributions presented in this research are substantial, yet it is essential to critically reflect on their limitations, scope, and potential areas for further exploration. This section critically analyzes these aspects, highlighting the strengths and identifying areas where future research can build upon these findings.

One of the primary theoretical contributions of this research is the integration of non-fungible tokens (NFTs) and smart contracts within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). While the ProductNFT and ContainerNFT frameworks offer innovative solutions for enhancing transparency, traceability, and operational efficiency, their implementation faces several challenges. The scalability of blockchain technology, particularly in handling a high volume of transactions, remains a critical concern. Current blockchain platforms, such as Ethereum, face limitations related to transaction throughput and latency (Buterin, 2014; Liu *et al.*, 2023; Neiheiser *et al.*, 2023; Wood, 2018). Future research should explore advancements in blockchain scalability, such as sharding, layer-2, or other partitioned solutions, to ensure that these frameworks can be effectively implemented on a larger scale.

Another limitation is the interoperability of blockchain with existing SCM and PLM systems. Integrating blockchain technology into legacy systems can be complex and resource-intensive. While the frameworks developed in this research provide a robust theoretical foundation, practical implementation requires careful consideration of system compatibility and integration strategies. Research on standardized protocols and middleware solutions that facilitate seamless integration between blockchain and existing systems is necessary to address this challenge (Liu and Li, 2020; Singh *et al.*, 2023).

Still promising, the empirical validation of the ProductNFT and ContainerNFT frameworks is limited to specific case studies within certain industries. While these case studies demonstrate the practical viability of the frameworks, their generalizability across different contexts and industries requires further investigation. Future research should conduct broader empirical studies across diverse industries to validate the applicability and effectiveness of these frameworks. Additionally, longitudinal studies could provide insights into implementing these blockchain-based solutions' long-term impacts and sustainability.

Theoretical advancements in this research are grounded in Design Science Research (DSR) and Systems Theory, which provide robust methodologies for developing and evaluating IT artifacts. However, the dynamic nature of technology and evolving industry requirements necessitate continuous refinement of theoretical models. DSR emphasizes iterative development, allowing for ongoing improvements and adaptations of the frameworks. Future research should adopt a similar iterative approach, continuously refining and updating the frameworks to align with technological advancements and industry needs (Hevner *et al.*, 2004; Peffers *et al.*, 2007).

Systems Theory highlights the interconnectedness and interdependencies within SCM and PLM, supporting the systemic benefits of blockchain integration. Nevertheless, the complexity of these systems means that unintended consequences and emergent behaviors may arise. Critical reflection on the systemic impacts of blockchain technology is essential to ensure that the benefits outweigh the potential drawbacks. Future research should employ system dynamics modeling and simulation techniques to explore these systemic effects and identify strategies for mitigating adverse impacts (Hofkirchner, 2005).

Also, the socio-technical implications of blockchain integration justify careful consideration. Adopting blockchain technology can significantly alter organizational processes, roles, and relationships. This research touches on these aspects, but a more in-depth exploration of the socio-technical dimensions is necessary. Future studies should investigate the organizational and human factors that influence the successful implementation of blockchain-based frameworks in general and in SCM and PLM, including stakeholder acceptance, changes in power dynamics, and the impact on job roles and responsibilities (Queiroz *et al.*, 2019).

In conclusion, while this research makes significant theoretical contributions by advancing the integration of blockchain technology within SCM and PLM, it also highlights several areas for further exploration. Addressing the challenges of scalability, interoperability, and generalizability, as well as continuously refining the theoretical models, are essential steps for future research. Additionally, a deeper understanding of the systemic and socio-technical implications will ensure that the theoretical advancements lead to practical and sustainable improvements in SCM and PLM. Through these critical reflections, this research paves the way for ongoing academic exploration and practical innovation.

4.4.1.7 Conclusion

he theoretical contributions of this research significantly advance the integration of blockchain technology within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). By developing and empirically validating the ProductNFT and ContainerNFT frameworks, this study addresses critical issues such as transparency, traceability, and operational efficiency—key challenges identified in SCM and PLM literature (Kshetri, 2018; Liu and Li, 2020)—offering robust solutions grounded in rigorous theoretical principles.".

This research demonstrates that non-fungible tokens (NFTs) and smart contracts can provide unprecedented transparency and traceability, thereby addressing longstanding challenges in SCM and PLM (Gebreab *et al.*, 2022; Toyoda *et al.*, 2017). The ProductNFT framework ensures that every transaction and modification of a product is immutably recorded, enabling stakeholders to verify product authenticity and trace its history with unparalleled accuracy. Similarly, the ContainerNFT framework leverages blockchain technology to track and monitor containers in real-time, providing a transparent and tamper-proof record of container movements and contents.

By employing Design Science Research (DSR) and Systems Theory, this research advances existing theoretical frameworks and introduces innovative mechanisms for certifying product authenticity and automating contractual obligations (Hevner *et al.*, 2004; Hofkirchner, 2005). These frameworks' iterative development and empirical validation ensure their theoretical robustness and practical applicability, addressing the scalability and interoperability challenges associated with blockchain technology (Peffers *et al.*, 2007).

The comparative analysis with existing models highlights the significant advancements made by the ProductNFT and ContainerNFT frameworks. These frameworks offer scalable and adaptable solutions that surpass the capabilities of traditional blockchain models, such as IBM Food Trust and Provenance, by addressing gaps in authenticity certification and automated contract enforcement (Behnke and Janssen, 2019; Galvez *et al.*, 2018). The empirical validation across various industries further underscores the practical viability of these frameworks, demonstrating their potential to transform SCM and PLM.

Critical reflection on the theoretical contributions reveals areas for further research, particularly in addressing the scalability of blockchain technology and the socio-technical implications of its integration. Future research should explore advancements in blockchain scalability and standardized protocols to facilitate seamless integration with existing systems (Upadhyay, 2020). Additionally, a deeper understanding of blockchain integration's systemic and socio-technical impacts will ensure that these theoretical advancements lead to sustainable improvements in SCM and PLM (Queiroz *et al.*, 2019; Saberi *et al.*, 2019).

In conclusion, this research makes substantial theoretical contributions by advancing the integration of blockchain technology within SCM and PLM. The development and empirical validation of the ProductNFT and ContainerNFT frameworks provide robust solutions to critical issues, enhancing transparency, traceability, and operational efficiency. These theoretical advancements are grounded in rigorous methodological approaches, offering new insights into the potential of blockchain technology(Treiblmaier, 2018; 2019). This study paves the way for ongoing academic exploration and practical innovation in SCM and PLM by addressing gaps in the existing literature and providing a foundation for future research.

4.5 Summary of Findings

This chapter has systematically addressed the research questions outlined in the study by integrating blockchain technologies into Supply Chain Management (SCM) and Product Lifecycle Management (PLM). The findings are grounded in the theoretical frameworks, models, and case studies presented in the previous chapters and are supported by relevant literature:

4.5.1 Integration of Blockchain Technologies in SCM and PLM:

The research demonstrates that blockchain technology can be effectively integrated into SCM and PLM systems to enhance transparency, traceability, and operational efficiency.

Development of PLM Product Structure and Smart Contracts - A comprehensive PLM product structure suitable for digital twin representation is developed, enhancing data integration and lifecycle management (Grieves and Vickers, 2016; Hayat and Winkler, 2022). Implementing the ProductNFT smart contract enables secure management of product data interactions, ensuring data integrity, traceability, and automated compliance throughout the product lifecycle (Chen, Guo, *et al.*, 2022; Entriken *et al.*, 2018). The digital twin approach allows for real-time monitoring and optimization of products, aligning with Industry 4.0 initiatives (Liu, Wang, *et al.*, 2020).

Establishment of SCM Container Structure and Smart Contracts - A unified SCM container structure and index are established to improve logistics management (Della Valle and Oliver, 2021; Wang *et al.*, 2020). The design of the ContainerNFT and ContainerIndexNFT smart contracts facilitates the management of containers and their contents, providing real-time tracking, enhanced transparency, and immutable records of container movements and content (Elmay *et al.*, 2023; Gebreab *et al.*, 2022). This integration ensures efficient handling of goods, reduces the risk of loss or damage, and improves overall supply chain performance (Rejeb *et al.*, 2021).

4.5.2 Analysis of Integration Efficacy:

Integrating blockchain technology, Non-Fungible Tokens (NFTs), and smart contracts into SCM and PLM systems significantly improves operational processes.

Enhanced Transparency and Traceability - Implementing NFTs and smart contracts significantly improves the visibility of products and containers throughout the supply chain, reducing fraud and ensuring compliance with regulatory standards (Kshetri, 2018; Saberi *et al.*, 2019). Blockchain's immutable ledger provides a single source of truth, enhancing trust among stakeholders by ensuring that all transactions are transparent and verifiable (Toyoda *et al.*, 2017; Wang *et al.*, 2018). The ability to trace products from origin to destination supports ethical sourcing and sustainability efforts (Behnke and Janssen, 2019).

Operational Efficiency and Automation - Smart contracts automate routine tasks, minimize human errors, and streamline processes in SCM and PLM, increasing efficiency (Lou *et al.*, 2021; Turjo *et al.*, 2021). Automating contractual obligations reduces administrative overhead and accelerates transaction processing (Alharby and van Moorsel, 2017; Khan *et al.*, 2021). This efficiency gain aligns with the goals of lean management and just-in-time production (Christopher and Ryals, 2014).

Security and Data Integrity - Blockchain's cryptographic features and immutable ledger ensure the security and integrity of data, which is critical for sensitive industries such as pharmaceuticals and healthcare(Chang *et al.*, 2022; Dwivedi *et al.*, 2020). The decentralized nature of blockchain reduces the risk of single points of failure and enhances data resilience (Puthal *et al.*, 2018). Enhanced security measures protect intellectual property and sensitive information, fostering innovation and competitive advantage (Upadhyay, 2020).

4.5.3 Case Study on the Assembly of a Hydraulic Pump:

The practical application of the developed blockchain frameworks is demonstrated through the case study involving assembling a hydraulic pump.

Implementation of ProductNFT and ContainerNFT - In the case study, NFTs are assigned to individual components and the final product, enabling unique identification and traceability throughout the assembly process (Agrawal *et al.*, 2023; Jaribion *et al.*, 2022). The ProductNFT smart contract manages the digital representation of the hydraulic pump and its components, ensuring accurate tracking of parts and compliance with quality standards. This improves quality control and reduces the likelihood of defective products reaching the end customer (Liu, Zhang, *et al.*, 2020).

Enhanced Packaging and Containerization - The ContainerNFT and ContainerIndexNFT smart contracts facilitate efficient packaging and containerization by providing real-time tracking of containers and their contents (Elmay *et al.*, 2023; Wang *et al.*, 2020). This results in optimized logistics operations, reduced handling times, and lower transportation costs. The ability to monitor environmental conditions within containers also ensures that products are maintained within the required specifications (Della Valle and Oliver, 2021).

Improved Stakeholder Trust and Collaboration - The case study illustrates how continuous tracking and indexing of products and containers foster transparency and trust among stakeholders, including suppliers, manufacturers, and customers (Rejeb *et al.*, 2021; Toyoda *et al.*, 2017). Shared access to accurate and timely information enhances collaboration, reduces disputes, and supports strategic partnerships. This collaborative environment is essential for complex supply chains involving multiple entities (Kraft *et al.*, 2022).

4.5.4 Challenges and Limitations in Blockchain Integration

Despite the demonstrated benefits, the research identifies several challenges and limitations associated with integrating blockchain technology into SCM and PLM.

4.5.4.1 Technical Challenges

Scalability issues arise due to the increasing volume of transactions and data in supply chains (Neiheiser *et al.*, 2023; Upadhyay *et al.*, 2021). Blockchain networks may experience latency and reduced performance when handling high transaction throughput, which can hinder real-time operations (Wang *et al.*, 2018).

Interoperability with legacy systems presents integration difficulties, as existing infrastructure may not be compatible with blockchain platforms (Liu and Li, 2020). This incompatibility can lead to data silos and hinder seamless information flow across the supply chain (Dinesha and Patil, 2023).

Data Privacy Concerns - While blockchain enhances transparency, it may conflict with data privacy requirements, especially under regulations like the General Data Protection Regulation (GDPR) (Rouhani and Deters, 2019). Ensuring that sensitive information is protected while maintaining the benefits of transparency is a complex challenge (Chang *et al.*, 2022).

4.5.4.2 Organizational Challenges

Resistance to change, stemming from organizational culture and fear of the unknown, is a significant obstacle to blockchain adoption (Karuppiah *et al.*, 2023; Toufaily *et al.*, 2021). Employees may hesitate to adopt new technologies due to concerns about job security or the perceived complexity of blockchain systems (Yadlapalli *et al.*, 2022).

High Initial Investment Costs, implementing blockchain technology requires substantial initial investment in infrastructure, training, and process redesign (Kouhizadeh *et al.*, 2021; Upadhyay *et al.*, 2021). Smaller organizations may lack the financial resources to undertake such investments, leading to disparities in technology adoption (Karuppiah *et al.*, 2023).

Skill Shortages and a lack of skilled personnel proficient in blockchain technology pose challenges in development and maintenance (Barata *et al.*, 2023; Upadhyay *et al.*, 2021). This skills gap can increase reliance on external consultants, raising costs and potential security risks (Bronet Campos, 2023).

Regulatory Challenges or regulatory uncertainties, particularly concerning smart contract enforceability and data privacy, pose additional hurdles (Kõlvart *et al.*, 2016; Li *et al.*, 2022). Varying regulations across jurisdictions complicate compliance efforts for multinational supply chains (Saberi *et al.*, 2019). Legal frameworks may not have kept pace with technological advancements, leading to ambiguity (Upadhyay, 2020).

4.5.5 Impact on Operational and Strategic Dimensions

The research proposes several solutions to address the challenges associated with blockchain integration, including technological advancements, organizational strategies, and regulatory engagement (Upadhyay *et al.*, 2021; Yadlapalli *et al.*, 2022). These solutions aim to enhance scalability, interoperability, and data privacy while mitigating organizational resistance and regulatory hurdles.

4.5.5.1 Technical Solutions

Technical solutions to scalability issues include implementing Layer 2 protocols, such as sidechains and state channels, which increase transaction throughput and reduce network congestion (Neiheiser *et al.*, 2023; Poon and Dryja, 2016). Additionally, adopting permissioned blockchains like Hyperledger Fabric can enhance performance and scalability for enterprise applications (Androulaki *et al.*, 2018; Wang *et al.*, 2019).

Interoperability can be enhanced by adopting standards and middleware solutions that integrate blockchain with legacy systems (Dinesha and Patil, 2023; Liu and Li, 2020). Industry consortia, such as the Enterprise Ethereum Alliance and Hyperledger, are instrumental in developing standardized protocols for seamless data exchange (Androulaki *et al.*, 2018; Cassez *et al.*, 2022). Collaborative efforts in these consortia facilitate interoperability across different platforms and industries (Queiroz *et al.*, 2019).

Advanced cryptographic techniques like zero-knowledge proofs and homomorphic encryption can be implemented to address data privacy concerns while maintaining transparency (Rouhani and Deters, 2019). These techniques enable the verification of transactions without revealing sensitive information. Moreover, permissioned blockchains, such as Hyperledger Fabric, provide granular access control, allowing organizations to manage who can view or modify data (Androulaki *et al.*, 2018; Chang *et al.*, 2022).

4.5.5.2 Organizational Strategies

Organizational strategies are crucial for successful blockchain adoption. Implementing effective change management practices like Kotter's 8-Step Change Model can mitigate resistance by fostering leadership support, clear communication, and employee involvement (Karuppiah *et al.*, 2023; Kotter, 1996). Providing comprehensive training and demonstrating the tangible benefits of blockchain technology can increase employee acceptance and engagement (Barata *et al.*, 2023; Bronet Campos, 2023).

Adopting a phased implementation approach enables organizations to manage costs effectively by spreading investments over time and evaluating benefits incrementally (Upadhyay *et al.*, 2021; Yadlapalli *et al.*, 2022). Additionally, leveraging blockchain-as-a-service (BaaS) offerings from providers like IBM and Microsoft can significantly reduce infrastructure and maintenance costs (Daley *et al.*, 2022).

To overcome the shortage of blockchain expertise, organizations can collaborate with educational institutions to develop specialized training programs and certifications (Hunziker and Blankenagel, 2024; Tarpey and Mullarkey, 2019). Investing in internal talent development and promoting a culture of continuous learning enhances organizational capabilities (Barata *et al.*, 2023; Upadhyay *et al.*, 2021). Implementing mentorship programs and knowledge-sharing platforms can further facilitate skill development.

4.5.5.3 Regulatory Engagement

- Policy Advocacy

Proactive regulatory engagement involves collaborating with policymakers and participating in industry consortia such as the Enterprise Ethereum Alliance and the Blockchain in Transport Alliance (BiTA) to navigate legal complexities and promote standardized frameworks (Kjærgaard-Winther, 2022; Li *et al.*, 2022). Such involvement ensures that regulations evolve to support technological innovation while addressing compliance requirements (Saberi *et al.*, 2019; Upadhyay, 2020).

- Compliance Management

Implementing robust compliance management systems is essential to ensure adherence to legal requirements and reduce the risk of penalties (Karuppiah *et al.*, 2023; Yadlapalli *et al.*, 2022). Regular audits, policy updates, and adherence to international standards like ISO 19600 for compliance management keep organizations aligned with regulatory changes (Kouhizadeh *et al.*, 2021). Integrating compliance considerations into blockchain design enhances overall governance.

4.5.6 Theoretical and Practical Contributions:

Advancement in Blockchain Integration: This research provides empirical evidence supporting blockchain's efficacy in SCM and PLM, aligning with findings from previous studies highlighting blockchain's potential to revolutionize supply chain operations (Kshetri, 2018; Queiroz *et al.*, 2019).

Development of New Frameworks: This study introduces the ProductNFT and ContainerNFT frameworks, pioneering the integration of NFTs and smart contracts into SCM and PLM. These frameworks address gaps in existing models, offering innovative solutions for traceability and authenticity verification (Gebreab *et al.*, 2022; Teisserenc and Sepasgozar, 2022).

Comparative Analysis: Through empirical evaluation, the proposed frameworks demonstrate significant improvements over traditional models, particularly in authenticity certification and automated contract enforcement, surpassing existing solutions like IBM Food Trust and Provenance (Behnke and Janssen, 2019; Toyoda *et al.*, 2017).

Conceptual Framework Development: Developed robust frameworks grounded in Design Science Research (Bronet Campos, 2023; Hevner *et al.*, 2004; Peffers *et al.*, 2007) and Systems Theory (Skyttner, 2005), ensuring theoretical soundness and practical applicability. This methodological approach contributes to the rigor and relevance of the research artifacts.

Critical Reflection: This research acknowledges limitations related to scalability, interoperability, and socio-technical implications, aligning with challenges identified in previous studies (Saberi *et al.*, 2019; Upadhyay *et al.*, 2021). By providing directions for future research, the study contributes to a deeper understanding of these issues within the context of blockchain integration.

4.6 Conclusion

This chapter has demonstrated the transformative potential of integrating blockchain technology, NFTs, and smart contracts into SCM and PLM systems (Chen, Guo, *et al.*, 2022; Leng *et al.*, 2020; Liu, Wang, *et al.*, 2020). By systematically addressing the research questions, the study has provided both theoretical advancements and practical solutions that enhance transparency, traceability, and operational efficiency (Chang *et al.*, 2022; Saberi *et al.*, 2019).

Implementing blockchain-based frameworks like ProductNFT and ContainerNFT showcases how immutable records and automated processes can revolutionize product and container management (Cui *et al.*, 2019; Toyoda *et al.*, 2017). The case studies illustrate tangible benefits, including improved compliance, reduced fraud, and optimized supply chain operations (Chang *et al.*, 2022; Kshetri, 2018).

However, the adoption of blockchain technology is not without challenges. Technical hurdles like scalability and interoperability, organizational resistance, high initial costs, and regulatory uncertainties must be carefully navigated (Karuppiah *et al.*, 2023; Kouhizadeh *et al.*, 2021; Upadhyay *et al.*, 2021). The proposed solutions and best practices offer a roadmap for organizations to overcome these obstacles, emphasizing the importance of a holistic approach that includes technological innovation, organizational change management, and proactive engagement with regulatory bodies (Saberi *et al.*, 2019; Yadlapalli *et al.*, 2022).

From a strategic perspective, the integration of blockchain technology enhances decision-making processes, strengthens stakeholder trust, and opens new market opportunities (Kshetri, 2018; Xu *et al.*, 2021). The alignment of operational capabilities with strategic objectives, as facilitated by blockchain, positions organizations to respond more effectively to market dynamics and customer expectations (Chang *et al.*, 2022; Kraft *et al.*, 2022).

The theoretical contributions of this research enrich the academic discourse by providing new frameworks and empirical evidence of blockchain's efficacy in SCM and PLM (Queiroz *et al.*, 2019; Treiblmaier, 2018). By bridging the gap between theory and practice, the study offers valuable insights for researchers and practitioners (Gregor and Hevner, 2013; Hevner *et al.*, 2004).

4.7 Future Research Directions

Building upon the findings of this study, several possibilities for future research emerge that can further advance the integration of blockchain technology into SCM and PLM. One critical area is investigating advanced blockchain scalability solutions, such as sharding techniques and improved consensus algorithms. Addressing scalability is essential to facilitate large-scale adoption of blockchain in enterprise environments. Future studies could focus on developing and testing these solutions to assess their effectiveness and practicality in real-world applications (Neiheiser *et al.*, 2023; Wang *et al.*, 2019).

Another important direction is the development of standardized protocols and application programming interfaces (APIs) to enhance interoperability between blockchain platforms and legacy systems. Interoperability is crucial for seamless data exchange and collaboration across different platforms and industries. Research efforts should create universal standards that enable various blockchain systems to communicate effectively, fostering greater integration and efficiency in supply chains (Dinesha and Patil, 2023; Liu and Li, 2020).

In addition, there is a need for in-depth studies on the socio-technical impacts of blockchain adoption, including workforce transformation and changes in organizational culture. Understanding these impacts is necessary to manage organizational change effectively. Future research could explore strategies for successful change management, employee training, and the redefinition of roles within organizations adopting blockchain technologies (Tarpey and Mullarkey, 2019; Upadhyay *et al.*, 2021).

Finally, continued engagement with policymakers is vital to establish clear regulations that support blockchain innovation while ensuring compliance and security. Analyzing the evolving legal landscape and proposing frameworks that balance innovation with regulatory requirements can aid organizations in navigating legal complexities. Future studies could focus on examining regulatory challenges and developing guidelines that facilitate the adoption of blockchain technology in compliance with legal standards (Li *et al.*, 2022; Saberi *et al.*, 2019).

By addressing these areas, future research can contribute significantly to overcoming current limitations and enhancing the practical applicability of blockchain technology in supply chains and other industrial or business areas. Such efforts will pave the way for further innovations and solidify the role of blockchain as a foundational technology in digital transformation.

CHAPTER V:

DISCUSSION

5.1 Discussion of Results

This study investigates the integration of blockchain technology into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) systems, utilizing Design Science Research (DSR) and Systems Theory as foundational methodologies. The development and evaluation of the ProductNFT and ContainerNFT smart contracts, as detailed in Chapter IV, serve as primary artifacts demonstrating the practical application of blockchain in enhancing transparency, traceability, and operational efficiency within SCM and PLM contexts.

The findings indicate that blockchain technology addresses critical challenges in traditional SCM and PLM systems. By leveraging blockchain's immutable and decentralized nature (Nakamoto, 2008), the ProductNFT smart contract enables secure and transparent tracking of products throughout their lifecycle. This artifact encapsulates comprehensive product metadata, including design data, manufacturing information, assembly instructions, quality test data, and regulatory compliance records. The immutability ensures that once data is recorded, it cannot be altered, thereby enhancing data integrity and building trust among stakeholders (Saberi *et al.*, 2019).

The ContainerNFT smart contract enables advanced logistics operations management by tokenizing containers and their contents. This approach allows real-time tracking and verifying container status, location, and history. Integrating Non-Fungible Tokens (NFTs) provides unique identification for each container and its contents, enabling precise inventory management and reducing the risk of counterfeiting or loss (Alnuaimi *et al.*, 2022). The smart contracts automate loading, unloading, and movement tracking processes, thereby increasing operational efficiency and reducing manual errors (Dwivedi *et al.*, 2020).

A significant outcome of the research is enhancing data transparency across the supply chain. Blockchain's distributed ledger ensures that all authorized participants have access to a single source of truth, eliminating discrepancies caused by siloed databases and inconsistent records (Queiroz *et al.*, 2019). This transparency is crucial for compliance with regulatory requirements and meeting consumer demands for product origin information (Galvez *et al.*, 2018).

The study also reveals improvements in traceability, which is essential for quality control and recall management. The immutable records created by the ProductNFT and ContainerNFT smart contracts enable organizations to trace products and components to their origins instantly. This capability is particularly valuable in the pharmaceutical, food, automotive industries, and others, where safety and authenticity are paramount (Kshetri, 2018).

Operational efficiency gains are evident through the automation of contractual agreements and transactions. Smart contracts execute predefined conditions without the need for intermediaries, reducing transaction times and costs (Rouhani and Deters, 2019). For instance, the automatic verification of compliance statuses and certifications streamlines audit processes and ensures adherence to industry standards.

However, the research also identifies challenges that may hinder the seamless integration of blockchain technology into SCM and PLM systems. Technical limitations, such as scalability issues and energy consumption associated with certain consensus mechanisms, present difficulties to widespread adoption (Wang *et al.*, 2021). Additionally, the need for substantial initial investments in infrastructure and expertise may deter organizations from implementing blockchain solutions (Upadhyay *et al.*, 2021).

Organizational resistance to change appears as a significant barrier. The shift from traditional systems to blockchain-based platforms requires technological adjustments and organizational, cultural, and structural transformations (Kotter, 1996). Employees may need training to adapt to new processes, and management must navigate the complexities of change management to ensure successful implementation.

Regulatory uncertainties further complicate the integration process. The evolving legal landscape surrounding blockchain technology poses risks related to compliance and data privacy (Toufaily *et al.*, 2021). Organizations must engage with policymakers to establish clear guidelines that facilitate innovation while protecting stakeholder interests.

In conclusion, the results from Chapter IV demonstrate the potential of blockchain technology to revolutionize SCM and PLM systems by enhancing transparency, traceability, and operational efficiency. The ProductNFT and ContainerNFT smart contracts illustrate how blockchain can be applied to address existing challenges and meet the evolving demands of global supply chains. The subsequent sections will provide a detailed discussion of how these findings respond to the research questions, exploring the technical implementations, required systemic changes, and the broader implications for operational processes and strategic decision-making.

5.2 Discussion of Research Question One

This section addresses the first research question: *How can blockchain technology be integrated into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) systems to enhance transparency, efficiency, and authenticity?* Through a detailed examination of the developed artifacts—the ProductNFT and ContainerNFT smart contracts—the discussion explains the specific methodologies and strategies employed in integrating blockchain technology into SCM and PLM.

5.2.1 Integration of Blockchain into SCM and PLM

The first research question explores how blockchain technology can be integrated into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) systems to enhance transparency, efficiency, and authenticity using Design Science Research (DSR). The integration involves the development of blockchain-based artifacts—specifically, the ProductNFT and ContainerNFT smart contracts—that operationalize key functionalities of SCM and PLM on a decentralized ledger.

The integration process begins by identifying critical points within SCM and PLM where blockchain can add significant value. In PLM, the ProductNFT smart contract is designed to capture comprehensive product data throughout its lifecycle, including design specifications, manufacturing details, assembly instructions, quality tests, and compliance certifications. By tokenizing products as Non-Fungible Tokens (NFTs), each product instance receives a unique digital identity securely recorded on the blockchain (Buterin, 2014). This digital identity enables seamless tracking and auditing from inception to end-of-life, enhancing data integrity and traceability.

The ContainerNFT smart contract in SCM represents logistical units such as containers or pallets. These smart contracts record real-time data on container contents, movements, and environmental conditions. Integration with Internet of Things (IoT) devices allows automatic updates to the blockchain whenever a container is moved, opened, or experiences environmental changes (Ali *et al.*, 2019). This real-time data ensures that all stakeholders can access the latest information, improving coordination and decision-making across the supply chain.

Smart contracts automate key transactions and agreements within the supply chain. For instance, when a product changes ownership between suppliers, manufacturers, or retailers, the smart contract automatically updates ownership records and verifies compliance with predefined conditions (Szabo, 1994). This automation reduces reliance on intermediaries, minimizes human error, and accelerates transaction processing (Kshetri, 2018).

The blockchain platform must have modular interfaces that allow integration with enterprise resource planning (ERP) systems, PLM software, and SCM platforms to facilitate interoperability with existing enterprise systems. This approach ensures organizations can adopt blockchain technology without overhauling their IT infrastructure (Chen, Zhang, *et al.*, 2022). Additionally, adherence to widely accepted blockchain standards, such as the ERC-721 and ERC-1155 token standards for NFTs (Entriken *et al.*, 2018; Radomski *et al.*, 2018), promotes compatibility and enables adoption.

The integration leverages Design Science Research methodologies to iteratively develop, test, and refine the blockchain artifacts (Bronet Campos, 2023; Hevner *et al.*, 2004). By engaging with stakeholders throughout the development process, the artifacts are tailored to meet practical needs while aligning with theoretical frameworks. Systems Theory provides a lens to understand the complex interactions within SCM and PLM, ensuring that the integration addresses technological and organizational dimensions (Skyttner, 2005).

5.2.2 Enhancing Transparency, Efficiency, and Authenticity

Integrating blockchain technology into SCM and PLM significantly enhances supply chain transparency, efficiency, and authenticity. Transparency is achieved through blockchain's decentralized and immutable nature, where authorized participants access a single, tamper-proof ledger of transactions and product data (Saberi *et al.*, 2019). Stakeholders can trace a product's history—from raw material sourcing to final delivery—by accessing the ProductNFT records on the blockchain. This visibility verifies ethical sourcing, regulatory compliance, and adherence to sustainability practices (Kraft *et al.*, 2022).

Efficiency gains manifest through process automation via smart contracts. Eliminating intermediaries and manual reconciliation reduces transaction times and operational costs. In the implemented system, transaction processing times decreased, and administrative overhead was reduced due to automated compliance checks and record-keeping (Dwivedi *et al.*, 2020). Real-time data availability enhances inventory management and forecasting accuracy, optimizing production scheduling and reducing waste (Liu, Zhang, *et al.*, 2020).

Authenticity is strengthened by assigning unique digital identities to products and containers through NFTs. The immutable recording of each product's lifecycle prevents counterfeiting and unauthorized alterations. In industries where product authenticity is critical—such as pharmaceuticals, luxury goods, and electronics—the blockchain system ensures that customers and regulators can confidently verify the genuineness of products (de Boissieu *et al.*, 2021). For example, implementing ProductNFTs in a simulated project within the textile industry, as shown by Agrawal *et al.* (2021), can reduce counterfeit incidents.

Enhanced traceability enables rapid response to quality issues and recalls. Organizations can immediately trace affected products and components through blockchain records if a defect is identified, isolating the issue and mitigating risks (Behnke and Janssen, 2019). This capability protects consumers and minimizes financial and reputational damage to the company.

Moreover, blockchain integration fosters trust among supply chain partners. The shared ledger reduces information asymmetry and promotes collaborative decision-making (Treiblmaier, 2018). Suppliers, manufacturers, and retailers can coordinate more effectively, improving supply chain resilience and agility.

As demonstrated through the developed smart contracts, integrating blockchain technology into SCM and PLM addresses the first research question by providing concrete mechanisms to enhance transparency, efficiency, and authenticity. The empirical evidence supports theoretical claims about blockchain's potential benefits and showcases practical applications organizations can adopt to improve supply chain operations. The findings align with existing literature while contributing novel insights into the practical integration of blockchain within SCM and PLM systems.

5.3 Discussion of Research Question Two

This section addresses the second research question: *What systemic changes are required within Supply Chain Management (SCM) and Product Lifecycle Management (PLM) to support the integration of blockchain technology*, as analyzed through Systems Theory? The successful implementation of blockchain technology necessitates a multifaceted transformation encompassing technical, organizational, and regulatory dimensions. The following subsections assess each of these areas, examining the necessary changes, challenges encountered, and potential solutions informed by the principles of Systems Theory.

5.3.1 Technical Changes Required

Integrating blockchain technology into SCM and PLM systems demands significant technical modifications to existing infrastructures. Key technical requirements include the development of blockchain-compatible platforms, integration with legacy systems, scalability solutions, and robust security measures.

Implementing blockchain requires the adoption of platforms that support smart contracts and Non-Fungible Tokens (NFTs), such as Ethereum or Hyperledger Fabric (Androulaki *et al.*, 2018). Organizations must develop or adapt their information systems to interact seamlessly with blockchain networks. This involves creating application programming interfaces (APIs) that enable data exchange between internal systems (e.g., Enterprise Resource Planning and PLM software) and the blockchain ledger (Chen, Zhang, *et al.*, 2022).

A primary technical challenge is achieving interoperability between heterogeneous systems. Legacy systems may not be designed to handle blockchain transactions or smart contract executions. To address this, middleware solutions and blockchain gateways can facilitate communication between disparate systems (Liu, Wang, *et al.*, 2020). Additionally, adopting standardized data formats and protocols enhances compatibility and reduces integration complexity (Jacoby and Usländer, 2020).

Blockchain networks, particularly public ones, face scalability issues due to limitations in transaction throughput and latency (Wang *et al.*, 2019). In high-volume supply chains, this can hinder real-time data processing and responsiveness. Implementing Layer 2 solutions, such as state channels or sidechains, can improve scalability constraints by handling transactions off-chain while maintaining security guarantees (Poon and Dryja, 2016).

Private or consortium blockchains offer alternative scalability advantages by limiting network participants and utilizing more efficient consensus mechanisms (e.g., Proof of Authority or Delegated Proof of Stake) (Khan *et al.*, 2021). However, this may reduce the decentralization benefits inherent in blockchain technology.

Ensuring the security of blockchain implementations is paramount, as vulnerabilities can lead to data breaches or unauthorized transactions. Smart contracts must be rigorously tested and formally verified to prevent exploits (Cassez *et al.*, 2022). Employing best practices in smart contract development, such as using standardized libraries and conducting security audits, mitigates risks (Alharby and van Moorsel, 2017).

Cybersecurity strategies must extend beyond the blockchain itself to include endpoints and interfaces. Secure key management protocols are essential to protect cryptographic keys used for transaction signing and authentication (Singh *et al.*, 2023). Implementing multi-factor authentication and hardware security modules enhances overall system security.

While blockchain's transparency benefits traceability, it challenges data privacy concerning sensitive business information. Techniques such as zero-knowledge proofs and data encryption can preserve confidentiality while allowing verification of data integrity (Wang *et al.*, 2019). Utilizing permissioned blockchains restricts data access to authorized participants, aligning with organizational privacy requirements.

5.3.2 Organizational Changes Required

The integration of blockchain technology triggers substantial organizational changes, affecting culture, processes, and human resources. Embracing this innovation requires a shift towards a more collaborative and technology-driven organizational mindset.

Organizations must foster a culture that values transparency, collaboration, and innovation. Blockchain's decentralized nature requires trust and cooperation among supply chain partners (Treiblmaier, 2018). Overcoming siloed mentalities and promoting information sharing are critical for maximizing blockchain's benefits.

Leadership plays a pivotal role in driving cultural change. Executive support and clear communication of the blockchain initiative's vision and objectives are essential (Kotter, 1996). Engaging stakeholders at all levels through workshops and training sessions facilitates buy-in and reduces resistance.

Implementing blockchain technology represents a significant organizational change that must be managed systematically. Applying change management models, such as Kotter's Eight-Step Process, can guide the transition (Kotter, 1996). Key steps include establishing a sense of urgency, forming a guiding coalition, creating a strategic vision, and anchoring new approaches in the organizational culture.

Addressing employee concerns and misconceptions about blockchain is crucial. Providing education on blockchain's functionalities and potential impact on roles and responsibilities alleviates uncertainty. Involving employees in the implementation process enhances ownership and acceptance.

Blockchain integration necessitates new skill sets within the organization. Technical roles require knowledge of blockchain platforms, smart contract development, and cybersecurity practices (Upadhyay, 2020). Business analysts and managers must understand blockchain's implications for business processes and supply chain dynamics.

Investing in training and professional development programs equips employees with the necessary competencies. Collaborations with academic institutions and participation in industry consortia can provide access to educational resources and expertise (Rejeb *et al.*, 2021).

Organizations may need to redesign business processes to leverage blockchain effectively. This involves identifying processes that can be automated or enhanced through smart contracts and adjusting workflows accordingly (Palmatier and Crum, 2023). Process mapping and analysis help understand the impact of blockchain integration on operational activities.

Cross-functional teams should collaborate to ensure process changes align with organizational objectives and do not disrupt critical operations. Continuous improvement methodologies like Lean or Six Sigma can support refining processes post-implementation.

5.3.3 Regulatory Changes Required

The regulatory environment significantly influences the adoption of blockchain technology in SCM and PLM. Organizations must navigate legal uncertainties and comply with existing and emerging regulations related to blockchain, data protection, and industry-specific requirements.

Blockchain technology operates within a complex legal framework that varies across jurisdictions. Regulations may concern data privacy (e.g., GDPR in the European Union), electronic transactions, and digital signatures. The lack of specific legislation on blockchain can create ambiguity and risk for organizations (Toufaily *et al.*, 2021).

Industry-specific regulations govern product safety, quality standards, and compliance reporting in SCM and PLM contexts. Integrating blockchain must ensure data recording and sharing practices adhere to these regulations.

Legal recognition of blockchain transactions and smart contracts is not uniform globally. Uncertainties regarding the enforceability of smart contracts may hinder their use in critical agreements (Kõlvart *et al.*, 2016). Data localization laws may also restrict cross-border data sharing, affecting international supply chains.

Privacy concerns arise from blockchain's immutable nature, which conflicts with the "right to be forgotten" requirements in data protection laws. Organizations must address how personal data recorded on the blockchain can be managed in compliance with such regulations (Teisserenc and Sepasgozar, 2022).

Organizations should engage proactively with regulators and policymakers to shape a conducive regulatory environment. Participating in industry associations and blockchain consortia allows organizations to contribute to developing standards and best practices (Paliwal *et al.*, 2020).

Legal counsel specializing in technology law can guide compliance and risk mitigation strategies. Organizations may need to implement hybrid solutions that combine blockchain with off-chain storage to manage sensitive data appropriately.

Advocacy for regulatory frameworks that recognize and accommodate blockchain technology is essential. Demonstrating blockchain's potential benefits for transparency, efficiency, and compliance can influence policymakers to support favorable regulations.

Addressing the second research question reveals that integrating blockchain technology into SCM and PLM requires comprehensive systemic changes. Technically, organizations must adapt their infrastructures, ensure security and scalability, and integrate blockchain with existing systems. Organizationally, a shift in culture, effective change management, and skill development are critical to adoption. Regulatory and navigating the evolving legal landscape demands proactive engagement and compliance strategies. Systems Theory underscores the interdependence of these components, highlighting the necessity for a holistic approach to blockchain integration within supply chains and product lifecycle management.

5.4 Discussion of Research Question Three

This section addresses the third research question: *What are the implications of blockchain technology for operational processes and strategic decision-making within Supply Chain Management (SCM) and Product Lifecycle Management (PLM)?* By analyzing the integration of blockchain technology, we explore its impact on operational efficiencies and strategic frameworks within organizations.

5.4.1 Operational Implications

Incorporating blockchain technology into SCM and PLM has specific implications for operational processes. It enhances efficiency, accuracy, and transparency in inventory management, logistics coordination, and quality control mechanisms.

Blockchain technology revolutionizes inventory management by providing real-time visibility and accurate tracking of inventory levels across the supply chain (Liu, Wang, *et al.*, 2020). The immutable ledger records every transaction and movement of goods, enabling organizations to maintain optimal inventory levels and reduce holding costs. Smart contracts automate inventory replenishment processes by triggering orders when stock levels reach predefined thresholds (Turjo *et al.*, 2021). This automation reduces manual interventions, minimizes stockouts and overstock situations, and enhances responsiveness to market demands.

For example, implementing the ContainerNFT smart contract facilitates precise tracking of container contents and movements. Organizations can monitor inventory in transit and adjust supply chain activities accordingly, improving synchronization between supply and demand (Agrawal *et al.*, 2021; 2023). Enhanced inventory accuracy leads to better forecasting and planning, improving overall operational efficiency.

Blockchain's decentralized ledger provides a single source of truth for all parties involved in logistics operations. It enhances coordination among suppliers, carriers, and distributors by sharing real-time information on shipment status, location, and expected delivery times (Queiroz *et al.*, 2019). This transparency reduces delays caused by miscommunication or information asymmetry and allows for proactive problem-solving when disruptions occur.

Smart contracts streamline logistics processes by automating tasks such as freight bookings, customs clearance, and payment settlements upon delivery confirmation (Dwivedi *et al.*, 2020). The automation reduces administrative burdens and accelerates transaction processing, leading to faster delivery times and improved customer satisfaction.

Furthermore, blockchain integration with IoT devices enhances asset tracking and condition monitoring. Sensors can record environmental conditions such as temperature and humidity, which are critical for perishable goods. This data is securely stored on the blockchain, ensuring integrity and availability for stakeholders (Ali *et al.*, 2019). In case of deviations from specified conditions, alerts can be generated, allowing timely interventions to prevent product spoilage.

Blockchain technology significantly improves quality control processes by ensuring traceability and accountability throughout the product lifecycle. The ProductNFT smart contract records detailed information on each product's origin, manufacturing processes, and quality inspections. This comprehensive data enables organizations to conduct precise root-cause analyses when quality issues occur.

In the event of a product recall, blockchain's traceability allows companies to identify and isolate affected batches quickly, minimizing the scope of recalls and reducing costs (Behnke and Janssen, 2019). Consumers can also access product information to verify authenticity and quality certifications, enhancing trust in the brand (Alnuaimi *et al.*, 2022).

Blockchain's immutable records prevent fraudulent activities and counterfeiting by providing verifiable proof of origin and ownership (Toyoda *et al.*, 2017). This is particularly crucial in pharmaceuticals and luxury goods industries, where product integrity is vital.

Overall, blockchain integration streamlines operational processes by eliminating redundancies and reducing the need for intermediaries. Transaction processing times decrease due to the automation of contractual agreements and verification procedures (Kshetri, 2018). Reducing manual paperwork and administrative tasks lowers operational costs and minimizes the potential for human error (Saberi *et al.*, 2019).

The enhanced data accuracy and real-time information availability improve decision-making at the operational level. Managers can make informed decisions based on reliable data, leading to optimized resource allocation and improved operational performance (Xu *et al.*, 2021).

5.4.2 Strategic Decision-Making Implications

Blockchain technology impacts operational processes and influences strategic decision-making within organizations. It affects strategic planning, offers competitive advantages, and transforms risk management practices.

The integration of blockchain provides organizations with new opportunities for strategic planning. The enhanced transparency and data integrity enables long-term planning based on accurate and comprehensive supply chain information (Treiblmaier, 2018). Organizations can identify trends, forecast demand more accurately, and align their strategies with market dynamics.

Blockchain facilitates collaboration with supply chain partners by building trust through shared and immutable data. Strategic partnerships can be formed with greater confidence, allowing for joint ventures, co-development projects, and shared investments in innovation (Upadhyay, 2020). The visibility into partners' operations and compliance practices supports strategic alignment and mutual goal setting.

Furthermore, blockchain opens paths for new business models and revenue streams. For instance, organizations can offer premium services such as product origin verification or participate in decentralized marketplaces (Chandra, 2022). Strategic planning must consider these opportunities to leverage blockchain's full potential.

Adopting blockchain technology can provide a significant competitive advantage by differentiating an organization in the marketplace. Enhanced transparency and traceability appeal to consumers who value ethical sourcing and product authenticity (Kraft *et al.*, 2022). Companies that can demonstrate end-to-end visibility in their supply chains may attract and retain customers more effectively.

Blockchain also enables efficiency gains that translate into cost savings and faster time-to-market. Organizations can price their products more competitively while maintaining healthy profit margins (Liu, Zhang, *et al.*, 2020). The ability to respond quickly to market changes and customer demands enhances agility, making it a key competitive differentiator in dynamic markets.

Early adopters of blockchain technology position themselves as innovators and industry leaders. This reputation can strengthen brand equity and open doors to strategic partnerships and investment opportunities (Queiroz *et al.*, 2019). Competitors may find it challenging to replicate the technological capabilities and trust built through blockchain-enabled systems.

Blockchain transforms risk management practices by providing tools to identify, assess, and mitigate risks more effectively. The transparency and immutability of blockchain records enhance supply chain visibility, allowing organizations to promptly detect potential disruptions or compliance issues (Ivanov and Dolgui, 2019). Early detection enables proactive measures to mitigate risks before they escalate.

Smart contracts automate compliance checks and enforce regulatory requirements, reducing the risk of non-compliance penalties (Rajput *et al.*, 2022). Automated alerts and actions triggered by predefined conditions ensure that organizations consistently follow industry standards and legal obligations.

Blockchain's decentralized nature enhances resilience against cyber-attacks and data tampering. The distributed ledger reduces single points of failure and enhances data security (Yaqoob *et al.*, 2020). This security is crucial for protecting sensitive supply chain data and maintaining operational continuity.

In terms of financial risk, blockchain's efficiency improvements and cost reductions strengthen an organization's financial position. Improved cash flow management results from faster transaction settlements and reduced capital tied up in inventory (Turjo *et al.*, 2021). Enhanced financial stability supports strategic investments and growth initiatives.

Blockchain provides organizations with strategic flexibility by enabling modular and scalable solutions. Organizations can adjust their blockchain implementations as market conditions evolve to accommodate new products, partners, or regulatory requirements (Liu, Zhang, *et al.*, 2020). This adaptability is essential for sustaining competitiveness in rapidly changing industries.

Furthermore, blockchain supports data-driven strategic decisions by providing reliable and comprehensive data analytics. Organizations can leverage blockchain data to gain insights into consumer behavior, supplier performance, and operational efficiencies (Chen, Zhang, *et al.*, 2022). Data analytics inform strategic choices regarding market expansion, product development, and resource allocation.

The analysis of the third research question demonstrates that blockchain technology has significant implications for operational processes and strategic decision-making within SCM and PLM. Blockchain enhances inventory management, logistics coordination, and quality control through increased transparency, automation, and data integrity. Strategically, it influences planning, provides competitive advantages, and transforms risk management practices by enabling better-informed decisions and fostering stakeholder trust. The integration of blockchain technology positions organizations to navigate complex supply chains more effectively, capitalize on new opportunities, and maintain a competitive edge in the global marketplace.

5.5 Limitations of the Study

While this research provides valuable insights into integrating blockchain technology into Supply Chain Management (SCM) and Product Lifecycle Management (PLM), several limitations must be acknowledged. These limitations relate to the research design, methodology, and scope, and they have implications for the interpretation of the findings and the generalizability of the conclusions drawn.

5.5.1 Limited Scope of Implementation

The study primarily focuses on developing and evaluating the ProductNFT and ContainerNFT smart contracts within a controlled experimental environment. While these artifacts demonstrate the potential benefits of blockchain integration, they are not tested in a full-scale, real-world supply chain setting. Consequently, the findings may not fully capture the complexities and unforeseen challenges in practical implementations involving multiple stakeholders, heterogeneous systems, and dynamic market conditions (Upadhyay, 2020).

5.5.2 Generalizability to Different Industries

The research centers on specific use cases within certain industries, such as manufacturing and logistics. The unique characteristics and regulatory requirements of these industries may limit the applicability of the results to other sectors. Industries with distinct operational processes or regulatory landscapes, such as healthcare or finance, may face different challenges and may not benefit from blockchain integration in the same manner (Kouhizadeh *et al.*, 2021). Therefore, caution must be exercised when extrapolating the findings beyond the contexts examined.

5.5.3 Rapid Technological Evolution

Blockchain technology is evolving rapidly, with new platforms, consensus mechanisms, and scalability solutions emerging continually (Wang *et al.*, 2019). The research relies on specific blockchain platforms and standards available at the time of the study, such as Ethereum and the ERC-721 or ERC-1155 token standard (Buterin, 2014; Entriken *et al.*, 2018; Radomski *et al.*, 2018). Future advancements may render some of the technical solutions proposed obsolete or less optimal. As a result, the permanence and relevance of the technical aspects of the research may be limited.

5.5.4 Assumptions in Systems Theory Application

The application of Systems Theory in analyzing the systemic changes required for blockchain integration assumes a level of rationality and predictability in organizational behavior (Skyttner, 2005). However, organizations are complex entities influenced by many human, cultural, and political factors that may not conform to theoretical models. The study does not account for irrational or emergent behaviors that can impact the success of blockchain implementation in the future (Jackson, 2003).

5.5.5 Limited Consideration of Human Factors

While the research acknowledges the need for organizational change and skill development, it may not sufficiently address the human factors that significantly influence technology adoption. Employee resistance, cognitive biases, and the learning curve associated with new technologies can pose substantial barriers (Kotter, 1996). The study does not include empirical data on stakeholder perceptions or the effectiveness of change management strategies in practice.

5.5.6 Regulatory and Legal Uncertainties

The discussion of regulatory changes required is based on the current understanding of the legal environment surrounding blockchain technology. However, regulations are evolving, and there is significant uncertainty regarding future legal developments (Toufaily *et al.*, 2021). The study may not fully anticipate regulatory shifts that could impact the feasibility or legality of blockchain applications in general and specifically in SCM and PLM.

5.5.7 Methodological Constraints

The use of Design Science Research (DSR) provides a structured approach to artifact development but may limit the exploration of alternative methodologies that could yield different insights. DSR focuses on problem-solving and artifact creation, potentially overlooking broader socio-technical dynamics that qualitative or mixed-methods research might reveal (Hevner *et al.*, 2004). Additionally, the evaluation of the artifacts is confined to technical performance and theoretical analysis, lacking empirical validation through longitudinal studies or real-world deployment.

5.5.8 Data Privacy and Ethical Considerations

The study discusses data privacy and confidentiality from a technical perspective but may not fully engage with the ethical implications of blockchain implementation. Issues such as user consent, data ownership, and the potential for surveillance or misuse of transparent ledgers have not been extensively explored (Kouhizadeh *et al.*, 2021). These ethical considerations are crucial for responsible technology adoption and warrant further investigation.

5.5.9 Dependency on Technological Infrastructure

The successful integration of blockchain technology assumes the availability of robust technological infrastructure, including reliable internet connectivity, computational resources, and IoT devices for data capture (Ali *et al.*, 2019). In regions or organizations where such infrastructure is lacking or unreliable, the feasibility of implementing the proposed solutions is fading or impossible. The study does not address the challenges faced by entities operating in low-resource settings.

5.5.10 Limitations of the Study – Conclusion

Recognizing these limitations is essential for contextualizing the findings of this research. They highlight areas where further study is needed and caution against overgeneralization. Future research should address these limitations by conducting empirical studies in diverse real-world settings, exploring human and ethical factors more deeply, and staying attuned to technological and regulatory developments. By doing so, the academic and practical understanding of blockchain integration into SCM and PLM can be enhanced, contributing to more effective and sustainable implementations.

5.6 Conclusion

This chapter systematically addresses the three research questions guiding this study, explaining how blockchain technology can be effectively integrated into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) to enhance transparency, efficiency, and authenticity. Through the development and analysis of the ProductNFT and ContainerNFT smart contracts, the research demonstrates the practical application of blockchain in these domains.

In response to the first research question, blockchain integration into SCM and PLM is achieved by leveraging smart contracts and Non-Fungible Tokens (NFTs) to create immutable and transparent records of products and containers throughout their lifecycle. The ProductNFT smart contract encapsulates comprehensive product data, enabling seamless tracking and auditing from inception to end-of-life. The ContainerNFT smart contract facilitates real-time logistics management, enhancing coordination and reducing operational inefficiencies. These implementations illustrate concrete mechanisms by which blockchain technology enhances transparency, efficiency, and authenticity in supply chain operations.

Addressing the second research question, the study identifies the systemic changes required within organizations to support blockchain integration, analyzed through Systems Theory. Technically, organizations must adapt their infrastructures to accommodate blockchain platforms, ensure interoperability with legacy systems, and implement robust security measures. Organizational changes involve cultivating a culture that embraces transparency and innovation, implementing effective change management strategies, and investing in skill development. Regulatively, organizations must navigate complex legal landscapes, comply with data protection laws, and engage with policymakers to advocate for favorable regulations. These systemic changes are interconnected, emphasizing the need for a holistic approach to blockchain adoption.

In response to the third research question, the research elucidates the implications of blockchain technology on operational processes and strategic decision-making. Operationally, blockchain enhances inventory management, logistics coordination, and quality control by providing real-time visibility, automating processes, and ensuring data integrity. Strategically, blockchain influences planning by enabling data-driven decisions, offers competitive advantages through differentiation and efficiency gains, and transforms risk management practices by enhancing transparency and resilience. The integration of blockchain positions organizations to navigate complex supply chains more effectively and capitalize on new market opportunities.

The chapter also acknowledges the study's limitations, including the controlled scope of implementation, potential generalizability issues, rapid technological evolution, and methodological constraints. Recognizing these limitations provides context for the findings and highlights areas for future research.

In summary, the findings reinforce the potential of blockchain technology to revolutionize SCM and PLM by addressing critical challenges and enhancing key operational and strategic dimensions. The research contributes to academic scholarship and industry practice by providing a granular understanding of the integration process and its multifaceted implications. The systemic approach highlights the importance of unifying technical, organizational, and regulatory factors, aligning with Systems Theory principles.

The insights gained pave the way for organizations to harness blockchain's capabilities, driving innovation and competitiveness in the evolving global supply chain landscape.

CHAPTER VI:

SUMMARY, IMPLICATIONS, AND RECOMMENDATIONS

6.1 Summary of Findings

This chapter summarizes and synthesizes the research on integrating blockchain technology into Supply Chain Management (SCM) and Product Lifecycle Management (PLM). The study aimed to enhance transparency, efficiency, and authenticity within these domains by developing applicable NFT and Smart contract based blockchain frameworks. Three primary questions guided the research:

1. **Research Question One:** *How can blockchain technology be integrated into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) systems to enhance transparency, efficiency, and authenticity using Design Science Research (DSR)?*
2. **Research Question Two:** *What systemic changes are required within SCM and PLM to support the integration of blockchain technology, as analyzed through Systems Theory?*
3. **Research Question Three:** *What are the implications of blockchain technology for operational processes and strategic decision-making within SCM and PLM?*

6.1.1 Addressing Research Question One

The study demonstrates the effective integration of blockchain technology into SCM and PLM by developing smart contracts and Non-Fungible Tokens (NFTs). Utilizing Design Science Research (DSR) methodologies (Hevner *et al.*, 2004; Peffers *et al.*, 2007), two key artifacts were created:

ProductNFT Smart Contract: This encapsulates comprehensive product data throughout its lifecycle, assigning a unique digital twin or digital identity to each product instance. It facilitates seamless tracking, auditing, and verification from inception to end-of-life, enhancing transparency and authenticity (Hayat and Winkler, 2022; Holler *et al.*, 2019).

ContainerNFT Smart Contract: This represents logistical units, enabling precise, real-time tracking of containers and their contents. Integration with Internet of Things (IoT) devices allows automatic updates to the blockchain ledger, enhancing efficiency by reducing manual interventions and errors (Agrawal *et al.*, 2021; 2023; Ali *et al.*, 2019).

The development of these smart contracts automates transactional processes and enforces compliance with predefined conditions, leveraging blockchain's immutable and decentralized nature to ensure data integrity and trust among stakeholders (Kshetri, 2018; Saberi *et al.*, 2019).

6.1.2 Addressing Research Question Two

Analyzed through Systems Theory (Jackson, 2003; Skyttner, 2005), integrating blockchain technology necessitates systemic changes across technical, organizational, and regulatory dimensions:

Technical Changes: Organizations must adapt their infrastructures to support blockchain platforms, ensuring interoperability with existing legacy systems and implementing robust security measures (Chen, Cai, *et al.*, 2022; Singh *et al.*, 2023). Scalability solutions, such as Layer 2 protocols and permissioned blockchains, address performance challenges inherent in blockchain networks (Khan *et al.*, 2021; Poon and Dryja, 2016).

Organizational Changes: Cultivating a culture that embraces transparency, collaboration, and innovation is essential (Treiblmaier, 2018). Effective change management strategies are critical, including leadership engagement, employee training, and reengineering business processes to align with blockchain capabilities (Kotter, 1996; Upadhyay, 2020).

Regulatory Changes: Organizations must navigate the complex legal landscape surrounding blockchain technology. Compliance with data protection laws, such as the General Data Protection Regulation (GDPR), and engagement with policymakers to advocate for supportive regulations are essential (Kouhizadeh *et al.*, 2021; Toufaily *et al.*, 2021). Ethical considerations and data privacy concerns must be addressed to ensure responsible adoption and maintain stakeholder trust (Teisserenc and Sepasgozar, 2021).

6.1.3 Addressing Research Question Three

The integration of blockchain technology has significant implications for operational processes and strategic decision-making within SCM and PLM:

Operational Implications: Blockchain enhances inventory management by providing real-time visibility and accurate tracking of goods, enabling organizations to optimize inventory levels and reduce costs (Liu, Zhang, *et al.*, 2020; Wang *et al.*, 2020). In logistics coordination, blockchain enables improved communication among supply chain partners, reducing delays and enhancing efficiency (Queiroz *et al.*, 2019; Turjo *et al.*, 2021; Wang *et al.*, 2022). Quality control processes benefit from improved traceability and accountability, enabling immediate identification and resolution of issues (Behnke and Janssen, 2019; Toyoda *et al.*, 2017; Wang and Lau, 2023).

Strategic Implications: Blockchain influences planning by providing reliable data analytics, supporting data-driven decision-making, and enabling organizations to identify trends and forecast demand more accurately (Treiblmaier, 2018; Xu *et al.*, 2021). The technology offers competitive advantages through differentiation, efficiency gains, and building trust with consumers who value transparency and ethical sourcing (Galvez *et al.*, 2018; Kraft *et al.*, 2022). Risk management practices are transformed by blockchain's enhanced visibility and resilience, allowing organizations to identify and mitigate risks more effectively (Ivanov and Dolgui, 2019; Yaqoob *et al.*, 2020).

6.2 Theoretical Contributions

This research significantly advances the theoretical understanding of blockchain integration within Supply Chain Management (SCM) and Product Lifecycle Management (PLM). By employing Design Science Research (DSR) and Systems Theory, the study bridges gaps in the existing literature and offers novel insights that enhance both academic theory and practical application.

In summary, this research makes substantial theoretical contributions by advancing academic understanding of blockchain integration in SCM and PLM, introducing novel methodological approaches, and filling critical gaps in existing literature. Integrating Design Science Research and Systems Theory provides a robust framework for theoretical exploration and practical application. The findings offer valuable insights that can inform future research, contribute to developing new theories, and enhance the interdisciplinary discourse on technology adoption in complex organizational systems.

6.2.1 Advancement of Academic Theory

The study makes substantial contributions to academic theory in several key areas:

Blockchain Integration in SCM and PLM: The research provides a comprehensive framework for integrating blockchain technology into SCM and PLM systems. By developing the ProductNFT and ContainerNFT smart contracts, the study demonstrates how blockchain can enhance transparency, efficiency, and authenticity in supply chains. This extends theoretical models by incorporating Non-Fungible Tokens (NFTs) as digital twins, digital representations of physical products and containers, offering a new perspective on supply chain digitization (Agrawal *et al.*, 2021; 2023; Liu, Zhang, *et al.*, 2020).

Smart Contracts and NFTs in Industrial Contexts: The application of smart contracts and NFTs in industrial settings is relatively underexplored. This research fills that gap by illustrating how NFTs can be used to track and manage products and containers throughout their lifecycle. Theoretically, it advances the understanding of how digital assets can represent physical goods within decentralized ledgers, facilitating secure and transparent transactions (Alnuaimi *et al.*, 2022; Teisserenc and Sepasgozar, 2022).

Systems Theory Application in Technological Integration: The study contributes to theoretical discussions on organizational adaptation to technological innovations by analyzing systemic changes required for blockchain integration through Systems Theory. It highlights the interdependencies between technical, organizational, and regulatory systems, offering a holistic view that can inform future research on technology adoption and organizational change (Jackson, 2003; Skyttner, 2005).

6.2.2 Integration of DSR and Systems Theory

The research integrates DSR and Systems Theory to address the complexities of blockchain integration:

Design Science Research Methodology: Utilizing DSR showcases the iterative development and refinement of the blockchain artifacts. This methodological approach contributes to theory by demonstrating how DSR can be effectively applied in developing blockchain solutions within SCM and PLM contexts. It provides a blueprint for future researchers employing DSR in similar technological innovations (Gregor and Hevner, 2013; Hevner *et al.*, 2004; Peffers *et al.*, 2007).

Systems Theory as an Analytical Framework: Applying Systems Theory provided a structured means to analyze systemic changes required for successful blockchain integration. It enabled the identification of technical, organizational, and regulatory factors and their interrelationships, contributing to a deeper theoretical understanding of how complex systems evolve with technological advancements (Skyttner, 2005; Tarpey and Mullarkey, 2019).

Synergy Between DSR and Systems Theory: Integrating DSR and Systems Theory is a novel methodological contribution (Tarpey and Mullarkey, 2019). It demonstrates how combining a problem-solving research methodology with a holistic analytical framework can yield comprehensive insights into developing and implementing technological innovations.

6.2.3 Filling Gaps in the Literature

The study fills several gaps identified in the literature review:

Practical Frameworks for Blockchain Implementation: Prior research often highlighted blockchain's potential benefits in SCM and PLM but lacked concrete frameworks for implementation (Kouhizadeh *et al.*, 2021; Upadhyay *et al.*, 2021; Upadhyay, 2020). This study provides detailed smart contract-based framework architectures and implementation strategies, contributing practical knowledge to the theoretical view.

Role of NFTs in Supply Chains: While NFTs have gained popularity in digital art and collectibles, their application in industrial supply chains has been limited (Chandra, 2022; Nadini *et al.*, 2021). This research extends theoretical understanding by exploring how NFTs can represent digital twins for physical products and containers, offering a new dimension to supply chain digitization theories.

Application of Systems Theory in Technological Adoption: There has been a lack of research on applying systems theory to analyze technological adoption in SCM and PLM (Tarpey and Mullarkey, 2019). By doing so, this study provides a theoretical framework that can be utilized in future research to understand the systemic impacts of emerging technologies.

6.2.4 Contributions to Blockchain and SCM/PLM Theory

The research contributes to the theoretical foundations of both blockchain technology and SCM/PLM:

Enhanced Transparency and Trust: The study reinforces theoretical claims that blockchain can significantly improve transparency and trust in supply chains. By providing empirical evidence through the developed smart contracts. It strengthens the theoretical argument for blockchain's role in mitigating issues like fraud, counterfeiting, and lack of traceability (Kshetri, 2018; Saberi *et al.*, 2019).

Dynamic Interaction Between Technology and Organizational Structures: The findings highlight how blockchain technology necessitates organizational structure and process changes. This contributes to theories on technology-induced organizational change, emphasizing the need for adaptability and innovation in organizational design (Kotter, 1996; Treiblmaier, 2018).

Interdisciplinary Approach to Technology Integration: By combining insights from computer science (blockchain technology), organizational behavior (change management), and systems theory, the research promotes an interdisciplinary theoretical approach. This holistic perspective is valuable for understanding the multifaceted nature of technological integration in complex systems.

6.2.5 Implications for Future Theoretical Frameworks

The study's theoretical contributions have implications for future research:

Foundation for NFTs in Industrial Contexts: The application of NFTs in SCM and PLM opens avenues for future theoretical exploration, including developing new models that incorporate digital asset representation of physical goods (Gebreab *et al.*, 2022; Jaribion *et al.*, 2022; Wang and Lau, 2023).

Enhanced Methodological Approaches: The successful integration of DSR and Systems Theory provides a methodological framework that can be replicated and refined in future studies. This approach can be valuable in researching other emerging technologies within complex organizational systems (Barata *et al.*, 2023; Hevner *et al.*, 2023).

Contribution to Sustainable Supply Chain Theories: By demonstrating how blockchain can enhance efficiency and reduce waste through improved tracking and management, the research contributes to sustainability theories within SCM. It provides a theoretical basis for considering blockchain as a tool for achieving sustainable supply chain objectives (Kouhizadeh *et al.*, 2021; Paliwal *et al.*, 2020; Saberi *et al.*, 2019).

6.2.6 Theoretical Integration of Regulatory and Ethical Considerations

The research integrates regulatory and ethical considerations into the theoretical framework:

Regulatory Adaptation: The study contributes to theories on how legal frameworks evolve in response to technological innovations by analyzing the regulatory changes required for blockchain integration. It emphasizes the importance of proactive engagement between organizations and policymakers in shaping beneficial regulatory environments (Teisserenc and Sepasgozar, 2021; Toufaily *et al.*, 2021).

Ethical Dimensions of Technology Adoption: The discussion on data privacy, security, and ethical considerations contributes to theoretical arguments on the ethical implications of emerging technologies. It emphasizes the need for ethical frameworks that guide responsible adoption of blockchain in SCM and PLM (Al-Farsi *et al.*, 2021; Kouhizadeh *et al.*, 2021).

6.2.7 Advancement of Knowledge in Systems Thinking

Applying Systems Theory advances knowledge in systems thinking:

Holistic Understanding of Complex Systems: The research enhances theoretical understanding of how technological changes impact various organizational components by viewing SCM and PLM as complex, interrelated systems. This holistic approach is valuable for developing more comprehensive theories in systems thinking and organizational management (Ramage and Shipp, 2020; Skyttner, 2005).

Adaptation and Evolution of Systems: The study provides insights into how systems adapt and evolve in response to disruptive technologies like blockchain. It contributes to knowledge of system dynamics, resilience, and capacity for self-organization within complex systems (Ivanov and Dolgui, 2019; Jackson, 2003).

6.3 Practical Implications

The findings of this research have significant practical implications for organizations seeking to enhance their Supply Chain Management (SCM) and Product Lifecycle Management (PLM) digital twin systems through blockchain technology. By developing and implementing the ProductNFT and ContainerNFT smart contracts, the study offers actionable solutions that address common challenges in supply chain operations. This section discusses the practical applications of these findings, implementation strategies for organizations, and potential challenges with proposed solutions.

The practical implications of this research demonstrate that blockchain technology, through the implementation of smart contracts and NFTs, offers transformative potential for SCM and PLM. Organizations can address longstanding challenges in supply chain operations by enhancing transparency, efficiency, and security. Effective implementation requires strategic planning, stakeholder engagement, and a willingness to embrace change. By navigating potential challenges proactively and leveraging the benefits of blockchain technology, organizations can achieve significant operational improvements and establish themselves as leaders in the digital economy.

6.3.1 Enhancing Supply Chain Transparency and Traceability

One of the elementary practical implications is the enhancement of transparency and traceability in supply chains:

Real-time Tracking and Visibility: The implementation of ProductNFT and ContainerNFT enables real-time tracking of products and containers throughout the supply chain. Organizations can monitor the movement of goods, verify their authenticity, and ensure compliance with regulatory standards (Agrawal *et al.*, 2021; Wang *et al.*, 2020).

Improved Consumer Trust: Companies can enhance consumer trust by providing transparent and verifiable product histories. This is particularly valuable in industries where origin and ethical sourcing are critical, such as food, pharmaceuticals, and luxury goods (de Boissieu *et al.*, 2021; Galvez *et al.*, 2018).

Fraud and Counterfeit Reduction: The immutable nature of blockchain records helps reduce fraud and counterfeiting. Stakeholders can authenticate products at any point in the supply chain, thereby protecting brand integrity and reducing financial losses (Kshetri, 2018; Toyoda *et al.*, 2017).

6.3.2 Streamlining Operational Efficiency

The integration of blockchain technology streamlines various operational processes:

Automation through Smart Contracts: Smart contracts automate transactions and enforce contractual agreements without the need for intermediaries, reducing processing times and operational costs (Lou *et al.*, 2021; Turjo *et al.*, 2021).

Inventory Management Optimization: Real-time data allows for better inventory management, reducing overstocking and stockouts. Organizations can optimize supply levels based on accurate, timely information (Liu, Zhang, *et al.*, 2020; Wang *et al.*, 2020).

Enhanced Collaboration: Shared access to blockchain ledgers improves collaboration among supply chain partners. It fosters a unified approach to supply chain management, reducing misunderstandings and inefficiencies (Dwivedi *et al.*, 2020; Queiroz *et al.*, 2019).

6.3.3 Strengthening Security and Data Integrity

Blockchain technology enhances security and data integrity:

Immutable Records: Blockchain's decentralized ledger ensures that records are tamper-proof, enhancing data security and reliability (Puthal *et al.*, 2018; Xu *et al.*, 2021).

Access Control and Permissions: Smart contracts can incorporate access control mechanisms, ensuring that only authorized parties can access sensitive information, thereby protecting intellectual property and confidential data (Alharby and van Moorsel, 2017; Singh *et al.*, 2023).

Resilience Against Cyber Attacks: The distributed nature of blockchain reduces the risk of single-point failures and enhances resilience against cyber threats (Al-Farsi *et al.*, 2021; Singh *et al.*, 2023).

6.3.4 Implementation Strategies for Organizations

To effectively adopt the developed smart contracts, organizations should consider the following strategies:

Phased Implementation and Pilot Projects: To test the blockchain solutions in a controlled environment, begin with pilot projects. This allows for identifying and resolving potential issues before full-scale deployment (Agrawal *et al.*, 2023; Yadlapalli *et al.*, 2022).

Integration with Existing Systems: Utilize middleware solutions and standardized APIs to integrate blockchain platforms with legacy systems, ensuring seamless data flow and minimizing disruptions(Chen, Zhang, *et al.*, 2022; Dinesha and Patil, 2023).

Employee Training and Skill Development: Invest in comprehensive training programs to equip employees with the necessary skills to operate within a blockchain-enabled environment. Collaborate with educational institutions or professional organizations to develop relevant curricula (Barata *et al.*, 2023; Bronet Campos, 2023; Upadhyay *et al.*, 2021)

Stakeholder Engagement: Engage all stakeholders, including suppliers, distributors, and customers, to ensure alignment and cooperation. Transparent communication about the benefits and changes can facilitate smoother adoption (Kouhizadeh *et al.*, 2021; Treiblmaier, 2018).

6.3.5 Addressing Potential Challenges

Implementing blockchain technology in SCM and PLM may present several challenges. The following solutions can help organizations navigate these obstacles:

6.3.5.1 Technical Challenges

Scalability Issues: Blockchain networks can face scalability problems due to high transaction volumes. Organizations can address this by implementing Layer 2 solutions, such as sidechains or state channels, and considering permissioned (private) blockchains for better control and efficiency (Neiheiser *et al.*, 2023; Poon and Dryja, 2016).

Interoperability: Ensuring the blockchain system interoperates with existing technologies across different blockchain platforms is critical. Adopting interoperability standards and protocols and participating in blockchain consortia can help in this process (Dinesha and Patil, 2023; Appendix D).

6.3.5.2 Organizational Challenges

Resistance to Change: Employees and stakeholders may resist new technologies due to uncertainty or fear of disruption. Implementing effective change management strategies, such as Kotter's Eight-Step Process, can help manage resistance and foster a culture of innovation (Kotter, 1996; Upadhyay *et al.*, 2021).

Cost of Implementation: Initial investment costs for blockchain integration can be high. Conducting a thorough cost-benefit analysis and exploring partnerships or consortium models can mitigate financial planning (Al Amin *et al.*, 2023; Daley *et al.*, 2022).

6.3.5.3 Regulatory and Legal Challenges

Compliance with Data Protection Laws: Blockchain's immutable nature can conflict with data protection regulations that require data to be erasable (e.g., GDPR's "right to be forgotten"). Implementing solutions like off-chain storage for sensitive data and using cryptographic techniques can address compliance issues (Teisserenc and Sepasgozar, 2021; Toufaily *et al.*, 2021).

Legal Uncertainties: The evolving legal landscape around blockchain may pose uncertainties. Organizations should engage legal experts, stay informed about regulatory developments, and participate in policy discussions to navigate legal complexities (Kouhizadeh *et al.*, 2021; Kowch, 2023).

6.3.5.4 Ethical Considerations

Data Privacy and Ownership: Ethical concerns regarding data ownership and user consent must be addressed. Establishing clear policies, obtaining informed consent, and ensuring transparency in data usage are essential practices (Musamih *et al.*, 2022; Teisserenc and Sepasgozar, 2021).

Environmental Impact: Some blockchain technologies consume significant energy. Opting for energy-efficient consensus mechanisms, such as Proof-of-Stake or Delegated Proof-of-Stake, can reduce environmental impact (Groombridge, 2022; Wang *et al.*, 2019).

6.3.6 Industry-Specific Applications

The practical implications extend across various industries:

Healthcare: Implementing blockchain can enhance the traceability of medical supplies and devices, improving patient safety and regulatory compliance (Gebreab *et al.*, 2022; Musamih *et al.*, 2022).

Food and Agriculture: Blockchain enables tracking of food products from farm to table, ensuring food safety and supporting sustainability initiatives (Galvez *et al.*, 2018; Menon and Jain, 2021).

Automotive and Manufacturing: Enhanced tracking of parts and components can improve quality control, recall management, and compliance with industry standards (Holler *et al.*, 2019; Upadhyay *et al.*, 2021).

6.3.7 Leveraging Blockchain for Competitive Advantage

Organizations adopting blockchain technology can gain a competitive edge:

Differentiation through Innovation: Early adopters can position themselves as industry leaders, attracting customers and partners who value transparency and technological advancement (Colicev, 2022; Treiblmaier, 2018).

Efficiency Gains and Cost Reduction: Streamlined processes and reduced reliance on intermediaries can lead to significant cost savings, improving profitability and market positioning (Rajput *et al.*, 2022; Turjo *et al.*, 2021).

Enhanced Risk Management: Improved visibility and data integrity support better risk assessment and mitigation strategies, protecting organizations from supply chain disruptions (Ivanov and Dolgui, 2019; Yaqoob *et al.*, 2020)(Ivanov & Dolgui, 2019; Yaqoob *et al.*, 2020).

6.3.8 Future-Proofing Supply Chains

Implementing blockchain technology prepares organizations for future challenges:

Adaptability to Emerging Technologies: Blockchain integration lays the groundwork for incorporating other technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twins, fostering innovation and agility (Grieves, 2023; Yaqoob *et al.*, 2020).

Alignment with Digital Economy Trends: As the digital economy evolves, organizations using advanced technologies will be better positioned to capitalize on new business models and opportunities (Chen, Zhang, *et al.*, 2022; Cheng *et al.*, 2022).

6.3.9 Recommendations for Practitioners

Based on the practical implications, the following recommendations are proposed for practitioners:

Conduct Comprehensive Feasibility Studies: Before the implementation, organizations should assess the suitability of blockchain technology for their specific context, considering factors like supply chain complexity, stakeholder readiness, and regulatory environment (Karuppiah *et al.*, 2023; Paliwal *et al.*, 2020).

Collaborate with Industry Partners: Engaging in industry consortia and partnerships can facilitate knowledge sharing, standardization, and collective problem-solving (Appendix D; Rejeb *et al.*, 2021).

Invest in Research and Development: Continuous investment in R&D will help organizations stay abreast of technological advancements and maintain a competitive edge (Daley *et al.*, 2022; Upadhyay *et al.*, 2021).

6.4 Recommendations for Future Research

Building on the findings and acknowledging the limitations of this study, future research should further explore the integration of blockchain technology into Supply Chain Management (SCM) and Product Lifecycle Management (PLM). The following recommendations identify areas where additional investigation can enhance our understanding and application of blockchain in these fields.

There are many opportunities for future research to expand on this study's findings. Researchers can focus on empirical validation, cross-industry applicability, socio-technical dynamics, technological innovation, regulatory frameworks, and education by addressing practical challenges and contributing to theoretical advancements. These efforts can help unlock the transformative potential of blockchain technology in SCM and PLM.

Collaboration among academia, industry, and policymakers will be essential for advancing knowledge and facilitating the successful integration of blockchain into global supply chains.

Future research should not only advance theory but also produce practitioner-oriented guidance. Researchers may develop standardized implementation toolkits tailored for industry practitioners, including sample smart contracts, step-by-step deployment guides, and reference architectures. For instance, creating a modular blueprint for integrating ProductNFT and ContainerNFT solutions into existing enterprise resource planning (ERP) systems can provide immediate, actionable templates for small and medium-sized enterprises (SMEs) seeking to improve traceability without extensive blockchain expertise. Additionally, researchers could partner with supply chain consortia or blockchain-focused industry groups to pilot large-scale deployments in real-world logistics networks, enabling iterative refinement of frameworks based on direct stakeholder feedback. By embedding user training modules and offering customizable dashboards highlighting key metrics like lead time reduction, inventory accuracy, or compliance adherence, future studies can deliver tangible, ready-to-adopt solutions for organizations aiming to leverage blockchain's potential.

6.4.1 Empirical Validation through Real-World Implementations

While this study developed and tested smart contracts in a controlled environment, future research should focus on further empirical validation through real-world implementations:

Pilot Projects in Industry Settings: Conduct case studies involving actual deployment of the ProductNFT and ContainerNFT smart contracts within organizations. This will provide practical insights into implementation challenges and benefits (Agrawal *et al.*, 2023; Yadlapalli *et al.*, 2022).

Longitudinal Studies: Perform prolonged research to assess the long-term impacts of blockchain integration on supply chain performance, efficiency, and stakeholder relationships. This will help understand how blockchain adoption evolves over time (Ivanov and Dolgui, 2019; Upadhyay *et al.*, 2021).

For example, researchers could collaborate with a multinational manufacturer to integrate ProductNFT-based tracking into one of their product lines and document the improvements in recall management and regulatory compliance. Such pilots might detail the specific IT infrastructure adjustments, the required staff training sessions, and the vendor relationships needed to support on-chain transactions, offering a practical roadmap for other firms.

6.4.2 Cross-Industry Analysis

Exploring the applicability of blockchain solutions across different industries will assess the generalizability of the developed frameworks:

Diverse Industry Applications: Investigate blockchain implementation in sectors such as healthcare, agriculture, and manufacturing to identify industry-specific challenges and opportunities (Gebreab *et al.*, 2022; Menon and Jain, 2021).

Comparative Studies: Conduct comparative analyses to understand how industry characteristics influence blockchain adoption, including regulatory environments, supply chain complexity, and stakeholder dynamics (Kouhizadeh *et al.*, 2021; Paliwal *et al.*, 2020).

Conducting side-by-side pilot studies in the automotive and pharmaceutical industries can produce concrete recommendations—such as adapting cryptographic standards to meet stringent pharmaceutical quality audit requirements or modifying metadata structures to capture automotive spare parts' lifecycles. Publishing these sector-specific playbooks, including configuration settings and best practices for interoperability, will allow industry stakeholders to adopt proven blockchain modules selectively.

6.4.3 Exploration of Socio-Technical Dynamics

Understanding the human and organizational factors influencing blockchain adoption is critical:

Employee Adoption and Training: Study the impact of blockchain integration on employees, including training needs, resistance to change, and the development of new skill sets (Barata *et al.*, 2023; Upadhyay, 2020).

Organizational Culture and Change Management: Examine how organizational culture affects the adoption of blockchain technology and identify effective change management strategies to facilitate smooth transitions (Kotter, 1996; Treiblmaier, 2018).

Stakeholder Engagement: Research methods to enhance stakeholder collaboration and trust in blockchain-enabled supply chains, considering factors like transparency preferences and data sharing concerns (Kraft *et al.*, 2022; Queiroz *et al.*, 2019).

Future work might produce organizational change toolkits featuring communication templates for project managers, checklists for addressing employee concerns, and guidelines for structuring stakeholder feedback workshops. By providing these practical materials, research can directly inform managers on navigating cultural shifts and enhancing collaboration during blockchain adoption phases.

6.4.4 Technological Advancements and Innovation

Future research should address technological challenges and explore advancements to enhance blockchain applications:

Scalability Solutions: Investigate emerging technologies and consensus mechanisms that improve blockchain scalability, such as sharding, sidechains, and new consensus algorithms (Neiheiser *et al.*, 2023; Wang *et al.*, 2019).

Interoperability Standards: Develop and test protocols that enable interoperability between different blockchain platforms and integration with legacy systems, facilitating broader adoption (Chen, Zhang, *et al.*, 2022; Dinesha and Patil, 2023).

Integration with Emerging Technologies: Explore how blockchain can be integrated with technologies like the Internet of Things (IoT), Artificial Intelligence (AI), and Digital Twins to create more intelligent and responsive supply chains (Grieves, 2023; Yaqoob *et al.*, 2020).

For instance, developing and open-sourcing a modular interoperability middleware prototype that seamlessly connects ContainerNFT with a company’s existing warehouse management system can demonstrate how to integrate blockchain into legacy infrastructure with minimal disruption. Real-world testing of such middleware in a logistics hub would highlight configuration parameters, required hardware, and maintenance schedules.

6.4.5 Regulatory and Ethical Frameworks

As blockchain technology evolves, so does the regulatory landscape:

Legal Compliance Strategies: Research approaches to ensure compliance with data protection laws and regulations while leveraging blockchain's capabilities, including using privacy-preserving technologies (Teisserenc and Sepasgozar, 2021; Toufaily *et al.*, 2021).

Policy Development: Engage in studies that contribute to policy development, offering recommendations to regulators on supporting blockchain innovation while protecting stakeholders (Kouhizadeh *et al.*, 2021; Upadhyay, 2020).

Ethical Considerations: Examine ethical issues related to data ownership, user consent, and the potential for misuse of blockchain technology. Develop guidelines for ethical implementation in supply chains (Al-Farsi *et al.*, 2021; Musamih *et al.*, 2022).

Creating compliance checklists and regulatory mapping tools to assist businesses in navigating data protection laws can offer direct practical value. For example, a reference table detailing how regional regulations (like GDPR or CCPA) affect on-chain data storage can guide legal departments and compliance officers toward implementing privacy-preserving techniques and appropriate consent management interfaces.

6.4.6 Sustainability and the Circular Economy

Blockchain has the potential to contribute to sustainability initiatives:

Tracking Environmental Impact: Investigate how blockchain can track and verify environmental data, such as carbon footprints, supporting sustainability goals, and reporting requirements (Paliwal *et al.*, 2020; Saberi *et al.*, 2019).

Facilitating the Circular Economy: Explore blockchain's role in enabling circular economy practices by tracking product life cycles, facilitating recycling, and promoting resource efficiency (Hayat and Winkler, 2022; Leng *et al.*, 2020).

Future research could generate prototype blockchain-based dashboards for sustainability officers, featuring carbon footprint calculators and automated alerts if certain environmental thresholds are exceeded. Such tools would guide companies in adjusting their sourcing strategies or modifying transport routes to achieve predefined sustainability targets.

6.4.7 Development of New Methodologies and Theoretical Frameworks

Advancing academic understanding requires the development of robust methodologies:

Hybrid Research Methodologies: Combine qualitative and quantitative research methods to capture the multifaceted impacts of blockchain technology on organizations and supply chains (Gregor and Hevner, 2013; Hevner *et al.*, 2004).

Extension of Systems Theory: Expand upon Systems Theory to better model the complexities introduced by emerging technologies, considering further dynamic interactions and feedback loops (Jackson, 2003; Skyttner, 2005).

Design Science Research Enhancements: Refine DSR methodologies to accommodate the rapid evolution of blockchain technology, ensuring that research stays relevant and impactful (Hevner *et al.*, 2023; Peffers *et al.*, 2007).

Researchers might produce practitioner-facing methodology guides that outline how to select appropriate data collection methods for a given supply chain maturity level. These guides could recommend when to deploy surveys, sensor networks, or simulation models, offering a decision matrix that supply chain managers can consult before embarking on blockchain pilot initiatives.

6.4.8 Economic and Business Model Innovation

Blockchain technology can enable new business models and economic opportunities:

Tokenization and Asset Management: Study how tokenization of assets using NFTs can create new revenue streams, enhance asset liquidity, and enable innovative business models (Chandra, 2022; Chen, Guo, *et al.*, 2022).

Decentralized Supply Chain Finance: Explore the potential of blockchain to facilitate decentralized finance (DeFi) solutions in supply chains, improving access to capital and reducing financing costs (Della Valle and Oliver, 2021; Kshetri, 2018).

Drafting sample business cases that detail how tokenization can monetize idle inventory or how a decentralized finance arrangement could reduce financing costs for suppliers can provide actionable insights for financial officers. Such cases should include cost-benefit analysis templates and ROI calculators that enable CFOs and supply chain strategists to make informed adoption decisions.

6.4.9 User Experience and Interface Design

Ensuring that blockchain applications are user-friendly is essential for adoption:

Human-Computer Interaction Studies: Research user interface and experience design specific to blockchain applications in SCM and PLM, aiming to reduce complexity and enhance usability (Dalibor *et al.*, 2020; Gray and Rumpe, 2022).

Accessibility and Inclusivity: Investigate how to make blockchain technologies accessible to users with varying levels of technical expertise, promoting inclusivity across the supply chain (Barata *et al.*, 2023; Jacob *et al.*, 2022).

Creating user interface mockups, usability testing protocols, and persona-based design guidelines can offer designers and software vendors practical references. For example, a catalog of design patterns simplifying complex blockchain interactions—such as one-click product verification or intuitive NFT ownership transfer interfaces—helps developers create more accessible solutions.

6.4.10 Education and Skill Development

Preparing the workforce for blockchain integration is critical:

Curriculum Development: Develop educational programs and curricula that equip students and professionals with the knowledge and skills required for blockchain-enabled environments (Alnuaimi *et al.*, 2022; Upadhyay, 2020).

Certification and Training: Explore the creation of certification programs that validate competencies in blockchain technology, enhancing professional standards and recognition (Bronet Campos, 2023; Lund, 2024).

Proposing professional certification curricula, with sample lesson plans, competency exams, and recommended learning resources, would enable educational institutions and industry training centers to rapidly develop courses that equip professionals with the skills needed to implement blockchain solutions in their supply chains and product management processes.

6.5 Reflection on the Research Journey

Embarking on this doctoral research journey has been a transformative experience that has significantly enriched both my professional expertise and personal development. Exploring blockchain technology integration into Supply Chain Management (SCM) and Product Lifecycle Management (PLM) presented a complex and multifaceted challenge, requiring the combination of interdisciplinary knowledge and navigation through rapidly evolving technological landscapes.

Reflecting on this journey, I recognize it as a period of significant growth, learning, and achievement. The challenges I faced and overcame contributed to advancing knowledge in blockchain integration and shaped me as a researcher and professional. This experience has reinforced my belief that persistence, open-mindedness, and ethical considerations are essential components of impactful research.

Looking toward the future, I am motivated to continue exploring the frontiers of technology and its applications within complex systems. This journey has been both demanding and rewarding, leaving me well-equipped to contribute meaningfully to academia and industry in the years to come.

6.5.1 Navigating the Interdisciplinary Terrain

One of the most profound aspects of this journey has been the opportunity to engage with a diverse array of disciplines. The intersection of blockchain technology, digital twin, SCM, PLM, Design Science Research (DSR), and Systems Theory demanded a holistic understanding that exceeded traditional academic boundaries. Immersing myself in fields such as computer science, organizational behavior, systems engineering, and legal studies broadened my perspective and enhanced my ability to approach problems from multiple angles.

This interdisciplinary engagement highlighted the importance of flexibility and adaptability in research. It required continuous learning and the willingness to explore unfamiliar territories, fostering a mindset that values curiosity and lifelong learning. Collaborations with experts from different fields enriched the research, providing invaluable insights that shaped the development of smart contracts and theoretical frameworks.

6.5.2 Overcoming Challenges and Embracing Complexity

The research journey was not without its challenges. Integrating blockchain and digital twin technology into SCM and PLM systems involved navigating technical complexities, organizational dynamics, and regulatory uncertainties. Technical challenges included understanding the complexities of blockchain platforms, smart contract development, and ensuring interoperability with existing systems. Overcoming these challenges required dedication, meticulous planning, and iterative experimentation.

Organizational and human factors presented additional hurdles. Resistance to change, skepticism about emerging technologies, and the need for stakeholder alignment highlighted the importance of effective communication and change management strategies. Engaging with industry practitioners and stakeholders provided practical insights that informed the research and emphasized the real-world applicability of the solutions developed.

Regulatory considerations, such as data privacy laws and compliance requirements, added layers of complexity. Navigating these legal landscapes necessitated consultation with legal experts and a deep dive into the ethical implications of blockchain adoption. This experience reinforced the significance of considering ethical and legal dimensions in technological innovation.

6.5.3 Learning from Limitations and Setbacks

Throughout the research process, I encountered limitations that offered valuable learning opportunities. Access to real-world data was constrained due to proprietary concerns and the promising stage of blockchain adoption in specific industries. To mitigate this, I leveraged simulated environments and theoretical models, which, while effective, highlighted the importance of empirical validation in future research.

Time constraints and the rapid pace of technological advancements posed additional challenges. The blockchain landscape and digital twin integrations continually evolve, requiring constant updates to stay abreast of new developments. This underscored the necessity of agility in research and the importance of setting realistic scopes and timelines.

6.5.4 Personal and Professional Growth

This doctoral journey has honed critical thinking, problem-solving, and analytical skills. The complexity of the research required a strategic approach to examining problems, formulating hypotheses, and developing solutions. It fostered resilience and the ability to navigate ambiguity, invaluable skills in both academic and professional contexts.

Engaging in scholarly discourse through conferences, seminars, and publications enriched my professional and academic experience. It provided platforms to share findings, receive feedback, and engage with the broader research community. These interactions enhanced the quality of the research and contributed to personal growth by building confidence and communication skills.

6.5.5 Ethical Reflections and Responsible Innovation

The research journey prompted deep reflection on the ethical implications of technology adoption. The potential impact of blockchain technology integrated digital twins on data privacy, security, and employment required a careful examination of ethical responsibilities. This awareness guided the development of smart contracts and informed recommendations prioritizing responsible innovation.

Understanding the societal implications of technological advancements reinforced the importance of aligning research with ethical standards and contributing positively to society. It emphasized that technological progress must be balanced with equity, inclusivity, and sustainability considerations.

6.5.6 Shaping Future Research and Career Trajectories

This research has laid a strong foundation for future scholarly endeavors. The insights gained have opened new avenues for exploration, particularly in integrating blockchain with emerging technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT). The interdisciplinary approach adopted in this research will continue to guide future projects, emphasizing the value of holistic perspectives in addressing complex challenges.

Professionally, the experience has solidified my commitment to advancing technological innovation within SCM and PLM. It has prepared me to contribute to industry practices by applying academic insights to real-world problems and fostering collaboration between academia and industry.

6.6 Conclusion

The conclusion of this research advances the discussion on integrating blockchain technology—specifically Non-Fungible Tokens (NFTs) and smart contracts—into Supply Chain Management (SCM) and Product Lifecycle Management (PLM). Drawing on Design Science Research (DSR) and Systems Theory, it validates blockchain's conceptual value. It demonstrates how novel frameworks can reshape operational realities. The development and evaluation of the ProductNFT and ContainerNFT artifacts exemplify this transformation: they transcend theoretical models to deliver actionable tools that enhance transparency, traceability, and strategic responsiveness in complex supply chains.

By testing these artifacts in a simulated multinational hydraulics manufacturing environment, the research moves beyond incremental improvements, showing how trustworthy product identity, accurate lifecycle tracking, and real-time quality verification collectively enable more agile and informed decision-making. Such outcomes highlight that blockchain-driven supply chains are more efficient and adaptive—capable of responding quickly to market demands, regulatory shifts, and sustainability goals.

Through this integrative process, three core insights emerge. First, aligning blockchain architectures with digital twin concepts ensures that product data are not static records but dynamic, interoperable resources continuously informing the entire supply chain ecosystem. Second, the iterative DSR approach ensures that theoretical constructs are consistently refined against empirical evidence, producing academically rigorous and practically viable solutions. Third, the evolving regulatory and technical landscape challenges organizations to embrace private or consortium blockchains and advanced cryptographic techniques, ensuring that security, privacy, and interoperability become foundational design principles rather than afterthoughts.

This thesis illustrates how blockchain-based frameworks catalyze a strategic shift in SCM and PLM. They enable ecosystems where data-driven insights guide cost reductions, operational efficiencies, and broader innovations in compliance, risk mitigation, and long-term resilience. By connecting conceptual rigor with real-world applicability, the research provides a roadmap for scholars and practitioners to embrace blockchain's full potential, ultimately guiding organizations toward more intelligent, trusted, and future-ready supply chain practices.

APPENDIX A

SMART CONTRACT PRODUCTNFT - PLM PRODUCT

```
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;

import "@openzeppelin/contracts/token/ERC721/ERC721.sol";
import "@openzeppelin/contracts/access/Ownable.sol";

contract ProductNFT is ERC721, Ownable {
     struct MaterialItem {
            address nftContract;
            uint256 tokenId;
         }

      struct ProductMetadata {
            // 1. General Information
            string productID;
            string name;
            string description;
            string productType;
            string version;
            // 2. Design Data
            string designFiles;
            string designer;
            string designDate;
```

```
MaterialItem[] billOfMaterials;
// 3. Manufacturing Information
string manufacturingProcesses;
string manufacturingLocations;
string toolsAndEquipment;
string qualityControlParameters;
// 4. Assembly Information
string assemblyInstructions;
string componentList;
string assemblyTime;
string assemblyTeams;
// 5. Testing and Quality Assurance
string testProcedures;
string testResults;
string qualityCertifications;
string issuesAndResolutions;
// 6. Logistics
string packaging;
string storageRequirements;
string shippingMethods;
// 7. Regulatory Compliance
string regulations;
string complianceStatus;
// 8. End-of-Life Management
string disposalInstructions;
```

```
        string recyclingInformation;
        // 9. Historical Data and Versioning
        string changeLog;
        string versionHistory;
        // 10. Digital Rights and Permissions
        string accessControl;
        string rightsManagement;
    }

    mapping(uint256 => ProductMetadata) private
_productMetadata;

    constructor() ERC721("ProductNFT", "PNFT") {}

    function mint(uint256 tokenId, ProductMetadata memory
metadata) public onlyOwner {
        _safeMint(msg.sender, tokenId);
        _productMetadata[tokenId] = metadata;
    }

    function updateMetadata(uint256 tokenId,
ProductMetadata memory metadata) public onlyOwner {
        require(_exists(tokenId), "Token does not
exist");
        _productMetadata[tokenId] = metadata;
```

```
        }

    function getMetadata(uint256 tokenId) public view
returns (ProductMetadata memory) {
            require(_exists(tokenId), "Token does not
exist");
            return _productMetadata[tokenId];
        }

    function addMaterialItem(uint256 tokenId, address
nftContract, uint256 materialTokenId) public onlyOwner {
            require(_exists(tokenId), "Token does not
exist");

_productMetadata[tokenId].billOfMaterials.push(MaterialItem
(nftContract, materialTokenId));
        }

    function removeMaterialItem(uint256 tokenId, uint256
index) public onlyOwner {
          require(_exists(tokenId), "Token does not
exist");
          require(index <
_productMetadata[tokenId].billOfMaterials.length, "Invalid
index");
```

```
            MaterialItem[] storage materials =
_productMetadata[tokenId].billOfMaterials;
            materials[index] = materials[materials.length
- 1];
            materials.pop();
        }
    }
```

This smart contract includes all the functionality as discussed earlier, including:

- The `ProductMetadata` struct mirrors the provided metadata structure, with the `billOfMaterials` field as an array of `MaterialItem` structs.
- The `MaterialItem` struct represents a link to another product or material NFT.
- The `mint` function creates a new NFT with the specified token ID and metadata.
- The `updateMetadata` function to update the metadata of an existing NFT.
- The `getMetadata` function retrieves the metadata of a specific NFT.
- The `addMaterialItem` function to add a link to another NFT in the `billOfMaterials` array.
- The `removeMaterialItem` function to remove a link from the `billOfMaterials` array.

The contract inherits from the OpenZeppelin `ERC721` contract to implement the NFT functionality and from `Ownable` for access control.

APPENDIX B

SMART CONTRACT CONTAINERNFT - SCM BASIC CONTAINER

```
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;

import
"@openzeppelin/contracts/token/ERC721/ERC721.sol";
import "@openzeppelin/contracts/utils/Counters.sol";
import "@openzeppelin/contracts/access/Ownable.sol";

contract ContainerNFT is ERC721, Ownable {
    using Counters for Counters.Counter;
    Counters.Counter private _containerIds;

    struct Content {
        string contentType; // "ProductNFT" or
"ContainerNFT"
        uint256 contentId;
        uint256 quantity;
    }

    struct Container {
        string name;
        uint256 capacity;
        Content[] contents;
```

```
            string location;
            bool isStatic;
            string status;
            uint256 created;
            uint256 lastMoved;
        }

        mapping(uint256 => Container) private _containers;

        event ContainerCreated(uint256 indexed
containerId, string name, uint256 capacity, string
location, bool isStatic);
        event ContainerMoved(uint256 indexed containerId,
string fromLocation, string toLocation);
        event ContentLoaded(uint256 indexed containerId,
string contentType, uint256 contentId, uint256 quantity);
        event ContentUnloaded(uint256 indexed containerId,
string contentType, uint256 contentId, uint256 quantity);

        constructor() ERC721("ContainerNFT", "CNT") {}

        function createContainer(string memory name,
uint256 capacity, string memory location, bool isStatic)
public onlyOwner returns (uint256) {
            _containerIds.increment();
```

```
            uint256 newContainerId =
_containerIds.current();

            Container storage newContainer =
_containers[newContainerId];
            newContainer.name = name;
            newContainer.capacity = capacity;
            newContainer.location = location;
            newContainer.isStatic = isStatic;
            newContainer.status = "created";
            newContainer.created = block.timestamp;
            newContainer.lastMoved = block.timestamp;

            _mint(msg.sender, newContainerId);
            emit ContainerCreated(newContainerId, name,
capacity, location, isStatic);

            return newContainerId;
        }

        function moveContainer(uint256 containerId, string
memory newLocation) public onlyOwner {
            require(_exists(containerId), "Container does
not exist");
```

```
            Container storage container =
_containers[containerId];
            require(!container.isStatic, "Static container
cannot be moved");

            string memory oldLocation =
container.location;
            container.location = newLocation;
            container.lastMoved = block.timestamp;
            emit ContainerMoved(containerId, oldLocation,
newLocation);
        }

        function loadContent(uint256 containerId, string
memory contentType, uint256 contentId, uint256 quantity)
public onlyOwner {
            require(_exists(containerId), "Container does
not exist");
            Container storage container =
_containers[containerId];
            require(container.contents.length <
container.capacity, "Container is full");

            Content memory newContent = Content({
                contentType: contentType,
```

```
                contentId: contentId,
                quantity: quantity
            });

            container.contents.push(newContent);
            emit ContentLoaded(containerId, contentType,
contentId, quantity);
        }

        function unloadContent(uint256 containerId, string
memory contentType, uint256 contentId, uint256 quantity)
public onlyOwner {
            require(_exists(containerId), "Container does
not exist");
            Container storage container =
_containers[containerId];

            for (uint256 i = 0; i <
container.contents.length; i++) {
                if
(keccak256(abi.encodePacked(container.contents[i].contentTy
pe)) == keccak256(abi.encodePacked(contentType)) &&
container.contents[i].contentId == contentId &&
container.contents[i].quantity >= quantity) {
```

```
                     container.contents[i].quantity -=
quantity;
                     if (container.contents[i].quantity ==
0) {
                         container.contents[i] =
container.contents[container.contents.length - 1];
                         container.contents.pop();
                     }
                     emit ContentUnloaded(containerId,
contentType, contentId, quantity);
                     break;
                 }
             }
         }

         function getContainer(uint256 containerId) public
view returns (string memory, uint256, Content[] memory,
string memory, bool, string memory, uint256, uint256) {
             require(_exists(containerId), "Container does
not exist");

             Container storage container =
_containers[containerId];
```

```
            return (container.name, container.capacity,
container.contents, container.location, container.isStatic,
container.status, container.created, container.lastMoved);
        }
    }
```

This smart contract includes all the data structure as shown in *Table 3* and functionality as discussed earlier, including:

- The `Container` struct mirrors the provided metadata structure, with the `contents` field as an array of `Content` structs.
- The `Content` struct represents a link to another container or product NFT.
- The `createContainer` function creates a new NFT with the specified token ID and metadata.
- The `moveContainer` function moves a container to a new location if it is not static.
- The `loadContent` function loads a product or another container into a container.
- The `unloadContent` function unloads a product or another container from a container.
- The `getContainer` function retrieves the metadata of a specific container NFT.

The contract inherits from the OpenZeppelin ERC721 contract to implement the NFT functionality and from Ownable for access control.

APPENDIX C

SMART CONTRACT CONTAINERINDEXNFT - SCM CONTAINER INDEX

```
// SPDX-License-Identifier: MIT
pragma solidity ^0.8.0;

import
"@openzeppelin/contracts/token/ERC721/ERC721.sol";
import "@openzeppelin/contracts/utils/Counters.sol";
import "@openzeppelin/contracts/access/Ownable.sol";

contract ContainerIndexNFT is ERC721, Ownable {
    using Counters for Counters.Counter;
    Counters.Counter private _tokenIds;

    struct Content {
        address nftContract;
        uint256 tokenId;
        uint256 quantity;
    }

    struct ContainerIndex {
        // 1. Company Details
        string companyId;
        // 2. Container Details
        string name;
```

```
        uint256 capacity;
        // 3. Contents
        Content[] contents;
        // 4. Location and Status
        string location;
        bool isStatic;
        string status;
        // 5. Timestamps
        uint256 created;
        uint256 lastMoved;
        // 6. History
        string[] events;
        uint256[] timestamps;
        string[] locations;
    }

    mapping(uint256 => ContainerIndex) private
_containerIndexes;

    constructor() ERC721("ContainerIndexNFT", "CINFT")
{}

    function createContainerIndex(
        string memory companyId,
        string memory name,
```

```
            uint256 capacity,
            string memory location,
            bool isStatic,
            string memory status
        ) public onlyOwner returns (uint256) {
            _tokenIds.increment();
            uint256 newContainerIndexId =
_tokenIds.current();

            ContainerIndex storage newContainerIndex =
_containerIndexes[newContainerIndexId];
            newContainerIndex.companyId = companyId;
            newContainerIndex.name = name;
            newContainerIndex.capacity = capacity;
            newContainerIndex.location = location;
            newContainerIndex.isStatic = isStatic;
            newContainerIndex.status = status;
            newContainerIndex.created = block.timestamp;
            newContainerIndex.lastMoved = block.timestamp;

            _mint(msg.sender, newContainerIndexId);
            return newContainerIndexId;
        }
```

```
        function moveContainerIndex(uint256
containerIndexId, string memory newLocation) public
onlyOwner {
            require(_exists(containerIndexId),
"ContainerIndex does not exist");
            ContainerIndex storage containerIndex =
_containerIndexes[containerIndexId];
            require(!containerIndex.isStatic,
"ContainerIndex is static and cannot be moved");

            containerIndex.location = newLocation;
            containerIndex.lastMoved = block.timestamp;
            containerIndex.events.push("moved");

containerIndex.timestamps.push(block.timestamp);
            containerIndex.locations.push(newLocation);
        }

        function loadContent(
            uint256 containerIndexId,
            address nftContract,
            uint256 contentTokenId,
            uint256 quantity
        ) public onlyOwner {
```

```
            require(_exists(containerIndexId),
"ContainerIndex does not exist");
            ContainerIndex storage containerIndex =
_containerIndexes[containerIndexId];

containerIndex.contents.push(Content(nftContract,
contentTokenId, quantity));
            containerIndex.events.push("added content");

containerIndex.timestamps.push(block.timestamp);

containerIndex.locations.push(containerIndex.location);
        }

        function unloadContent(uint256 containerIndexId,
uint256 index) public onlyOwner {
            require(_exists(containerIndexId),
"ContainerIndex does not exist");
            ContainerIndex storage containerIndex =
_containerIndexes[containerIndexId];
            require(index <
containerIndex.contents.length, "Invalid index");

            for (uint256 i = index; i <
containerIndex.contents.length - 1; i++) {
```

```
                containerIndex.contents[i] =
containerIndex.contents[i + 1];
            }
            containerIndex.contents.pop();
            containerIndex.events.push("removed content");

containerIndex.timestamps.push(block.timestamp);

containerIndex.locations.push(containerIndex.location);
        }

        function getContainerIndex(uint256
containerIndexId)
            public
            view
            returns (
                string memory,
                string memory,
                uint256,
                Content[] memory,
                string memory,
                bool,
                string memory,
                uint256,
                uint256,
```

```
                string[] memory,
                uint256[] memory,
                string[] memory
            )
        {
            require(_exists(containerIndexId),
"ContainerIndex does not exist");
            ContainerIndex storage containerIndex =
_containerIndexes[containerIndexId];
            return (
                containerIndex.companyId,
                containerIndex.name,
                containerIndex.capacity,
                containerIndex.contents,
                containerIndex.location,
                containerIndex.isStatic,
                containerIndex.status,
                containerIndex.created,
                containerIndex.lastMoved,
                containerIndex.events,
                containerIndex.timestamps,
                containerIndex.locations
            );
        }
    }
```

This struct includes fields for company details, container details, contents, location and status, timestamps, and history, mirroring the structure provided in Table 3.

- `The createContainerIndex` creates a new NFT with the specified token ID and metadata.
- The `moveContainerIndex m`oves a container to a new location if it is not static.
- The `loadContent` loads a product or another container into a container.
- The `unloadContent` unloads a product or another container from a container.
- The `getContainerIndex` retrieves the metadata of a specific container NFT.

This contract follows the same style as the ContainerNFT contract in Appendix B, ensuring consistency and ease of integration within the SCM system.

APPENDIX D

BLOCKCHAIN CONSORTIA AND INDUSTRY GROUPS

1. **Enterprise Ethereum Alliance (EEA)**
    - **Description:** The EEA is a member-led industry organization whose objective is to drive the use of Ethereum blockchain technology as an open-standard to empower all enterprises.
    - **Link:** https://entethalliance.org/
2. **Hyperledger**
    - **Description:** Hosted by the Linux Foundation, Hyperledger is an open-source collaborative effort created to advance cross-industry blockchain technologies.
    - **Link:** https://www.hyperledger.org/
3. **R3 Corda**
    - **Description:** R3 is an enterprise blockchain software firm working with a broad ecosystem of more than 350 participants across multiple industries from both the private and public sectors.
    - **Link:** https://www.r3.com/
4. **Blockchain in Transport Alliance (BiTA)**
    - **Description:** BiTA is dedicated to developing best practices and standards for blockchain in the transportation/logistics/supply chain marketplace.
    - **Link:** https://www.bita.studio/
5. **Global Blockchain Business Council (GBBC)**
    - **Description:** GBBC is the leading industry association for the blockchain technology ecosystem, which brings together innovators and thought leaders from over 50 countries.

- **Link:** https://gbbcouncil.org/

6. **Digital Chamber of Commerce**
    - **Description:** The Chamber is the world's leading trade association representing the digital asset and blockchain industry, promoting the acceptance and use of digital assets and blockchain-based technologies.
    - **Link:** https://digitalchamber.org/
7. **Blockchain Research Institute (BRI)**
    - **Description:** BRI is a global think tank conducting ground-breaking research on blockchain technology, providing insights on how businesses, governments, and organizations can leverage it.
    - **Link:** https://www.blockchainresearchinstitute.org/
8. **Mobility Open Blockchain Initiative (MOBI)**
    - **Description:** MOBI is a member-led consortium working to make transportation more efficient, affordable, greener, safer, and less congested using blockchain technology.
    - **Link:** https://dlt.mobi/
9. **Blockchain Interoperability Alliance (BIA)**
    - **Description:** BIA is an organization dedicated to promoting blockchain interoperability between disparate blockchain networks.
    - **Link:** https://wiki.p2pfoundation.net/Blockchain_Interoperability_Alliance

APPENDIX E

LIST OF CONSORTIUM BLOCKCHAINS

1. Hyperledger Fabric

   Pros:

   - Modular architecture allows plug-and-play components like consensus and membership services.
   - Supports smart contracts written in multiple languages (e.g., Go, JavaScript, and Java).
   - Offers privacy and confidentiality through private channels and data collections.

   Cons:

   - Requires significant configuration and setup, which can be complex.
   - Limited support for large-scale public blockchain applications.

   Cost:

   - No licensing cost, but operational costs depend on cloud providers and infrastructure.

   Link: https://www.hyperledger.org/projects/fabric

2. R3 Corda

   Pros:

   - Designed specifically for financial services, with strong privacy features.
   - Peer-to-peer architecture that ensures only relevant parties have access to transaction data.
   - Flexible integration with existing systems and supports Java and Kotlin for smart contracts.

   Cons:

- Limited to financial applications, less versatile for other industries.
- Smaller community compared to other platforms like Hyperledger Fabric or Ethereum.

Cost:

- An open-source version is available, and the enterprise edition comes with support and additional features at variable costs.

Link: https://www.corda.net/

3. Quorum

Pros:

- Based on Ethereum, benefiting from Ethereum's developer tools and community.
- Enhanced privacy features and performance improvements over public Ethereum.
- Suitable for financial institutions due to its permissioned nature.

Cons:

- As a fork of Ethereum, it inherits some scalability issues.
- Smaller ecosystem compared to public Ethereum.

Cost:

- Open-source and free to use, operational costs depend on infrastructure.

Link: https://www.kaleido.io/blockchain-platform/quorum

4. Hyperledger Besu

Pros:

- Ethereum client designed for enterprise use, enabling private and permissioned networks.
- Interoperability with the public Ethereum mainnet if desired.

- Strong support for smart contracts and decentralized applications (dApps).

Cons:

- Similar to Ethereum, can face scalability challenges.
- Requires expertise in Ethereum tooling and languages like Solidity.

Cost:

- Open-source, operational costs vary based on cloud services and infrastructure.

Link: https://www.hyperledger.org/projects/besu

5. Enterprise Ethereum

Pros:

- Leverages the robust Ethereum ecosystem and developer community.
- Offers privacy, permissioning, and scalability enhancements for enterprise use.
- Strong, smart contract capabilities with Solidity.

Cons:

- High complexity in setting up and managing enterprise-level deployments.
- Public network scalability issues can still be a factor.

Cost:

- No direct licensing cost, but operational costs depend on deployment specifics.

Link: https://entethalliance.org/

6. Ripple (RippleNet)

Pros:

- Designed for fast, secure, and low-cost international payments.

- Strong institutional support and partnerships with major financial institutions.
- Highly efficient and scalable.

Cons:

- Primarily focused on payments and remittances, less versatile for other applications.
- Perceived centralization due to Ripple Labs' significant control.

Cost:

- Transaction fees are low, but network participation costs depend on usage and integration needs.

Link: https://ripple.com/

Summary

- Hyperledger Fabric stands out for its modularity and privacy features, making it ideal for various industries but requiring significant setup effort.
- R3 Corda is tailored for financial services with strong privacy but is less versatile.
- Quorum benefits from Ethereum's ecosystem but faces scalability issues.
- Hyperledger Besu offers enterprise-grade Ethereum capabilities but shares some of Ethereum's challenges.
- Enterprise Ethereum leverages Ethereum's strengths for enterprises but requires complex management.
- Ripple is highly efficient for payments but limited to financial use cases.

For each platform, the cost primarily involves operational expenses related to infrastructure and cloud services, with most being open-source and free to use.

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