

Architecting Resilience in Pharmaceutical Supply Chains: A Design Science Framework for Algorithmic Dynamic Capabilities

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Abstract

Global drug supply chains are now more vulnerable than ever before to both external shock impacts on the entire system and to counterfeiting. In terms of structure or resiliency, while blockchain represents an opportunity to create resiliency through decentralization, it has been implemented as separate simulations that do not strategically integrate or manage other decentralized systems. Therefore, to leverage technology in order to provide a structural answer to this problem, we have employed a sequential two phase approach. In Phase 1, macroscopic forecasting is used to forecast the research literature (2020-2026). These results were then utilized to identify fragmented institutions and converge at the macro level in terms of technology. In Phase 2, as part of our Design Science Research (DSR), we created a new type of architecture by utilizing our findings as input into our DSR process. We introduced the theory of Algorithmic Dynamic Capabilities. We demonstrated how combining IoT for autonomous data collection/processing (sensing); permissioned distributed ledgers for cryptographic seizure; Artificial Intelligence for predictive transformation; allow for networks to dynamically absorb, respond to and recover from disruption. Our framework is intended to elevate decentralized architectures from being passive IT tools that support inter-organization governance, to be active agents of inter-organization governance. Overall, our study provides managers/policymakers with a practical and deployable framework which will assist in overcoming collaboration barriers; ensuring compliance with all applicable regulations globally; and providing assurance to the origin of life saving medications.

Keywords: technological forecasting, technology management, technology governance, blockchain technology, internet of things, decentralized traceability

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1. Introduction

The global pharmaceutical supply chain is a mission critical logistics network that disruptions in operations cause significant socio-economic and health crises (Goodarzi et al. 2020; Kochakkashani et al. 2023). This critical system for society still has a very high degree of fragility due to poor inter-organizational coordination and vulnerability to macro-shocks (Privett and Gonsalvez 2014). To mitigate failures within the system requires going beyond traditional logistics to forecast and materialize resilient architectures and technological driven systems with continuous adaptation.

1.1. The Vulnerability of Pharmaceutical Ecosystems

The structural vulnerability of the global pharmaceutical supply chain has been clearly illustrated by the global impact of the COVID-19 pandemic on the global pharmaceutical supply chain. The COVID-19 pandemic created an unprecedented global crisis which caused total collapse of the global supply chains. The collapse of these global supply chains revealed severe shortcomings with the legacy tracking systems for monitoring inventory and also demonstrated that legacy supply chain infrastructure is not capable of absorbing or responding to significant

and/or systemic disruption (Miller et al. 2021). The inherent vulnerability of the global pharmaceutical supply chain was further exacerbated by its physical nature. In addition, there were many problems related to the rapid and global distribution of unique and temperature sensitive medical products i.e., advanced biologics and mRNA based vaccine products, throughout cold chain distribution. As a result of this failure in logistics, a substantial number of therapeutically relevant products were spoiled. These product losses occurred primarily as a direct consequence of a lack of knowledge about the environmental conditions (and visibility) at each tier of complex, multi-tiered global supply chain networks (Parast et al. 2026).

The increased frequency and severity of both environmental and logistical disruptions to supply chain operations have been exacerbated by a rapidly increasing number of fake or counterfeited medical products. Traditional, opaque, and fractured drug delivery systems present broad opportunities for fraudsters to remain undetected in their illegal activities; counterfeit drugs continue to infiltrate traditional, legitimate distribution networks with great regularity (Mackey et al. 2015). Recent studies have reported that since the pandemic, there has been a rapid increase in the infiltration of substandard and falsified medicines into the global healthcare system; previously thought to be minor operational inefficiencies are now recognized as significant risks to global patient safety and public health (Syed and Milburn 2024; Gomasta et al. 2023).

This urgent convergence of a systemic fragility crisis and an increasing threat from counterfeiting has caused public health organizations and government agencies to establish strong mandatory regulations for all industries in order to force drastic increases in the transparency of industry. The graphic representation shown in Figure 1, illustrates how the pharmaceutical industry is under extreme pressure from two opposing forces at present; exogenous shocks that are rapidly increasing (top track), and legal mandates that will be strictly enforced (the bottom track).

Figure 1: Timeline of Exogenous Shocks and Regulatory Mandates (2020–2026)

The WHO called upon all nations to immediately implement traceability protocols as demonstrated by the timeline. All regulatory bodies worldwide have since imposed strict regulations concerning product serial number tracking (Melia et al. 2024). In the United States, the U.S. Food and Drug Administration's (FDA) Drug Supply Chain Security Act (DSCSA) implemented an absolute deadline of 2023 requiring drug manufacturers to be able to electronically track their products at the packaging unit level via interoperable software (Sarkar 2022). Further, it is now clear that the need for a regulatory stability period into 2024 has proven that legacy central computerized database platforms cannot meet the required level of interoperability. As illustrated by Figure 1, the pressure from both directions indicates that there will ultimately be a convergence point in 2026. Therefore, for companies to remain viable during this time of unprecedented volatility and satisfy their decentralized requirements, they can no longer depend solely on disparate data bases. Companies must adopt decentralized, non-trust based inter-organization ledgers or risk being out of compliance.

1.2. The Decentralized Imperative: Forecasting Technological Convergence

The increased number of external shock events and increased regulatory requirements have shown that there is an inherent weakness within existing legacy IT infrastructures. Legacy IT architectures have historically used central databases for tracking and distribution management in the pharmaceutical industry. However, centralized architectures can never be scaled to meet the current size of the global pharmaceutical supply chain's needs for interoperability and security. Data in centralized

architectures is always segregated into separate data silos, resulting in extreme information imbalance or asymmetric information; where all relevant parties cannot see the entire end-to-end process and history (provenance) of the data (Musamih et al. 2021). In addition, given the complexity of most multi-participant ecosystems, using a centralized approach will never ensure that the origin and processing history of products are secure, thereby increasing risks to patients' safety, as well as financial risks and failure to comply with regulations (Vasileiou et al. 2025).

Therefore, the move toward decentralized technology cannot simply be seen as an operational improvement; it is now an absolute structural necessity in order for organizations to survive and remain compliant with regulations. Blockchains that are permissioned and consortium-based address the failure of centralized systems through a tamper-proof, distributed ledger. Platforms like Hyperledger Fabric allow private, permissioned networks to be established among various stakeholders in the pharmaceutical industry (e.g., manufacturers, distributors, etc.) that provide secure, decentralized execution of track-and-trace functionality that does not require a single monopolistic entity controlling all the data exchange (Uddin 2021). The key benefit of this decentralized cryptography is the ability to fulfill strict regulatory requirements for exchanging data while also providing end-to-end protection of the entire cyber-physical supply chain from evolving threats and ensuring automated compliance (Mylrea and Gourisetti 2018). However, to successfully accomplish the paradigm shift described above, ensuring the integrity of the digital audit trail constitutes only half of what is needed. Therefore, the blockchain network must be fully merged with the Internet of Things (IoT) to ensure that there are no questions about whether or not the medical products being transported physically exist. This critical link between the two Industry 4.0 technologies enables both the autonomous collection of real time environmental data via IoT sensor systems and provides immutable anchoring for this collected data to avoid the loss of product due to cold chain spoilage or counterfeiting (Chen et al. 2023). Ultimately, the depth of connectivity between IoT sensor systems and blockchain networks will transform the pharmaceutical supply chain from a fragmented reactive tracking system to a unified, highly resilient digital ecosystem (Al-Banna et al. 2023) which is exactly what was necessary to provide an established base for an evolved self-governing supply chain able to function within the hyper-volatile environment of the post-pandemic world.

1.3. Ontological and Epistemological Foundations

To establish a theoretically consistent framework for the convergence of strategic management and

technology, this study relies on the pragmatic paradigm. While most previous studies are limited to identifying or recording what currently exists ("what-is"), pragmatism states that an idea has value based upon both its consequences and potential for constructing the desired future ("to-be") (Goldkuhl 2011). The lack of traceability data within fragmented global pharmaceutical supply chain systems is a condition needing to be actively intervened with; it is not simply something to be observed (Goldkuhl 2011). Therefore, DSR is utilized as a methodology and considers the construction of useful and effective solutions for problems equal in importance to theoretical correctness (Goldkuhl 2011).

Ontologically, this study understands technological artifacts, more specifically, the combination of blockchain and the Internet of Things (IoT) as not merely a non-active IT infrastructure; but rather as an actively constructed artifact to support these practical problems (Weigand et al. 2021). In terms of the Design Science Research (DSR) ontology for this study, blockchain based technology acts as "artifact universals" with certain capabilities that enable bridging of the make context and the use context (Weigand et al. 2021). By applying strategic management frameworks on top of a decentralised architecture it has been assumed that inter-organisation trust and resilience can be engineered through algorithms. As such, the proposed artifact conceptualised here as "Algorithmic Dynamic Capabilities" is assessed via how well it performs practically regarding its capability to realise technological innovation, transform supply chains from simulated silos into an integrated network and generate highly positive use effects in practice (Goldkuhl 2011; Weigand et al. 2021).

1.4. Research Gap and Objectives

Although it is widely agreed that a decentralized architecture of systems is necessary; however, the research on this topic is still highly fragmented. In other words, some authors have studied blockchain as a completely independent technological artifact (a kind of IT thing) while others propose abstract conceptual models in which they do not provide actual design architectures (Wang et al. 2019; Ghadge et al. 2023). The isolation of these approaches has resulted in an inability to implement inter-organizational resilience within unstable healthcare networks.

To address the theoretical gap, and bring into technological innovation, this research employs a sequential, two-phase research design. Macro-forecasting (Donthu et al. 2021) is employed in Phase 1 to provide an objective means of defining the structural boundaries of the domain; and providing insight into how themes within the domain have evolved in response to macro shocks that have

occurred recently. The purpose of empirical analysis conducted during Phase 1 is simply to diagnose where we are today. Strategic Management (Sullivan et al. 2023) is used to support development of a Design Science Research (DSR) framework in Phase 2. This DSR framework conceptualizes the intersection of Decentralized Technologies through the novel theoretical lens of Algorithmic Dynamic Capabilities. This analytical forecasting and architectural synthesis are directed by four of the below listed research questions:

- **RQ1.** What is the initial trajectory of publications and geographic locations for research on decentralized pharmaceutical supply chains between 2020 and 2026?
- **RQ2.** How do exogenous macro-shocks and global regulatory mandates affects the thematic evolution of the research literature?
- **RQ3.** To what degree has the research moved from isolated theoretical simulations to cross-disciplinary Design Science Research (DSR) networks?
- **RQ4.** In which ways, formerly separate technologies (e.g., Blockchain, IoT, Digital Twins) are integrating into single “Algorithmic Dynamic Capabilities” within multi-participant systems?

2. Theoretical Background

The research in use of distributed technology as an enhancement of supply chains is a developing area of study; however, the current literature is still fragmented with respect to structure. As can be seen from Table 1, previous reviews are primarily based upon descriptive approaches for development of conceptual classifications within health care, agricultural production, and logistics in general.

Although there is a comprehensive literature review for blockchain, this body of work has significant gaps. These foundational studies have universally evaluated blockchain solely as a passive Information Technology (IT), and not as a tool to enhance organizational resilience. More importantly, none of the foundational studies utilize or reference Strategic Management Theory. In addition, none of the foundational studies provide DSR architecture that can be used to operationalize the results of the research. This section establishes the theoretical basis for resolving the collective void of existing studies on blockchain technology. Rather than providing static descriptive analyses of blockchain use cases, this study elevates decentralized ledgers from passive tracking mechanisms to an active structural backbone. Moreover, it introduces the new theoretical framework of Algorithmic Dynamic Capabilities to enable and optimize pharmaceutical supply chain networks.

Table 1: Summary of Prior Literature Reviews and Identified Gaps

Reference	Application Domain & Scope	Primary Analytical Method	Core Theoretical Lens	Architectural Output	Unaddressed Gap
Qu et al. (2022)	General Supply Chain Management	Systematic Literature Review (SLR) and Content Analysis	Not explicitly stated	Synthesis of literature, mapping of applications, and a future research agenda	Treats blockchain as a disruptive IT application; lacks a functional DSR architecture and the lens of Algorithmic Dynamic Capabilities.
Chun et al. (2022)	Health care frameworks, prototypes, and implementations	SLR (PRISMA), bibliometric, functional, and technical analyses	Not explicitly stated	Bibliometric mapping, architectural taxonomy (One-CA, Multi-CA), and performance evaluations	Evaluates conceptual architectures but fails to provide a functional DSR framework; treats blockchain primarily as a technical enhancement.
Ka	Blockchain	Content-	Not	Identification	Treats blockchain

ur et al. (2022)	and IoT in Food Supply Chain Management (FSCM)	analysis-based literature review	technical issues, and regulatory barriers	of potentials, technical issues, and regulatory barriers	as an IT accessory rather than a core structural spine; lacks a DSR framework and strategic management theory.
Demestichas et al. (2020)	Agriculture and agri-food traceability	Extensive literature review	Not explicit	Taxonomy of concepts, chronological mapping, and future prospects	Evaluates blockchain merely as a traceability tool; fails to operationalize Algorithmic Dynamic Capabilities via a DSR architecture.
Park and Lim (2021)	Supply chain sustainability (ESG) in food and logistics	SLR combined with case study analysis	Not explicit	Conceptual evaluation of sustainability indicators and a research agenda	Treats blockchain as a digital database; fails to model algorithmic reconfigurations or provide a functional DSR architecture.
Dolguit et al. (2020)	Smart contracts in cyber-physical supply chains involving multiple	Mathematical modeling, dynamic control theory, and optimization	Not explicit	Bi-objective dynamic scheduling model and a BPMN-based	Treats blockchain primarily as an IT accessory to record feedback; lacks a formal DSR architecture bridging

0)	logistics providers	algorithm control	ed.	prototype	strategy and technology.
Chang and Chen (2020)	General SCM across diverse sectors (distribution, agriculture, pharmaceuticals)	SLR supplemented by descriptive and citation analysis	Not explicit	Literature blueprint highlighting critical issues (traceability, stakeholder involvement)	Treats blockchain primarily as an emerging information technology; fails to utilize Algorithmic Dynamic Capabilities to solve institutional fragmentation.

2.1. From Blockchain to Algorithmic Dynamic Capabilities

The global pharmaceutical supply chain has serious structural flaws which have been identified as major impediments to functioning in a decentralized fashion. Due to the opacity of multi-national networks counterfeit drugs are routinely able to enter legitimate markets and create substantial patient safety risks (Mackey et al. 2015). Furthermore, traditional logistics systems frequently suffer from tracking gaps when moving advanced biologics or vaccines that require strict temperature control, resulting in undetected temperature excursions and devastating spoilage (Ng et al. 2020). All of these failures are exacerbated by outdated central database architectures that lack end-to-end transparency and create dangerous single points of failure (Musamih et al. 2021). This architecture also fosters severe information asymmetry that traps stakeholders in isolated data silos that paralyzes their ability to synchronize performance (Ma et al. 2022) therefore resilient supply chains require seamless collaboration (Haque and Islam 2018), but centralized data monopolies create an unprecedented deficit of trust among inter-organizational entities and thus there needs to be a radical shift toward decentralized architectures.

To build up on trust in that way, permissioned blockchains create an immutable, decentralized record of all transactions as they occur, in effect creating a mathematically-secure environment where parties do not need to have intermediary organizations in order to trust each other (Malik et al. 2019). However, proving

what has occurred in the physical world is difficult using purely digital evidence. The inclusion of sensors via the Internet of Things (IoT), allows for real-time data from temperature and location sensors to be tied directly to a blockchain, thus providing environmental provenance (Singh et al. 2020). The integration of these two technologies enables a form of hybrid governance model (Khan et al. 2021), utilizing smart contract technology to automatically enforce business rules at runtime by removing manual intermediate entities (Bandhu et al. 2023). Furthermore, dealing with large amounts of IoT-generated data can be addressed through large-scale architectures such as Hyperledger Fabric (Khan et al. 2024), which supports both high-throughput data processing, along with protection of sensitive data, utilizing advanced encryption techniques.

Assessing this technology stack simply as an operational system for IT also fails to recognize the true value it holds strategically. When in a highly volatile environment, both information technology (IT) systems and knowledge management systems are the main enablers of an organization's ability to adapt to changing conditions through their development of dynamic capabilities (Sher and Lee 2004), which include sensing opportunities for growth, seizing them, and then rapidly configuring internal and external resources. As such, the utilization of a blockchain is a systemic capability that enables networked organizations to better absorb shocks and create profound levels of inter-organizationally based resiliency (Pattanayak et al. 2023). Therefore, it can enable sustainable, circular supply chain practices (Meier et al. 2023).

In line with Teece et al. (1997) strategic paradigm for dynamic capabilities, IoT sensor technology operationalizes the sensing dimension by autonomously monitoring the environment for environmental deviation (Sullivan et al. 2023). Simultaneously, smart contract can provide the ability to quickly execute the transform and seizure dimensions. However, a number of authors have noted that digital supply chain strategy will be dependent on embedded advanced analytics to allow institutions to strategically manage dynamic institutional pressure (Gupta et al. 2020), therefore enabling the continuous self optimization of the network through autonomous integration of predictive machine learning algorithms with immutable ledger data to autonomously trigger smart contract execution. The combination of distributed trust, physical sensing and machine intelligence represent an evolutionary advancement in strategic theory which we define as Algorithmic Dynamic Capabilities, this concept forms the basis of our proposed architecture.

2.2. Design Science Research (DSR) in Supply Chains

Traditional behavioral studies focus upon describing and explaining current phenomena; however, achieving a resolution for the long-standing institutional fragmentation within the pharmaceutical supply chain will require an applied, solution-focused approach. Therefore, the present study employs Design Science Research (DSR), as it bridges the analytical-practical divide by providing a way to develop novel IT artifacts that address identified, real-world organizational challenges. In order to provide the most robust possible foundation from which to construct our proposed architecture, we have followed the standard DSR process model, as described by Hevner et al. (2004) for IS DSR. The process is comprised of identifying problems, defining objectives, designing artifacts, and evaluating concepts (Peffer et al. 2007).

The complexity inherent in a supply chain network as a sociotechnical environment, requires methodologies to create the structure for an organization's multi-tiered, inter-organization architecture. The recent development of DSR methodology emphasizes the use of design echelons to decompose complex problem spaces into logical and coherent manageable parts that do not lose focus on the overall system (Tuunanen et al. 2024). Researchers have been using structured DSR approaches in modern supply chain management to develop conceptual artifacts and technical frameworks for enhancing real time inbound logistics, optimizing virtual stock management, and establishing supply chain visibility (Kalaivasan et al. 2023).

The majority of the literature suggests that Design Science Research (DSR) is currently the most effective way to create and implement a Blockchain enabled Supply Chain Architecture. In addition to creating designs for blockchain based collaborative networks, DSR was also able to facilitate design science research to be used in developing smart contract based information systems which were capable of resolving issues related to asymmetric information (Wang et al. 2021), and creating machine-human reconciliation processes through mathematical means to increase consumer confidence across borders (Cao et al. 2021). Additionally, the use of DSR allowed researchers to engineer blockchain architectures that were designed to provide for both horizontal and vertical collaboration among multiple logistics providers with no need for central intermediates (Alacam and Sencer 2021).

This is especially important in health care, where DSR offers the discipline needed to develop stakeholder-focused blockchain systems that protect very private information like electronic health records, and comply with regulations (Beinke et al. 2019). This article

builds on existing methods for conducting research and uses section 4.2 of this study to synthesize the results from our empirical bibliometric analysis into a new conceptual artifact. Using DSR methodology, we can use the empirical evidence to identify patterns among the fractured technology clusters. Therefore, we constructed the Proposed DSR Framework for Algorithmic Dynamic Capabilities (see Figure 8) which is an operational architecture to implement the theoretical potential of blockchain and IoT to build a reliable, resilient, deployable ecosystem for pharmaceuticals.

3. Methodology: A Two-Phase Approach

To make technological innovation in decentralized pharmaceutical supply chain, we adopted a sequential, two-phase method. In phase one, the research uses macroscopic bibliometric forecasting to objectively track the structural changes and convergence of Blockchain and Internet of Things using large databases (Han et al. 2020; Kumar 2025). These macro-level insights are used as the base data layer. The second phase uses the results from the first stage as part of a Design Science Research (DSR) framework to develop a new model for Algorithmic Dynamic Capability.

3.1. Study Design: Forecasting and Artifact Construction

This study employs an empirical, quantitative bibliometric methodology to depict the intellectual structure and interdisciplinarity within decentralized pharmaceutical supply chain literature. In order to maintain methodological transparency; in addition to ensuring that findings can be replicated by others; in accordance with the standards of highest quality scholarship; the findings of this study are constrained by the “Guidance List for the repORting of Bibliometric AnaLyses (GLOBAL)” (Ng et al. 2026). The use of the GLOBAL reporting framework minimizes reporting bias through systematic documentation of search strategies, mapping parameters, and evaluation criteria.

The steps followed in the execution of this analysis are as per the four step bibliometric workflow proposed by Donthu et al. (2021) which has been supplemented by current standards on handling a large dataset (Kumar 2025). These sequential steps include; (1) establishing the objectives of the interdisciplinary research, (2) identifying reliable sources of information from the database(s) used and developing the dataset, (3) analyzing performance and structuring a scientific map, and (4) determining how the network results provide direct answers to the research questions. In addition, the entire data curation process including all of the validation of metadata and the classification of themes were performed manually by authors. Manual oversight is essential to achieve high accuracy levels

in classifying nuances that exist within an interdisciplinary study such as “Blockchain Technology” within a body of literature, eliminating the potential for errors created through use of automated tool processes.

Theoretically based on the Design Science Research (DSR) methodological approach due to the fact that this research paper will track the transition from theory-based models to practical, multi-party systems. DSR offers an idealized design process model for the development and assessment of new, innovative Information Technology products i.e., integrated blockchain, smart contract, and Internet-of-Things technology solutions, developed to address real world, complex organization-wide issues (Peffer et al. 2007). This study uses bibliometric mapping using a DSR perspective in order to provide objective visualization of how previously separate technological silos have coalesced into fully tested, and effective algorithmic dynamic capabilities within the supply chain domain.

3.2. Phase 1: Literature Search and Human-Led Data Curation

Data gathering was done using the Scopus and Web of Science (WoS) Core Collection databases. The WoS is one of two databases that are considered to be among the top sources in their respective fields. This repository provides high quality metadata and indexing for accurate structural science mapping (Singh et al., 2021; Amofa et al., 2023). A Tri-Partite Boolean Logic Framework (Table 2) was used as part of our search strategy to include all possible combinations of Decentralized IT (Blockchain, Smart Contracts), Pharmaceutical Constraints (Cold Chain, Vaccines), and Supply Chain Functionalities (Queiroz et al. 2020; Franco and Alfonso-Lizarazo 2017). We included the time frame from 2020-2026 as we wanted to document how technology has grown due to recent outside influences on technology (Exogenous Macro-Shocks). Our search parameters were limited to Peer-Reviewed Articles written in English and published within 6 years of when this research was completed (Ng et al. 2026; Donthu et al. 2021).

Table 2: Database Search Protocol

Parameter	Scopus	Web of Science (WoS) Core Collection
Field Tags	TITLE-ABS-KEY (Title, Abstract, Keywords)	TS (Topic: Title, Abstract, Author Keywords, Keywords Plus)

Parameter	Scopus	Web of Science (WoS) Core Collection
Boolean Search String	TITLE-ABS-KEY (("blockchain*" OR "distributed ledger*" OR "DLT" OR "smart contract*" OR "hyperledger" OR "Ethereum" OR "decentrali* network*") AND ("pharmaceutic*" OR "pharma*" OR "medicine*" OR "drug*" OR "vaccine*" OR "biopharma*" OR "cold chain*" OR "cold-chain*") AND ("supply chain*" OR "logistic*" OR "traceab*" OR "provenance" OR "track and trace" OR "distribution network*")) AND PUBYEAR > 2019 AND	TS=(("blockchain*" OR "distributed ledger*" OR "DLT" OR "smart contract*" OR "Hyperledger" OR "Ethereum" OR "decentrali* network*") AND ("pharmaceutic*" OR "pharma*" OR "medicine*" OR "drug*" OR "vaccine*" OR "biopharma*" OR "cold chain*" OR "cold-chain*") AND ("supply chain*" OR "logistic*" OR "traceab*" OR "provenance" OR "track and trace" OR "distribution network*")) AND PY=(2020-2026) AND DT=(Article OR

Parameter	Scopus	Web of Science (WoS) Core Collection
	PUBYEAR < 2027 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re")) AND (LIMIT-TO (LANGUAGE , "English"))	Review) AND LA=(English)

To ensure that there was no bias introduced by the use of algorithms and to guarantee the integrity of methodology, all of the data underwent a strict, exclusively human led curation process which is well-documented as per the PRISMA 2020 guidelines (Page et al. 2021) (see Figure 2). Manual deduplication of an original 1114 documents resulted in removal of 419 duplicate documents. No automated citation manager (e.g. Zotero, Rayyan.ai) was utilized; therefore, subsequent citation weighting was not artificially increased (McKeown and Mir 2021). Additionally, 11 retracted documents were manually removed from the set so as to maintain the theoretical validity of the network (Teixeira da Silva et al. 2025). A further human led title and abstract screening procedure identified and eliminated 434 false positives; thus, providing for accurate and reliable identification of the interdisciplinary boundaries which are commonly incorrectly identified by automated algorithms (Agnello et al. 2023). Lastly, manual DOI metadata verification eliminated 14 additional structural document records that were deemed incompatible with the established mathematical framework; ultimately, yielding a mathematically correct forecasting data set consisting of 236 individual documents (Franceschini et al. 2015).

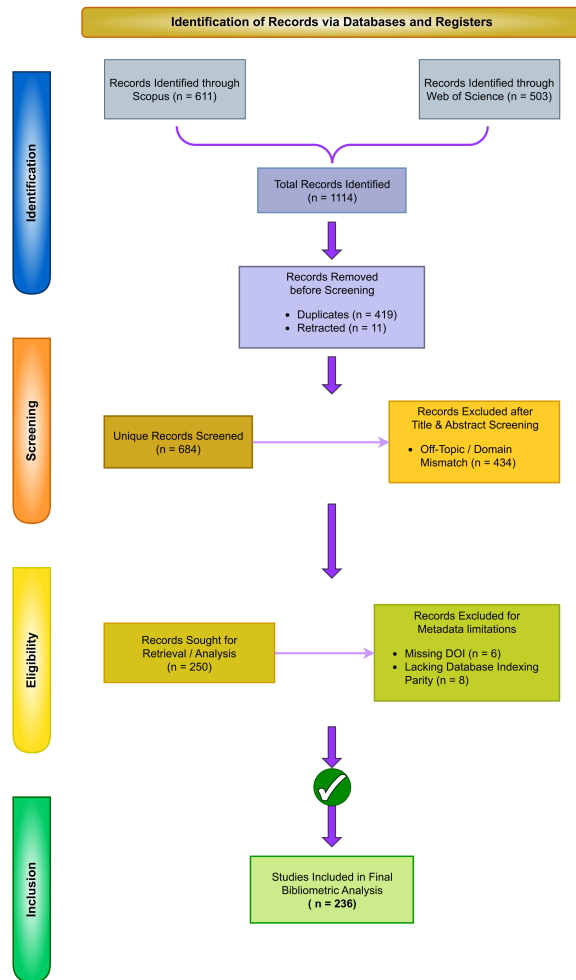


Figure 2: PRISMA 2020 Flow Diagram

To analyze the corpus of data as well as predict future thematic shifts in the discipline, the software tools Biblioshiny (the bibliometrix R package) (Aria and Cuccurullo 2017) and VOSviewer (Van Eck and Waltman 2010), were used. The Louvain clustering algorithm (Cobo et al. 2011) was chosen for its ability to identify thematic sub-domains within a given field without artificially creating overlapping areas. Additionally, fractional counting was applied to both co-authorship and keyword co-occurrence networks so that mathematical normalization could be applied to link weights; thereby preventing extremely collaborative research papers from altering the actual structure of the field of study (Perianes-Rodriguez et al. 2016; Zupic and Čater 2015). These specific forecasting parameters ultimately allowed us to visually map the existing inter-organizational “simulation silos”, therefore allowing us to expose the necessary structural gaps to architect the Algorithmic Dynamic Capabilities artifact in Phase 2.

3.3. Phase 2: DSR Artifact Design Parameters

In building on the structural deficiencies and technological convergences outlined in Phase 1; Phase

2 is to be used for the creation of an Design Science Research (DSR) artifact. The artifact was built according to general principles of DSR (Hevner et al. 2004). It was specifically designed to address a highly significant socio-technical problem, that being the fragmentation of inter-organizationally based trust as well as the existence of numerous silos or isolated simulation systems throughout the world-wide pharmaceutical supply chain.

The most important goal in developing the architecture was to bring the theory of Algorithmic Dynamic Capabilities into being. In order to do that, we had to map traditional strategic management models concerning organizational resiliency from Teece et al. (1997) onto a technology based distributed architecture. Mapping these traditional models onto our new architecture gave us three parameters to consider when creating our blue print.

- **Autonomous Sensing (IoT Telemetry):** Our system needed an ingestion level that could ingest real time sensor readings (i.e. temperature) without human interaction so it could replace the current method of manual input with an immutable record.
- **Algorithmic Seizing (Smart Contracts):** We need to have smart contracts that can automatically determine if the sensor reading is compliant with applicable laws/mandates (FDA DSCSA, EU FMD etc.). If there are issues due to shocks that happen at a macro-level, then these smart contracts will be able to quickly take action.
- **Decentralized Transformation (Distributed Ledger Architecture):** Since we wanted our architecture to allow for global collaboration across borders, we decided on using Hyperledger Fabric. We chose Fabric because it has better performance than legacy frameworks like Hyperledger Composer that have scalability issues. Additionally, Fabric has the capability to handle large amounts of dynamic data from multiple organizations while providing a clear distinction through use of Next Block Hashes and therefore has the ability to maintain consistent states at high throughput rates necessary for pharmaceutical tracking systems around the world.

By setting such high standards of rigor as to how they are defined, this research can ensure that the DSR framework it develops in Section 4.2 has developed into something that is not simply a theoretical model; however, through its technical viability, and structural integrity it becomes a viable plan of action for both technological governance and managerial use.

4. Results

The curated dataset of 236 documents underwent computational analysis with the purpose of forecasting technological convergence. Phase 1 was conducted in accordance with recognized methodological protocols (Donthu et al. 2021). In this context, Section 4.1 provides an overview of the major macroscopic findings from Phase 1 regarding the thematic progression and structural fragmentation of the field. The results from Phase 1 form a basis for the primary scientific contribution made in Phase 2. Section 4.2 outlines that contribution, architecturally designing a new Design Science framework for Algorithmic Dynamic Capabilities designed to address these identified gaps.

4.1. Phase 1 Insights: Bibliometric Forecasting and Science Mapping

This subsection describes the macroscopic forecasting that was completed as part of phase 1. The use of the trajectories, thematic shift, and institutionally dynamic aspects of the literature allowed for an empirical validation of the existence of isolated “simulation silos”, and identified the technology convergence needed to create the design science artifacts subsequently.

4.1.1. Performance Trajectory and Geography

The longitudinal trajectory for the 236 curated documents shows clearly that research on decentralized pharmaceutical supply chain is progressing with increasing rapidity. As illustrated by the data presented in both Table 3 and Figure 3, the domain has experienced a Annual Growth Rate (AGR) of 11.29%.

Table 3: Annual Scientific Production Data

Year	Articles
2020	10
2021	29
2022	29
2023	41
2024	39
2025	69
2026	19*

Note: 2026 represents a partial indexing year.

Annual Growth Rate: 11.29%. Peak Year: 2025

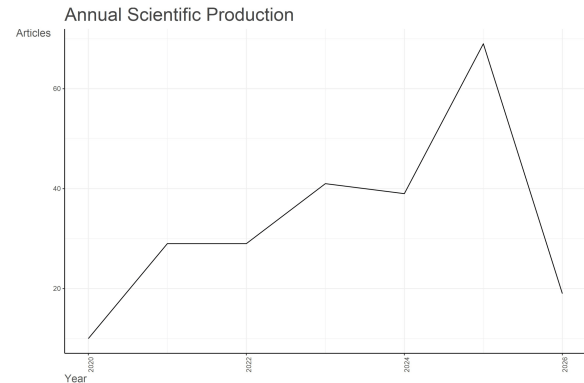


Figure 3: Annual Scientific Production Growth Trend

An initial, pre-pandemic baseline was consistent with an earlier, theoretical view of supply chains (Sunny et al. 2020); however, a clear structural increase in the amount of literature published on this topic, as well as other related topics, occurred after 2023 when the entire global pharmaceutical industry came together to address the many vulnerabilities created by the COVID-19 pandemic. As such, research began to move away from focusing solely on detecting counterfeits via blockchain technology (Trautmann et al. 2024) toward developing full-fledged implementation frameworks for utilizing blockchain-based technologies (Ghadge et al. 2023). To illustrate how these fields have developed over time a Three Fields Plot (See Figure 4), which illustrates the proportionate flow of publications among productive countries, authors, and keywords is provided.

Figure 4: Three-Fields Plot - Countries to Authors to Keywords

Figure 4 illustrates significant geographic centralization in the output volume. The UAE, China, and India are the top hubs with respect to their production volumes. Although keywords appear throughout the map, the concentration of keywords along the right-hand edge of the map clearly illustrate that the technological stack is comprised of a single Core set of technologies: “blockchain”, “ethereum”, “traceability”, “supply chain”, “smart contracts”, and “security”. These define the baseline for measuring Structural Convergence within this Field.

4.1.2. Thematic Evolution and Institutional Landscape

The thematic development analysis established that the intellectual structure of the industry had evolved through a transition from a crisis response (2020-2023) to technological maturity (2024-2026), as depicted in Figure 5.

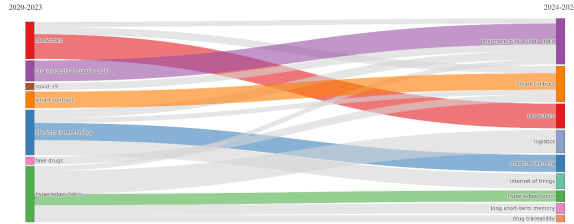


Figure 5: Thematic Evolution Map – Pre-2023 vs. Post-2023 Shift

At first, the network's landscape was based on foundational permissioned architectures that are referred to as “hyperledger fabric”, in order to provide initial data provenance (Musamih et al. 2021) of the network. By post-2023, the network has experienced a significant divergence. The emergence of “internet of things” represents an evolution toward the inclusion of a physical layer of sensors for active temperature sensing (Turki et al. 2023), while the presence of “machine learning” indicates an evolutionary change toward the use of machine learning-based algorithms for predictive optimization (Omidian 2024).

However, mapping the institutional co-authorship structure illustrates an important contradiction. Although certain institutions have generated high numbers of citations to what can be called foundational literature (Table 2), these same institutions' ability to collaborate with others is very limited (Figure 6).

Table 4: Institutional Collaboration Metrics (Top 20 Organizations)

Organization	Documents	Citations
Department of Electrical Engineering and Computer Science, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates	5	426
Department of Industrial and Systems Engineering, Khalifa University of Science and Technology, Abu Dhabi, United Arab Emirates	5	426
School of Business, Nanjing Audit University, Nanjing, 211815, China	3	49
Department of Electrical Engineering, COMSATS University Islamabad, Islamabad, 45550, Pakistan	2	0
Department of Information Systems, King Abdul Aziz University, Jeddah, Saudi Arabia	2	0
Department of Math and Computer Science, Brandon University, MB, Canada	2	52
LedgerDomain, Las Vegas, NV, United States	2	26
Muroran Institution of Technology, Department of Sciences and Informatics, Muroran, 050-8585, Japan	2	16
Research Centre for Interneural Computing, China Medical University, Taichung, Taiwan	2	52
School of Business, Central South University, Changsha, 410083, China	3	140
School of Logistics and Transportation, Central South University of Forestry and Technology, Changsha, 410004, China	2	38
UCLA Health, Los Angeles, CA, United States	2	26
Zhengzhou University of Light Industry, College of Food and Bioengineering, Zhengzhou, 450001, China	2	16
Zhengzhou University of Light Industry, College of Software	2	16

Engineering, Zhengzhou, 450001, China		
College of Software Engineering, Zhengzhou University of Light Industry, Zhengzhou, 450001, China	3	10
Department of Computational Sciences, Brainware University, West Bengal, Kolkata, India	2	7
Department of Computer Science and Engineering, Institute of Technology, Nirma University, Gujarat, Ahmedabad, 382481, India	2	7
Department of Computer Science and Engineering, National Institute of Technology, Himachal Pradesh, Hamirpur, India	2	33
School of Computer Engineering, KIIT Deemed to be University, Odisha, Bhubaneswar, India	2	269
School of Computer Science and Engineering, VIT University, Tamil Nadu, Vellore, 632104, India	2	14

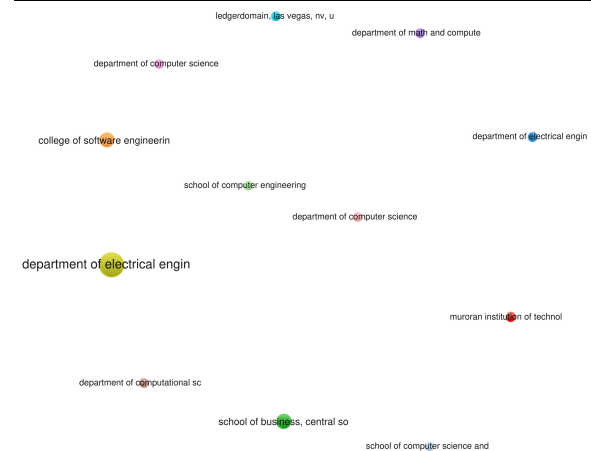


Figure 6: Institutional Co-authorship Network – Visualizing Scattered Simulation Silos

Rather than an interconnected web, Figure 6 illustrates a collection of discrete nodes that exist in isolation or operate as separate silos for simulation purposes. Each highly referenced hub such as Khalifa University (Uddin et al. 2021; Yaqoob et al. 2022) and Central South University (Chen et al. 2023) has a cross-institutional link strength of zero. Since all decentralized ledger technologies depend on multi-actor consensus, this organizational disconnection represents a significant vulnerability; i.e., the current body of literature consists almost exclusively of localized agent based simulations (Lohmer et al. 2020) and lacks deployable inter-jurisdictional architectures.

4.1.3. Technological Convergence Mapping

While institutional structures are still in some degree of disarray, this can be seen as evidence through the keyword co-occurrence mapping (see Figure 7) that the basic technology is moving toward an increasingly unifying, interdisciplinary stack.

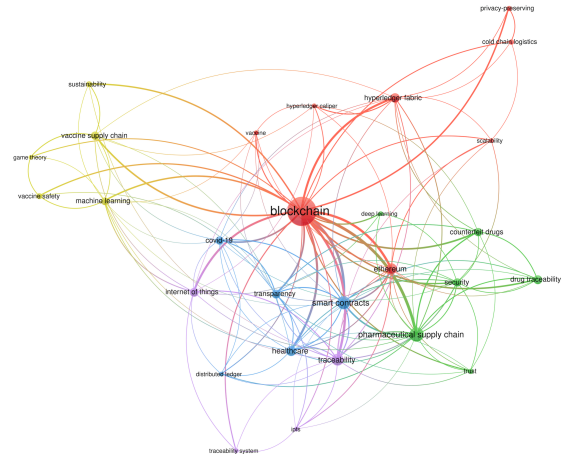


Figure 7: Keyword Co-occurrence Network – The 5 Integrated Color Clusters

The algorithm-based mapping illustrates a new ecosystem that consists of five interconnected areas (Bodkhe et al. 2020) — the Red Cluster has an underlying system for permissioned ledgers (“blockchain”, “cold chain logistics”); the Purple Cluster is connected to it through a mathematical validation process in the direction from the blockchain to autonomous IoT sensors that perform the same temperature monitoring tasks (Singh et al. 2020); the Blue Cluster (“smart contracts”, “healthcare”) acts as the algorithmic governance level which executes automation of compliance; finally, the Green and Yellow Clusters are at their maximum maturity level and they combine AI (“machine learning”) with drug tracking (“drug traceability”) to create proactive security models (Abbas et al. 2020).

The results from this phase 1 confirm that although the technological building blocks to enable resilient communities are in existence, there is currently a theoretical gap in their application as well as a physical separation (silos) within which these building blocks reside. Therefore, this study will need to develop a second phase or blueprint, the “Algorithmic Dynamic Capabilities” framework; that provide a mechanism to integrate all elements into a single model.

4.2. Phase 2: Architecting the DSR Framework for Algorithmic Dynamic Capabilities

Bridging isolated “simulation silos” as described by the Phase 1 forecasting requires a solid architectural blueprint. Therefore, we define an artifact for Design Science Research (DSR) based on Teece et al. (1997) strategic paradigm. This framework defines the new concept of “Algorithmic Dynamic Capabilities”, or the

ability of a decentralized network to identify disruption, cryptographically capitalize on it, and algorithmically transform its operation (Figure 8).

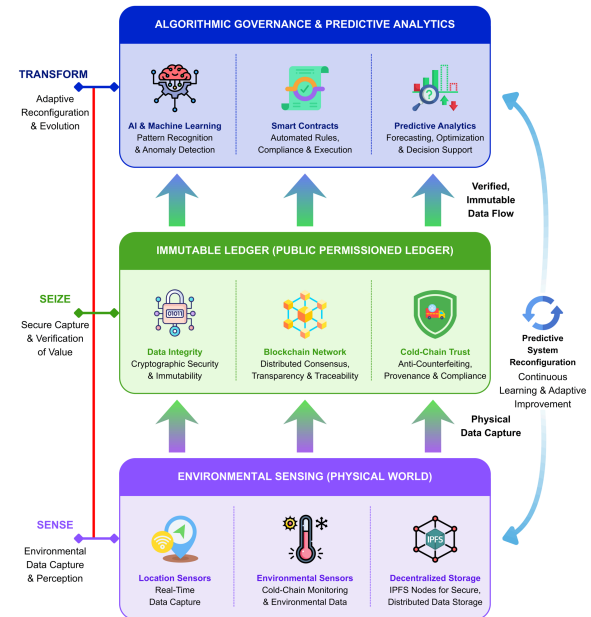


Figure 8: Proposed DSR Framework for Algorithmic Dynamic Capabilities

Layer 1 (Autonomous Sensing) enables environmental sensing as a means of providing a platform for the use of advanced Internet of Things (IoT) technology to collect and transmit temperature-sensitive logistics information in real time, cold chain telemetry (Sharma et al. 2020). In order to ensure that network performance is scalable despite an ongoing stream of data being received from various sources; The artifact has utilized the Interplanetary File System (IPFS) for decentralized off-chain storage (Azbeget al. 2022).

In Layer 2 (Cryptographic Seizing) Blockchain is the Immutable Structural Backbone. It is essential that to manage a complex, multi-actor supply chain data matrix, the DSR parameters strictly prefers Hyperledger Fabric vs. legacy frameworks such as Composer. Fabric Architecture provides exact cryptographic distinctions in regards to Next Block hashes enabling cross-border trust and preventing counterfeit entries into an organization’s inter-organization data (Malik et al. 2018; Peron et al. 2025).

The ability of network to continue adapting in real time is enabled through Smart Contracts which provide automatic enforcement of all compliance regulations (Chang et al. 2019). Through the integration of Artificial Intelligence within an immutable ledger, machine learning algorithms can analyze validated data to identify emerging anomalies (Chithanuru and Ramaiah 2023) and thereby enhance proactive optimization of procurement (Yadav and Singh 2025).

Through embedding predictive AI as the apex driver (Wang et al. 2026), Layer 3 (Algorithmic Transformation), enables autonomous trigger for reconfiguring of Layers 1 enabling macro-shock resilience throughout the entire supply chain ecosystem.

5. Discussion: Materializing Technological Innovation

A feasible solution to bridge the institutional “simulated silos” from Phase 1 exists with an architectural blue print that can be implemented using the Algorithmic Dynamic Capabilities framework (see Section 4.2). Since a decentralized ledger requires multiple actors to collaborate on developing true supply chain transparency (Francisco and Swanson 2018), just as a simple computer system cannot achieve such objectives by itself; therefore, simply having technology sophistication does not meet the requirements. The theory behind this tool is synthesized within this section, providing actionable decision options for managers attempting to transform their companies through technology, identify the necessary policy governance structures needed to support them and define a strategic research agenda to create inter-organizationally resilient systems.

5.1. Synthesis: The Shift from Simulation Silos to Algorithmic Capabilities

The empirical gap established through Phase 1’s findings of technological convergences being blocked by institutional fragmentation creates an important theoretical void within the contemporary body of literature surrounding Supply Chain Management. This void has resulted from simulation research being conducted in regional or localized silos to date; thereby hindering these studies from achieving the structural compatibility necessary for implementation into actual supply chains. To bridge this divide, the DSR artifact developed in Section 4.2 represents a significant advancement over extant strategy development theories by providing a tangible representation of “Algorithmic Dynamic Capabilities”.

The traditional strategic model such as the ERBV (Extended Resource-Based View) assert that firms need to have a shared capability with other firms in order to survive at all levels of competition (Yang et al. 2019). Exogenous macro-shocks require continuous structural adaptations to mitigate them, an idea first presented by Teece et al. (1997), who termed this as the human based process of being able to “sense”, “seize”, and “transform” one’s competences. Therefore, our study synthesizes theory suggesting that in decentralized, fast paced pharmaceutical network environments, Human Dynamic Capabilities (HDCs) are far too slow and fragmented to provide

sufficient resiliency (Bahrami and Shokouhyar 2022; Meier et al. 2023).

By applying the Teece et al. (1997) paradigm to a decentralized tech stack, this proposed solution engineers an algorithmic autonomous paradigm:

- **Algorithmic Sensing:** Instead of waiting for humans to report incidents, the environment can be sensed in digital format. IoT combined with IPFS (Internet Protocol File System) (Sharma et al. 2020; Azbeg et al. 2022) removes delay and subjectivity from receiving data that has been ingested by the network and allows the network to see the physical world as it occurs.
- **Cryptographic Seizing:** The traditional way of trusting a supply chain is vulnerable to friction due to institutions. Permissioned Distributed Ledgers (Malik et al. 2018; Peron et al. 2025) are used to anchor the architecture of the system, mathematically engineering cold-chain trust and preventing counterfeits from infiltrating while preventing private institutional boundaries from being exposed.
- **Autonomous Transformation:** The final theoretical evolution is to move from managing reactively to maintaining proactively. Smart Contracts (Chang et al. 2019) along with Predictive Machine Learning (Chithanuru and Ramaiah 2023; Yadav and Singh 2025) are used to parse immutable data, identify anomalies, and continue to optimize itself.

Ultimately, by integrating AI as the highest level of control (Wang et al. 2026), “Algorithmic Dynamic Capabilities” can be structured as an ongoing, reinforcing loop. The proposed model demonstrates that breaking through silos in institutional simulation is contingent on transitioning from static forms of IT systems to self-optimizing algorithmic systems.

5.2. Managerial Decisions for Technological Transformation

Executing the Algorithmic Dynamic Capabilities framework for pharmaceutical executives requires making significant decisions on organizational shifts. First, managers must re-evaluate how resources are allocated. The initial capital expenditure of legacy systems overhaul & deployment of IoT-sensors stacks is an adoption barrier (Jabbar et al. 2021). Executives must shift from viewing this infrastructure as a traditional it cost center to a strategic economic asset. Decentralized architectures enhance long-term economic sustainability by eliminating massive financial losses related to cold-chain spoilage and product recalls through algorithmic means (Munir et al. 2022).

The second imperative for executives is that they need to require an operational shift from self-contained, proprietary systems to collaborative relationships among organizations. The existence of “simulation silos” as identified through empirical analysis, demonstrates an important managerial failing: developing decentralized solutions without cross-organization interaction. Given that Distributed Ledger Technology (DLT) relies solely on the effect of the network, then cross border supply chain collaboration is a necessary condition for creating a network based on DLT (Rejeb et al. 2021). Therefore, in order to create this new technology, it is necessary for leaders in the pharmaceutical industry to provide capital to develop consortia including multiple stakeholders. By requiring commonality in technological development practices and protocols among competitive companies, vendors and distributors; Pharmaceutical Company Managers can make the decisions needed to remove barriers to deployment and migrate from laboratory proof of concept to deployable global networks (Kouhizadeh et al. 2021).

5.3. Technology Governance and Policy Implications

Beyond managerial strategy, the proposed DSR framework provides a mechanism for navigating the complex web of global regulatory governance. The prevalence of fake pharmaceutical products has led to strict policy mandates throughout the world, including in the United States with the Drug Supply Chain Security Act (DSCSA), and by the World Health Organization (Zakari et al. 2022). The Algorithmic Dynamic Capabilities framework directly operationalizes these legislative guidelines as it embeds smart contracts into Hyperledger Fabric. This results in automated reporting under regulations while establishing an unalterable cryptographic audit trail that guarantees the source of pharmaceutical goods. As such, it satisfies demands from all regulators for traceability of medicine over its entire value chain while locking counterfeits out of the legitimate supply chain (Uddin 2021).

The health care industry is further complicated by an additional governance paradox relative to the translation of immutable ledger technologies. This additional paradox relates to the tension that exists in the relationship between immutable ledger technologies and data privacy regulations; i.e., how can supply chain managers reconcile the fact that blockchain based systems maintain a permanent record of all transactions associated with those systems with strict regulatory requirements which mandate a “right to be forgotten” from both patients and other stakeholders (e.g., GDPR). The proposed artifact addresses this governance paradox by utilizing

architectural governance. Architectural governance allows for reconciling the above mentioned paradigm through the use of decentralized and privacy preserving architectures for off-chain data storage using IPFS. Hashes of sensitive patient and/or proprietary institutional data are stored on-chain only for purposes of verification (Dwivedi et al. 2019) while ensuring compliance with international anti-counterfeit policies through integration of advanced cryptographic identities (Cao et al. 2024)

5.4. Future Research Agenda

To prevent the proposed DSR artifact from becoming obsolete in future years, this subsection provides a systematic forecasting framework for technology. By establishing which paradigms are imminently emerging at the frontier of current knowledge, we can convert the Algorithmic Dynamic Capabilities model into a planning tool that encompasses long term strategies and resilient socio-technical governance approaches to support such efforts. Table 5 elaborates on these specific research questions and their underlying domains of technology.

Table 5: Strategic Future Research Directions

Research Domain	Specific Unanswered Research Questions (RQs)	Underlying Technologies
1. Cyber-Physical Synchronization	How can pharmaceutical supply chain virtual replicas proactively predict and autonomously mitigate cold-chain disruptions?	Digital Twins, Web 3.0
2. Decentralized Processing	How much does network-periphery computational consensus offloading reduce high-	Edge/Fog Computing, 5G/6G Networks

Research Domain	Specific Unanswered Research Questions (RQs)	Underlying Technologies
	frequency IoT sensor latency and energy?	
3. Advanced Cryptographic Privacy	How can competing pharma firms collaboratively train predictive AI without exposing sensitive proprietary data?	Federated Learning, Zero-Knowledge Proofs
4. Post-Quantum Resilience	What architectural reconfigurations will secure the immutable ledger against imminent quantum decryption?	Post-Quantum Cryptography, Quantum Key Distribution
5. Autonomous Inter-organizational Governance	Can code-based incentives and decentralized governance replace centralized regulators in global logistics?	DAOs, Tokenomics, Smart Contracts

The first imperative requires movement toward “Cyber-Physical Synchronization” by integrating

supply chain digital twins into larger Web 3.0 ecosystems. Networks can then move away from simply recording history and perform real time predictive simulation on the optimization of physical pharmaceutical logistics (Gai et al. 2022; Chang et al. 2022). Second, to solve bandwidth issues in all Global IoT Architecture, future research should look at “Decentralized Processing”. Investigate how much processing is done for environmental telemetry at the sensor periphery with edge computing and 5G/6G. This would be able to solve latent trust and data congestion crises (Hu et al. 2021; Srinivasu et al. 2021).

Third, removing barriers to competition from multiple actors requires “Advanced Cryptographic Privacy”. In order for competing companies to collaborate in training of predictive artificial intelligence systems using ZKPs and federated learning, the immediate empirical focus should be placed on developing methods that allow them to do so without revealing their proprietary transaction data while complying with patient confidentiality requirements (Sun et al. 2021; Singh et al. 2022). Fourth, the literature has an urgent need to recognize the “Quantum Threat” due to the fact that new developments in quantum computers have the capability to break many of the current consensus algorithms used by blockchains. Developing cryptographic primitives that are designed to function post-quantum will require significant governance efforts to ensure the long term integrity of all pharmaceutical provenance (Pulipeti and Kumar 2023; Fernandez-Carames and Fraga-Lamas 2020). Fifth, it will also be important for researchers to study “Autonomous Inter-Organizational Governance” through Decentralized Autonomous Organization (DAOs). By analyzing how decentralized autonomous organizations use automated tokenomics and smart contracts to enforce compliance they can create global supply chains which are independent of central regulatory agencies and function independently as resilient ecosystems (Faqr-Rhazoui et al. 2021; Nguyen et al. 2023).

5.5. Limitations

While this research has developed a robust framework, there are some limitations in terms of methodology to be considered when interpreting the results. Firstly, the scope of our data collection were limited to English language peer reviewed articles within Scopus and Web of Science databases. This is likely to have excluded other types of sources including grey literature and localised, non-English publications (Donthu et al. 2021; Diekhoff et al. 2013). Although we did limit ourselves to these two databases, it was a necessary limitation to allow us to maintain the pure metadata integrity needed to process the networks using the algorithms used in this research (Moral

Muñoz et al. 2020). Secondly, citation metrics are subject to a temporal bias; newer architectures published in 2025-2026 will appear less influential than their older counterparts that form the foundations upon which they build (Su et al. 2020).

To address both of the above limitations and provide a prospective perspective on the future direction of architecture, rather than just conducting a retrospective analysis, this research adopted a two phase design. In addition to citation metrics we utilised keyword co-occurrence tracking to identify emerging frontier technologies. These emerging technologies were then validated through the Phase 2 Design Science framework (Donthu et al. 2021). The boundaries identified here therefore do not undermine the structural validity of the proposed Algorithmic Dynamic Capabilities model.

6. Conclusion

In order to address growing concerns with vulnerabilities associated with pharmaceutical supply chain security, this study was able to deploy an interdisciplinary research method of two phases to develop models based on theory that could be used as deployable, multi-organization-based resilience. Phase 1 bibliometric analysis demonstrated a critical structural paradox: although the technological base upon which the simulations are built continues to converge, stakeholders continue to be confined within their individualized simulation silos.

To bring technological innovation to fruition and resolve this disruption of supply chains phase 2 architected a design science research framework for operationalizing “Algorithmic Dynamic Capabilities” by combining internet of things for autonomous sensing; permissioned ledgers with cryptographic seizing; and artificial intelligence for algorithmic transformation. By synchronizing these three components, this product enables networks to dynamically adapt and recover from extreme macro-shocks. Finally, as supply chains develop into industry 5.0 ecosystems that are highly resilient this framework provides managers and policy makers with the governance blueprint they need to establish trust through algorithmization and guarantee provenance of life-saving medical goods worldwide.

Declaration

Author Contribution: S. U. handled the conceptualization, methodology, software, formal analysis, data curation, original draft preparation, and visualization. P. D. provided supervision, project administration, validation, and review and editing. R. Y. contributed through investigation, resources, validation, and review and editing.

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