Next-Generation Inventory Management: Blockchain Solutions for Industry 4.0 Supply Chains

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ABSTRACT

The evolution of Industry 4.0 has reshaped global supply chains through the intesssgration of advanced technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and Big Data analytics, with inventory management remaining a central determinant of efficiency, resilience, and competitiveness. Conventional inventory systems often face challenges including limited visibility, fragmented data, and susceptibility to human error, resulting in inefficiencies and higher operational risks. Blockchain technology has emerged as a transformative enabler to address these challenges by providing decentralized, transparent, and tamper-resistant data management. This study examines the role of blockchain in revolutionizing inventory management within Industry 4.0 supply chains, with particular focus on its contextual significance in enhancing traceability, enabling real-time monitoring, and fostering stakeholder trust. The research further explores how blockchain can be integrated with IoT-enabled sensors and AI-driven analytics to improve data accuracy, predictive capabilities, and operational agility. Smart contracts are highlighted as a powerful mechanism to automate procurement, replenishment, and compliance processes, thereby minimizing manual intervention, reducing delays, and enhancing coordination across supply chain actors. Beyond operational efficiency, blockchain is also recognized for its potential contribution to sustainable supply chain practices by enabling full product lifecycle visibility, reducing waste, and ensuring regulatory compliance in global operations. Drawing on contemporary literature and industry case applications, this study provides a comprehensive understanding of blockchain-enabled inventory management and its alignment with Industry 4.0 principles, while acknowledging technical, financial, and organizational barriers to adoption. The findings suggest that blockchain-driven solutions present unprecedented opportunities for creating agile, resilient, and sustainable supply chains, thereby positioning blockchain as a next-generation inventory management framework that redefines traditional reactive models into intelligent, data-driven, and trust-based operations tailored for the complexities of Industry 4.0.

Keywords: Blockchain Technology, Inventory Management, Industry 4.0, Smart Contracts, Supply Chain Resilience.

INTRODUCTION

Industry 4.0 is ushering in a new era of supply chain operations where interconnected systems, automation, digital data streams, and real-time responsiveness are essential. Traditional inventory management methods are increasingly misaligned with the complexities of modern supply networks, which include numerous stock keeping units (SKUs), multiple sourcing points, fluctuating customer demand, and significant delays or errors in information transfer. Such inefficiencies lead to overstocking, stockouts, high holding costs, and poor service levels. Recent literature has documented these challenges clearly. For example, companies face information silos and lack of end-to-end visibility, which erode decision-making quality and resilience.

Blockchain technology has emerged in response as a promising solution to many of these issues. Its distributed ledger structure ensures immutable, transparent records; smart contracts can automate inventory replenishment, procurement, and compliance tasks; and integration with IIoT (Industrial Internet of Things) devices enables

real-time tracking of goods, their status, and their movement across supply chain tiers. Recent review studies indicate blockchain and IIoT as a strong combination for sustainable supply chain management, improving traceability, enabling environmental monitoring, and supporting real-time updates.

However, despite its promise, full adoption of blockchain in inventory management remains limited. Key barriers include scalability such as transaction throughput, latency, interoperability among multiple blockchains and legacy systems, high implementation costs, regulatory and privacy concerns, and lack of digital maturity in many firms especially SMEs.

Given this context, this research seeks to investigate how blockchain can be effectively deployed for next-generation inventory management in Industry 4.0 supply chains. It will examine what architectural frameworks are most viable, how smart contracts and real-time data integrations can be operationalized, what trade-offs are involved cost vs. performance as well as privacy vs. transparency and under what organizational and regulatory conditions adoption is feasible. By doing so, the study aims to contribute both theoretically by clarifying the design and constraints of blockchain solutions in inventory contexts and practically by offering guidance for firms seeking to modernize their supply chain inventory processes.

Problem Statement

Blockchain technology has been widely recognized as a disruptive enabler for supply chain management, offering features such as immutability, traceability, smart contracts, and real-time data sharing. However, despite the growing conceptual discourse, empirical evidence on blockchain's actual impact on inventory management performance remains scarce. Existing studies largely focus on theoretical discussions or adoption intention models, but they fall short of demonstrating how blockchain directly improves inventory accuracy, turnover, carrying costs, or resilience. This creates a significant knowledge gap, particularly in understanding blockchain's role beyond adoption, in delivering measurable and sustainable performance outcomes.

Furthermore, most current research examines blockchain in isolation rather than as part of the broader Industry 4.0 ecosystem. The lack of studies integrating blockchain with complementary technologies such as IoT and artificial intelligence limits the understanding of its synergistic potential in enhancing visibility, traceability, and predictive capabilities for inventory control. This narrow scope reduces the ability of both scholars and practitioners to conceptualize blockchain as part of an interconnected digital supply chain strategy.

The contextual bias in the literature further compounds this issue. Research is predominantly conducted in developed economies and among large multinational corporations, leaving small and medium-sized enterprises (SMEs) in developing contexts, such as Malaysia, underexplored. Given SMEs' resource constraints and unique operational challenges, the factors influencing blockchain adoption such as knowledge sharing, trading partner pressure, and regulatory clarity may differ significantly, as may the resultant impacts on inventory efficiency. The omission of such contexts reduces the generalizability of existing findings and weakens their practical utility for SMEs in developing economies.

Finally, critical mechanisms and boundary conditions that shape blockchain's effectiveness remain underexplored. Mediators such as supply chain transparency and inter-partner trust, and moderators such as firm size, regulatory support, and digital readiness, are often assumed but not empirically tested. This omission prevents a nuanced understanding of how blockchain adoption translates into operational outcomes. Without addressing these gaps, the literature cannot provide robust theoretical models or practical frameworks to guide firms in leveraging blockchain for inventory optimization under Industry 4.0.

Research Objectives

1. To examine the influence of blockchain features and technology adoption determinants on inventory management performance in Industry 4.0 supply chains.
2. To investigate the mediating role of supply chain transparency and inter-partner trust in the relationship between blockchain adoption and inventory outcomes.

3 To analyze the moderating effects of firm size, regulatory support, and technology readiness on blockchain's impact in inventory management.
4 To contextualize blockchain adoption and performance outcomes within SMEs in Malaysia as a developing-economy case.

Research Questions

1 How do blockchain features and technology adoption determinants affect inventory management performance in Industry 4.0 supply chains?
2 To what extent do supply chain transparency and inter-partner trust mediate the relationship between blockchain adoption and inventory performance?
3 How do firm size, regulatory support, and technology readiness moderate the relationship between blockchain adoption and inventory outcomes?
4 What are the contextual implications of blockchain-enabled inventory management for SMEs in Malaysia?

LITERATURE REVIEW

Recent literature on inventory management under Industry 4.0 reveals growing evidence that blockchain technology offers significant benefits especially when integrated with digital technologies such as IoT, big data analytics, and automated systems to improve traceability, information sharing, and operational efficiency. Studies such as Inventory Management and Information Sharing Based on Blockchain Technology (2023) present structural frameworks in which blockchain enables end-to-end traceability, real-time updates, faster asset transfers, and contract automation, showing measurable improvements in supply chain responsiveness.

Inventory Management and Supply Chain Performance

Many recent studies posit Supply Chain Performance (SCP), Supply Chain Transparency, Supply Chain Resilience, Financial Performance, and Operational Efficiency as key dependent variables. For example, Inventory Management and Information Sharing Based on Blockchain Technology (2023) examines how structural changes enabled by blockchain in real-time updates, contract automation, asset transfer which leads to improvements in cost, time, and resilience in supply chains. In the healthcare industry, research shows that blockchain's features such as traceability, smart contracts and data quality significantly affect transparency and resilience in supply chains. Also, in the SME context, blockchain adoption is reported to enhance Supply Chain Efficiency and Export Performance, though its direct effect on Financial Performance was less clear in one study. These works establish on the outcomes researchers are trying to influence with blockchain and related innovations.

Blockchain Features

Blockchain's core features are central to its application in inventory and supply chain management, serving as strong independent variables in research frameworks. Immutability ensures that once data is recorded, it cannot be altered, thereby enhancing the reliability of inventory records and reducing the risk of fraud or manipulation (Casino et al., 2019). Traceability allows supply chain actors to monitor product movement across stages, improving visibility and compliance with regulatory standards (Saberi et al., 2019). Smart contracts, as programmable agreements, automate inventory transactions and replenishment, reducing manual intervention and minimizing delays. Additionally, consensus mechanisms guarantee accuracy by validating transactions across distributed nodes, while real-time data sharing enhances collaboration between stakeholders (Kouhizadeh et al., 2021). These features collectively strengthen trust, transparency, and efficiency, thus forming the technological foundation for blockchain-enabled inventory management.

Technology Adoption Determinants

In addition to inherent blockchain features, determinants of technology adoption significantly shape the extent to which blockchain can be deployed in inventory systems. Factors derived from the Unified Theory of

Acceptance and Use of Technology (UTAUT), such as performance expectancy, effort expectancy, social influence, and facilitating conditions, have been widely applied to explain user intention to adopt blockchain in supply chain operations (Queiroz & Fosso Wamba, 2019). For instance, performance expectancy relates to the perceived benefits of blockchain in enhancing accuracy and efficiency, while effort expectancy reflects the perceived ease of integrating blockchain with existing enterprise systems. Facilitating conditions, including organizational readiness and IT infrastructure, also influence adoption decisions, particularly in small and medium-sized enterprises (SMEs) with limited resources (Raimo et al., 2023). Social influence, including pressure from partners and regulators, further drives adoption. These determinants act as independent variables by shaping behavioral intention and organizational willingness to invest in blockchain technologies.

Immutability

As a distinct blockchain feature, immutability refers to the inability to alter or delete records once they are validated, making it a critical independent variable for inventory integrity. In practice, immutability ensures that stock entries, shipment records, and audit trails remain tamper-proof, thereby reducing errors and fraudulent reporting (Casino et al., 2019). This creates confidence among supply chain partners, especially in industries prone to counterfeiting or compliance risks, such as pharmaceuticals and electronics. Recent studies highlight that immutable records enhance accountability and facilitate smoother audits, thus improving transparency and trust across global supply chains (Biswas & Gupta, 2019).

Traceability

Traceability has emerged as a prominent blockchain feature that enhances inventory visibility across the supply chain network. It enables stakeholders to track goods in real time from production to consumption, which is particularly vital in managing recalls, ensuring food safety, and meeting sustainability requirements (Saberi et al., 2019). Traceability as an independent variable has been linked with outcomes such as customer trust, compliance with green supply chain standards, and improved operational resilience. Recent studies also suggest that blockchain-driven traceability reduces information asymmetry among partners, creating competitive advantage (Kouhizadeh et al., 2021).

Smart Contracts

Smart contracts are automated, self-executing agreements coded on blockchain that streamline inventory management processes. By eliminating intermediaries, smart contracts facilitate automated order replenishment, payments, and compliance verification, which significantly reduce lead time and administrative costs (Queiroz et al., 2020). In research, smart contracts are considered an independent variable that drives operational efficiency, responsiveness, and agility within Industry 4.0 supply chains. For instance, in the healthcare industry, smart contracts have been shown to increase transparency and resilience by ensuring that suppliers adhere to pre-set delivery and quality standards (Morkunas et al., 2019).

Data Quality and Real-Time Data Sharing

Data quality and real-time data sharing are additional blockchain-related independent variables that influence inventory management performance. High-quality, accurate, and tamper-proof data provided by blockchain ensures reliable demand forecasting, production planning, and inventory control (Saberi et al., 2019). Real-time data sharing further enhances collaboration by enabling simultaneous visibility of transactions, thereby reducing information delays and bullwhip effects (Wamba & Queiroz, 2020). Together, these factors improve decision-making, reduce redundancies, and optimize resource allocation, making them central predictors of blockchain's impact on supply chains.

Adoption Drivers: Knowledge Sharing and Partner Pressure

Beyond technical features, external pressures and organizational practices also act as significant independent variables driving blockchain adoption. Knowledge sharing among partners enhances collective learning and increases trust in the adoption of new digital technologies (Queiroz & Fosso Wamba, 2019). At the same time, trading partner pressure and regulatory requirements push organizations to integrate blockchain in order to

remain competitive and compliant. These determinants influence how effectively blockchain technologies are implemented and scaled within supply chain networks, ultimately impacting overall performance (Raimo et al., 2023).

Research Gaps

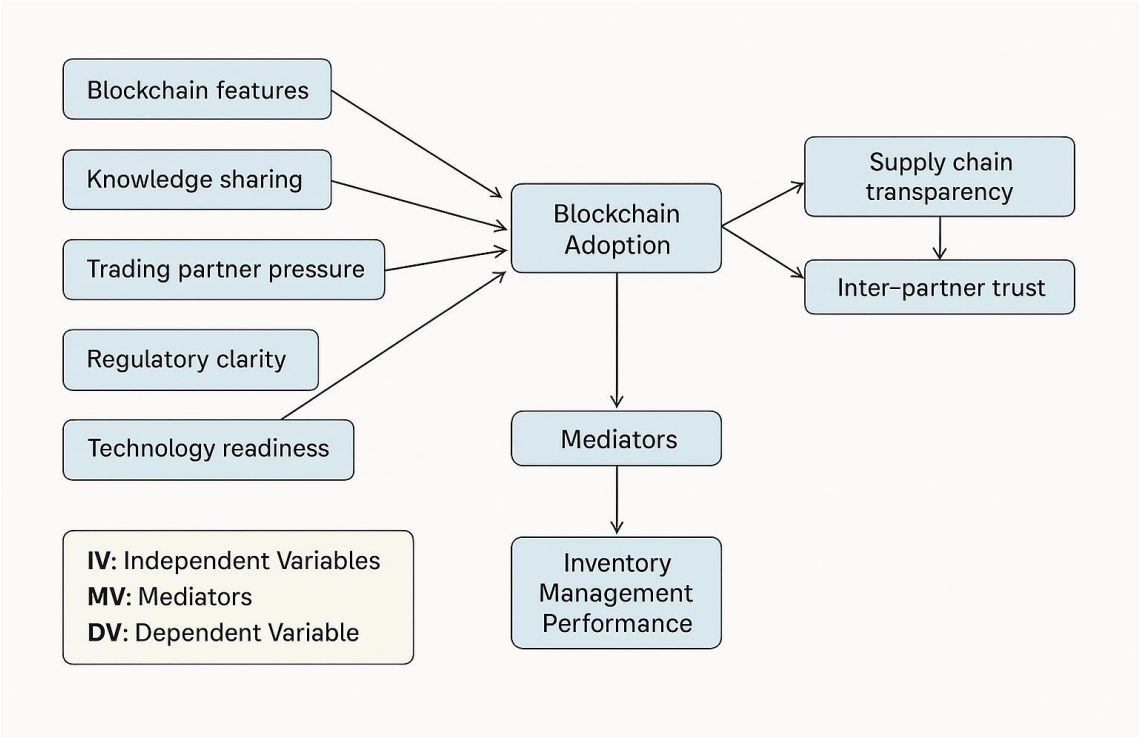
Although blockchain technology has attracted substantial attention in supply chain management, its application to inventory management within Industry 4.0 remains underexplored. Much of the existing literature remains conceptual, focusing on features such as immutability, traceability, and smart contracts, but offering limited empirical validation of their impact on inventory outcomes like stock accuracy, turnover, and carrying costs. Similarly, many studies emphasize adoption intention through frameworks such as UTAUT or TOE, yet neglect to assess whether blockchain implementation translates into measurable operational improvements. This creates a lack of practical evidence to justify blockchain investments for inventory optimization.

Another key limitation lies in the narrow technological and contextual scope of current research. Blockchain is often studied in isolation, despite Industry 4.0 requiring integration with technologies such as IoT, AI, and cloud computing to enhance real-time visibility and predictive forecasting. Moreover, existing studies are largely centered on developed economies, offering little insight into SMEs in developing contexts such as Malaysia, where resource constraints, organizational readiness, and partner pressures may shape both adoption decisions and performance outcomes. These gaps restrict the broader applicability and relevance of existing findings.

Finally, the literature seldom investigates mediating and moderating mechanisms that condition blockchain's impact, such as supply chain transparency, inter-partner trust, firm size, or digital maturity. Its potential contributions to sustainable and resilient inventory management, including waste reduction and recovery from disruptions, remain under-researched. Compounding these issues, most studies rely on conceptual or cross-sectional designs, with few longitudinal or cross-industry investigations to track blockchain's dynamic effects over time. Together, these shortcomings highlight the need for empirical, contextual, and integrative research that connects blockchain adoption to tangible inventory outcomes, particularly within emerging economies navigating Industry 4.0 transformation.

Proposed Conceptual Framework for the studies

(Proposed Conceptual Framework)



METHODOLOGY

Research Design

This study adopts a quantitative, deductive research approach, grounded in the positivist paradigm. The deductive approach is suitable because the study develops testable hypotheses from existing theories, specifically Technology-Organization-Environment (TOE) and Unified Theory of Acceptance and Use of Technology (UTAUT), and empirically validates the relationships between blockchain adoption determinants, mediating mechanisms, and inventory management performance.

Research Type

The research is designed as an explanatory study that seeks to establish causal relationships between blockchain features, adoption determinants, mediating factors (supply chain transparency and inter-partner trust), and inventory management performance. The study also incorporates moderation analysis to assess contextual influences such as firm size, regulatory support, and technology readiness.

Population and Sampling

The population for this study consists of manufacturing firms in Malaysia, a sector that is both a cornerstone of the national economy and central to the adoption of Industry 4.0 technologies. Malaysian manufacturers face mounting pressures to enhance supply chain efficiency, inventory optimization, and digital integration, making them an appropriate context for investigating blockchain's role in inventory management. The unit of analysis is organizational, with respondents drawn from supply chain managers, inventory managers, and IT decision-makers, as these roles are directly responsible for technology adoption and inventory-related decision-making, ensuring the relevance and accuracy of responses. Furthermore, to capture variation across firm types, a stratified random sampling method will be used to ensure adequate representation of both SMEs and large firms, as firm size is recognized as a potential moderating factor influencing blockchain adoption and performance outcomes. Consistent with structural equation modelling (SEM) requirements, a minimum of 300 responses will be targeted (Hair et al., 2020), with over 500 questionnaires distributed to account for anticipated non-responses. This approach strengthens the reliability of subgroup comparisons, such as multi-group analysis (MGA), while enhancing the generalizability of findings to the wider Malaysian manufacturing sector.

Data Analysis

The data analysis for this study will adopt a quantitative approach, leveraging structural equation modeling (SEM) as the primary analytical technique. SEM is chosen due to its capability to simultaneously examine multiple relationships between independent, dependent, moderating, and mediating variables, while also accounting for measurement errors. This makes it suitable for testing the complex theoretical framework of blockchain adoption, supply chain transparency, and inventory management performance within Industry 4.0 manufacturing contexts. The analysis will follow a two-stage process: first, the assessment of the measurement model to ensure validity and reliability, and second, the evaluation of the structural model to test the hypothesized relationships.

In the measurement model phase, confirmatory factor analysis (CFA) will be conducted to assess construct reliability, convergent validity, and discriminant validity. Internal consistency will be tested using Cronbach's alpha and composite reliability, while convergent validity will be measured through average variance extracted (AVE). Discriminant validity will be established using Fornell-Larcker criterion and HTMT ratios. These tests are essential to ensure that blockchain features, adoption determinants, mediators, and inventory performance are accurately represented by their respective measurement items.

The structural model analysis will involve testing the direct, indirect, and moderating effects proposed in the framework. Path coefficients will be examined to determine the strength and significance of relationships between blockchain features, adoption determinants, and inventory performance outcomes. Mediation analysis

will be employed to assess the role of supply chain transparency and inter-partner trust, while moderation effects will be tested for firm size, regulatory support, and technology readiness. Bootstrapping methods with resampling will be used to generate robust standard errors and confidence intervals, enhancing the accuracy of hypothesis testing.

Finally, model fit will be evaluated through multiple indices, including the comparative fit index (CFI), Tucker-Lewis index (TLI), root mean square error of approximation (RMSEA), and standardized root mean square residual (SRMR). These indices will provide evidence of whether the proposed theoretical framework adequately represents the data. Additionally, multi-group analysis (MGA) will be conducted to explore potential differences between SMEs and large firms in blockchain adoption and its impact on inventory performance. This comprehensive data analysis strategy ensures both rigor and depth, enabling robust testing of the proposed hypotheses and offering valuable insights for both academia and industry.

Ethical Considerations

Ethical considerations play a crucial role in ensuring the integrity and credibility of this research. Given that the study involves data collection from supply chain managers, inventory managers, and IT decision-makers in Malaysian manufacturing firms, informed consent will be obtained from all participants prior to their involvement. Respondents will be provided with a clear explanation of the research purpose, procedures, expected duration, and their right to withdraw at any stage without consequences. This approach ensures transparency and respects participants' autonomy in line with established ethical research standards. Additionally, ethical approval will be sought from the relevant institutional research ethics committee prior to data collection. This step provides an additional layer of oversight and assurance that the study complies with established academic and professional ethical guidelines. By upholding the principles of beneficence, non-maleficence, and respect for participants, the research will contribute meaningful insights to both academia and industry while maintaining the highest standards of ethical responsibility.

CONCLUSION

This conceptual research highlights the transformative potential of blockchain technology in reshaping inventory management within the broader framework of Industry 4.0 supply chains. By integrating blockchain features such as immutability, traceability, real-time data sharing, and smart contracts with established technology adoption determinants, the study presents a comprehensive framework for understanding how blockchain adoption can enhance transparency, trust, and ultimately inventory performance. The inclusion of mediating variables, such as supply chain transparency and inter-partner trust, and moderating variables, including firm size, regulatory support, and technological readiness, strengthens the theoretical lens through which blockchain's role in inventory optimization is examined.

The proposed framework advances the academic discourse by bridging gaps in existing literature that often treat blockchain adoption and supply chain performance in isolation. It provides an integrative model that captures the multi-dimensional impact of blockchain adoption on inventory outcomes, offering a platform for future empirical validation. For practitioners, the study provides insights into how blockchain-enabled digitalization can support resilience, efficiency, and competitive advantage in a rapidly evolving manufacturing landscape.

In conclusion, this paper contributes to both theory and practice by extending the understanding of blockchain adoption in inventory management systems and positioning it as a catalyst for supply chain innovation under Industry 4.0. Future research should empirically test the proposed framework using robust methodologies such as structural equation modeling across diverse industrial settings, thereby validating the conceptual arguments and uncovering sector-specific dynamics. By doing so, this line of inquiry has the potential to inform both academic scholarship and managerial strategies, driving the next generation of sustainable and digitally empowered supply chains.

Future research and implications

Future research should focus on empirically validating the proposed framework through large-scale

quantitative studies across different manufacturing sectors. Structural equation modeling (SEM) can be employed to test the relationships among blockchain features, adoption determinants, and inventory management performance. Comparative studies between SMEs and large firms would also offer valuable insights into how organizational size and resource availability moderate blockchain adoption and its outcomes. Such empirical validation would help refine theoretical assumptions and enhance the generalizability of findings.

From a policy perspective, this research emphasizes the need to align blockchain adoption with Malaysia's Industry4WRD national strategy, which seeks to accelerate digital transformation in the manufacturing sector. Policymakers should establish clearer regulatory frameworks to support blockchain deployment, particularly in critical areas such as data governance, digital contract enforcement, and cross-border trade compliance. In addition, government-driven initiatives such as financial incentives, tax exemptions, and targeted grants can play a crucial role in reducing the adoption barriers faced by both SMEs and large firms. Embedding blockchain into the broader Industry4WRD roadmap will not only enhance manufacturing competitiveness but also ensure inclusivity, enabling SMEs to participate actively in the digitalization journey. By prioritizing blockchain adoption as a strategic enabler of transparency and resilience, Malaysia can strengthen its position as a regional hub for smart manufacturing and digital supply chains.

From a managerial standpoint, blockchain adoption should be viewed not merely as a technological upgrade but as a strategic initiative that enables greater efficiency, trust, and resilience in inventory management systems. Manufacturing managers are encouraged to approach adoption incrementally, starting with pilot projects in areas such as inventory tracking and smart contracts before scaling to enterprise-wide integration. Building organizational capability is essential; therefore, firms should invest in workforce training, digital supply chain analytics, and blockchain literacy programs to close existing skill gaps. Managers should also foster collaboration and knowledge-sharing with supply chain partners, as blockchain's value is maximized when multiple actors participate. Furthermore, integrating blockchain with complementary Industry 4.0 technologies including IoT, AI, and big data analytics can unlock synergies that enhance real-time visibility, predictive forecasting, and sustainable practices. Such initiatives will not only align with Industry4WRD priorities but also enable Malaysian firms to compete effectively in global markets by meeting demands for transparency, sustainability, and resilience.

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