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Standardization of Supply Chain Monitoring Tools for Small and Medium Manufacturing Enterprises

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Abstract: The growing digitalisation of manufacturing supply chains has introduced a desperate requirement of interoperability and visibility amidst the global production networks. Nonetheless, the adoption of advanced methods of supply chain monitoring by Small and Medium-sized Enterprises (SMEs) is notably challenging because of the scarcity of resources, decentralized computer systems, and the lack of unified frameworks. The issue of technological fragmentation is discussed in the review through systematical literature review of the standardization of supply chain monitoring tools and its consequences on competitiveness of SME. The aims were to (1) present technological and organizational trends affecting the use of monitoring, (2) examine the current situation in the standardization efforts, (3) single out the barriers to implementation peculiar to SMEs, and (4) introduce a conceptual framework that would meet the needs of SMEs. The review took manufacturing SMEs as the focal case study, consolidating the results of both empirical and ideational researchers. Findings indicate that IoT, AI, and blockchain technologies have improved monitoring abilities, but the dispersed implementation and varying data standards make the technologies less interoperable. Bringing in standardization, such as the use of International Organization for Standardization, Global Standards and Supply Chain Operations Reference becomes one of the major facilitators of inclusiveness, scalability, and effectiveness. The proposed framework combines technological alignment, organizational preparedness and collaborative ecosystems as mutually supporting pillars in SME digital transformation. Finally, the standardization is a technical and strategic tool that democratizes digital transformation allowing SMEs to be more competitive and sustainable in global value chains. The research provides both theoretical and practical insights to policymakers, consortia in the industry and leaders of SMEs that aim to create fair digital systems.

Keywords: Supply Chain Monitoring, Standardization, Interoperability, Small and Medium-sized Enterprises and Digital Transformation.

INTRODUCTION

Monitoring supply chain has become a paramount aspect in production in three dimensions of operational visibility, traceability, and data-driven decision-making in the digital transformation era. Internet of Things sensors, Artificial Intelligence algorithms, blockchain-traceability systems, and big data analytics technologies enable companies to gather, analyze, and respond to real-time information throughout their supply chain of production and distribution (Khurana *et al*., 2022; de Koning *et al*., 2024; Gupta *et al*., 2024). These are used to facilitate proactive risk management, predictive maintenance, and performance optimization particularly in global value chains which are complex and volatile (Ivanov & Dolgui, 2021; Kamble *et al*., 2022). As a result, the supply chain monitoring has ceased to be an addition to the process and has become a strategic asset, which increases the competitiveness, sustainability, and resiliency of industrial ecosystems (Sahoo *et al*.,2022; Ajaz Khan & Abonyi, 2022). Digital convergence has transformed supply chains away to dynamic digital environments that are characterized by connectivity, transparency, and synchronization (Goel *et al*., 2023).

Although the digital tools have been advanced, the technological ecosystem of supply chains is still disjointed and incoherent. Proprietary platforms and incompatible data standards do not interact with each other, and they do not share a common communication standard (Ajaz Khan & Abonyi, 2022; de Koning *et al*., 2024). This disintegration is detrimental to digital transformation through information silos, visibility, and coordination issues among suppliers, manufacturers, and logistic partners (Scuotto *et al*., 2021; Soni *et al*., 2022). The lack of interoperable standards leads to redundancy and inefficiencies, especially to the small and medium-sized enterprises, which in most cases do not have the technical and financial resources to integrate systems across the border (Goel *et al*., 2023). Therefore, SMEs are experiencing an increasing digital divide that limits their inclusion in globalized, data-driven supply chains.

In emerging economies, SMEs represent approximately 90 percent of industrial work and more than 50 percent of the value creation (Goel *et al*., 2023; OECD, 2021). However, they are less digitally mature than larger companies because of the lack of financial means, the lack of proper

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infrastructure, and little digital literacy (Soni *et al*., 2022; Horváth & Szabo, 2019). The prohibitive price of technology adoption, unpredictable returns, and poor coordination mechanisms further deter the use of digital ecosystems (Cotrino *et al*., 2020; Chouki *et al*., 2020). Such technological gap decreases their effectiveness and competitiveness within the global supply chains, and SMEs become both vulnerable and of strategic importance in the discourse of the monitoring systems standardization (Omol *et al*., 2023; Pan *et al*., 2021).

Standardization is a way to eliminate these systemic challenges through facilitating interoperability, transparency, and scalability in digital supply chains (Zimon & Madzík, 2020). Existing international standards like ISO 9001 (Quality Management Systems), ISO/IEC 27001 (Information Security Management), ISO 28000 (Supply Chain Security), and GS1 standards on global data synchronization have proven to be able to standardize the structure of data and enable cross-platform communication (Ajaz Khan & Abonyi, 2022; de Koning *et al*., 2024; GS1, 2022; ISO, 2023). In the case of SMEs, standardized monitoring tools may help to lower the costs of integration, address the demands of larger partners related to the digital compliance aspect, and determine shared performance norms (Henninger & Mashatan, 2021; Chauhan & Singh, 2020). The idea of standardization is not only a technical approach but also a strategy that enables inclusion, which helps smaller companies to become part of the global production networks safely (Scuotto *et al*., 2021; Soni *et al*., 2022). Harmonized monitoring systems with the aim of democratizing the digital transformation process can make the technological benefits fair, as well as make the industrial process more sustainable and resilient globally (Sahoo *et al*.,2022; de Koning *et al*., 2024; Guarin, A. Y. L. 2024).

Although there is an increased interest in digital supply chains, the standardization of monitoring tools in SMEs has yet to be explored. The focus of the existing studies is usually either technological innovation or organizational preparedness and does not combine both dimensions in a single framework (Scuotto *et al*., 2021; Khurana *et al*., 2022). The majority of the empirically-based studies focus on large firms, and they provide little information regarding SME-specific adoption issues or standardization practices (Soni *et al*., 2022). Hence, there is an evident gap in the research in relation to models integrating technological, organizational, and institutional attitudes to standardization (Goel *et al*., 2023; Ajaz Khan & Abonyi, 2022). The given work is expected to cover that gap by means of a systematic literature review, which (1) will identify the trends in technology and organization, (2) will map the ongoing standardization efforts, (3) will analyze the obstacles of SME adoption, and (4) will offer a conceptual framework to inform future research and policy. Finally, the review aims at promoting digital inclusiveness and sustainable competitiveness to SMEs in international supply chains.

CONCEPTUAL BACKGROUND

Supply Chain Monitoring in Manufacturing

Supply chain monitoring refers to the continuous tracking, analysis, and optimization of materials, information, and financial flows throughout the manufacturing supply chain. It makes suppliers, suppliers visible, traceable, and responsive by allowing real-time awareness of events between suppliers and end customers (Ivanov & Dolgui, 2021; Gunasekaran *et al*., 2020). This is aimed at minimizing uncertainties, increasing coordination, and resilience, especially in the complex and multi-level manufacturing networks. With successful monitoring, the supply chain is no longer reactive, but it becomes predictive, which allows making decisions proactively and reacting to disruptions as quickly as possible (Hernández-Linares *et al*., 2021).

Introduction of digital monitoring devices, including the Internet of Things devices, Radio-Frequency Identification systems, Big Data analytics, and Artificial Intelligence algorithms, has transformed the manner of manufacturing. IoT sensors provide communication between machines and monitoring of their conditions, which is constant data on the health of equipment and their status in a process (Kamble *et al*., 2022). RFID tags can improve the traceability of items and record their movement at every point of logistics (Zhong *et al*., 2017). These huge data streams are further processed into actionable information using big data analytics and AI models, which allow predicting maintenance, forecasting demand, and detecting anomalies (Ogbuke *et al*., 2022; Gupta *et al*., 2024). All these technologies combine to form cyber-physical supply chains, which combine strategic decision systems with operational data.

The effects of monitoring supply chain on productivity and competitiveness are far reaching.

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Vision increases lead time, minimizes waste, and maintains consistent quality, among the main requirements of lean manufacturing and just-in-time systems (Swink *et al*., 2024). Besides, companies that use digital monitoring tools are more responsive to disturbances like material shortage or logistics delay and resulting in enhanced competitiveness on the market, eventually (Ivanov & Dolgui, 2021; Gupta *et al*., 2024). Sustainability objectives are also helped by the integration of the monitoring tools to maximize energy consumption and minimize waste, which are also part of a triple-bottom-line performance in manufacturing.

Table 1: Major Supply Chain Monitoring Tools and their functions

Tool	Core Function	Application Area	Example Studies
IoT (Internet of Things)	Real-time data collection from machines, assets, and products	Equipment monitoring, predictive maintenance	Kamble *et al*. (2022); Chauhan & Sing (2020)
RFID (Radio-Frequency Identification)	Automatic identification and tracking of goods and materials	Logistics, warehousing, product traceability	zhong *et al*. (2016); Kamble *et al*. (2020)
Big Data Analytics	Processing large data sets for trend detection and optimization	Forecasting, performance management	Gupta *et al*. (2024); Ogbuke *et al*. (2022)
Artificial Intelligence (AI)	Predictive modeling, anomaly detection, and decision support	Quality control, inventory management	Gunasekaran *et al*. (2020); Ivanov & Dolgui (2021)
Blockchain	Secure and immutable transaction records	Supplier traceability, data sharing	Francisco & Swanson (2018); Kouhizadeh *et al*. (2021)
Cloud Computing	Centralized data storage and real-time collaboration	Cross-site data access, analytics	Dubey *et al*. (2021); Pan *et al*. (2021)

SMEs and Digitalization Challenges

Small and Medium-sized Enterprises are the pillars of manufacturing and trade in the world. They represent more than 90 percent of the world's businesses and almost half of the global employment and output (OECD, 2020; World Bank, 2023). SMEs are significant in industrial support systems in regions, usually as suppliers or subcontractors to other companies (Cotrino *et al*., 2020). They are needed to diversify the supply chains, particularly in the industries that need individualized responses and fast decision-making (Chouki *et al*., 2020). Although they are vital, SMEs often have a problem in implementing sophisticated supply chain monitoring equipment that would enable them to become digital in the Industry 4.0 paradigm.

Resource constraint is one of the challenges that affect SMEs the most, both financially and in terms of human resources. The small and medium enterprises have a small capital budget, which limits investment in such technologies as IoT, AI, or Big Data systems that demand high initial investment and integration skills (Soni *et al*., 2022; Horváth & Szabo, 2019). Also, the lack of digital skills of managers and shop-floor workers is a barrier to the implementation and maintenance of such tools (Cotrino *et al*., 2020). Poor broadband connection and outdated legacy systems are further infrastructure barriers that contribute to digitalization issues (Zhong *et al*., 2017). All of this leads to poor levels of digital maturity when compared to large businesses (OECD, 2021; Hernández-Linares *et al*., 2021).

According to the empirical research, adoption levels of supply chain monitoring tools amongst the SMEs are low. An example is that not more than 30 percent of European manufacturing SMEs report using real-time monitoring systems (European Commission, 2022), and the adoption rates are even lower in the developing areas with weaker digital infrastructure and financing (Elhusseiny & Crispim, 2022). Although SMEs generally realize the possible advantages of traceability, predictive analytics, and transparency, the implementation complexity and interoperability serve as an issue of concern (Chouki *et al*., 2020; Khurana *et al*., 2022). As a result, although the digital transformation initiatives are extensive, there is a disjointed and uneven implementation of the integrated monitoring systems.

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The constant obstacles underscore the importance of standardized, affordable, and interoperability supply chain monitoring solutions that are SME-centric. Standardization may lower the cost of customization, improve compatibility with other platforms, and make implementation easier in companies with small technical capabilities (Goel *et al*., 2023). The creation of frameworks and certification models adapted to SME-friendly scale, in line with international conventions, can enable the smaller manufacturers to reach digital integration and visibility without unnecessary expenses or complexity. This preludes the following section of standardization and interoperability, which examines frameworks and policies underpinning homogenization of digital supply chain networks.

Standardization and Interoperability

Standardization in supply chain monitoring refers to homogeneous data models, processes, and technical interfaces that facilitate free flow of information between various platforms, tools, and organizations. It is applied in manufacturing to make sure that data gathered by a number of different digital systems can be perceived, processed, and acted upon in a consistent manner (IoT sensors, ERP systems, or logistics platforms) (Zimon & Madzík, 2020). The foundations of scalable and integrated digital ecosystems are the increased levels of trust, interoperability, and efficiency in the software process ensured by standardization (Ahmed *et al*., 2021). In the absence of standardized structures, the supply chain information is disorganized, which restricts visibility and makes it more difficult to coordinate partners.

The idea of interoperability goes hand in hand with standardization and deals with the capability of different systems to communicate, exchange, and utilize the information efficiently (Burns *et al*., 2019). The concept of interoperability is essential in the current supply chains where numerous stakeholders, such as suppliers, manufacturers, logistics providers, and customers, must use various digital tools. When it comes to the SMEs, the issue of interoperability is frequently related to the software compatibility, the data format heterogeneity, and non-conformity to international standards (Feizabadi *et al*., 2019; Burns *et al*., 2019). The problems result in data silos, manual coordination, and inefficiencies in tracking operations, especially when SMEs are trying to connect to bigger, digitally mature partners.

A number of global standards exist that deal with quality management, data protection, and traceability of the supply chain monitoring systems. Such are ISO 9001 (Quality Management Systems), ISO/IEC 27001 (Information Security Management), or GS1 Standards, which are utilized to manage the exchange of data in logistics and inventory management (GS1, 2022; ISO, 2023). Also, the ISO 28000 assists in supplying the chain of security, whereas ISO 8000 is all about the data quality and integrity. Adherence to these standards enables SMEs to enhance credibility and information quality in a situation of cooperation with multinational businesses (Zimon & Madzík, 2020). Nevertheless, small companies still have difficulties with full compliance because of certification fees, technicalities, and a lack of awareness (Goel *et al*., 2023).

In the case of SMEs, the notion of lightweight/modular standardization frameworks is emerging as a means to realize interoperability, without going through the heavyweight certification process. Such initiatives as the Smart Manufacturing Standards Consortium and Industry 4.0 Reference Architectures (e.g., RAMI 4.0, IIRA) offer flexible frameworks that would benefit SMEs looking to be digitally integrated (Burns *et al*., 2019). These models focus on harmonization of data, semantic interoperability, and open architectures, facilitating scalable transformation of value chains through digital transformation. Standardization is therefore a strategic facilitator and leveler as it enables the SMEs to play a competitive role in global digital ecosystems at a low cost and with operational flexibility.

Table 2: Key International Standards Related to Supply Chain Monitoring

Standard	Focus Area	Relevance to Supply Chains	SME Applicability
ISO 9001:2015	Quality Management Systems	Ensures process consistency and product reliability across manufacturing operations	Applicable to all SMEs seeking quality certification
ISO/IEC 27001:2022	Information Security Management	Protects digital supply chain data and ensures communication integrity	Useful for SMEs handling digital transactions and IoT data
ISO	Supply Chain Security	Addresses logistics and supplier	Relevant for SMEs in

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28000:2022	Management	network risk management	global sourcing and export sectors
ISO 8000:2015	Data Quality and Master Data Management	Promotes accuracy and interoperability in data exchange	Suitable for SMEs integrating ERP or monitoring systems
GS1 Standards	Global identification and data exchange (e.g., barcodes, EPCIS)	Improves traceability and logistics efficiency	Widely used by SMEs in packaging, warehousing, and retail
IEC 62264 / ISA-95	Enterprise-Control System Integration	Defines standard interfaces between ERP, MES, and shop-floor control systems	Supports SMEs implementing IoT-enabled production
RAMI 4.0 (Germany)	Reference Architecture Model for Industry 4.0	Standardized layers for smart manufacturing and system interoperability	Adaptable to SMEs for modular, phased digital adoption

REVIEW OF EXISTING LITERATURE

Technological Foundations of Supply Chain Monitoring Tools

The tools of supply chain monitoring have developed as the digital spine of the manufacturing systems, allowing real-time monitoring, traceability, and predictive control. The modern monitoring systems are based on technologies like the Internet of Things, blockchain, analytics of Big Data, and Artificial Intelligence. Shrestha Pundir *et al*. (2024) indicate that IoT sensors and AI analytics establish so-called smart feedback loops, collecting data around the production lines, logistics, and suppliers continuously, to optimize the flow efficiency. These systems minimize the duration between the capture of information and the decision-making process, which will create a data-driven culture, a key competitive factor in Industry 4.0 manufacturing (Burn *et al*., 2019).

The IoT offers real-time perception and monitoring by integrating sensors, RFID devices within the production and logistics network. Moshood *et al*. (2021) emphasize the role of IoT perception layers in creating the basis of end-to-end supply chain visibility, especially when tasked with cloud-based dashboards. The IoT in manufacturing has been used in machine health monitoring, inventory optimization and automation, and optimization of logistical routes. Yet, according to Ahmed *et al*. (2021), in the absence of standardized data formats, the IoT systems have interoperability issues, particularly among SMEs operating a heterogeneous set of devices, as well as legacy software platforms.

The IoT is supplemented by blockchain technology that introduces the immutability of data and decentralized verification of the monitoring processes. The role of blockchain is defined by de Koning *et al*. (2024) and Sahoo *et al*. (2022) as such that ensures the transparency and invulnerability of transactional information stored in blockchains. This comes in especially handy in industries that have compliance checks that need to be checked and traced, like food and pharmaceuticals. However, the implementation of blockchain in the manufacturing sector is associated with difficulties when it comes to integrating it because of its high computing expenses and scanty standard frameworks in cross-chain interoperability (Ahmed *et al*., 2021).

Big Data analytics also improves the monitoring process by converting raw IoT and blockchain data into actionable insights. As illustrated by Shrestha Pundir *et al*. (2024), predictive maintenance, demand forecasting, and risk analysis across the supply chains are all possible through the application of Big Data. Firms can forecast the disruptions before they happen by combining data from production sensors, supplier databases, and logistics networks. Nonetheless, useful analytics presuppose regular data management, so standardization of data models and interoperability protocols gain significance (Ajaz Khan & Abonyi, 2022).

Artificial Intelligence is the analytical platform of contemporary monitoring systems, which offers anomaly detection, autonomous decision-support, and optimization. The article by Nabi *et al*. (2024) presents a new AI-based enterprise resource planning (ERP) system that incorporates machine learning models and traceability systems implemented on blockchains. Such architectures enhance the responsiveness and robustness of complicated manufacturing ecosystems. As Burns *et al*. (2019) note, the actual value of AI is that it combines with IoT and Big Data to generate smart supply chain nervous systems that can be controlled dynamically and adaptively.

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The more recent integration architecture, the Digital Twin, Cyber-Physical Systems (CPS), and Industrial Internet of Things (IIoT) frameworks can allow viewing manufacturing and supply chain data as a single entity. According to Ahmed *et al*. (2021) and Kamble *et al*. (2022), such frameworks as RAMI 4.0 and OPC-UA offer layered architectures, integrating IoT sensing with blockchain validation and AI analytics. The models can be used as the reference architectures of standardized monitoring ecosystems, which connect operational technology (OT) with information technology (IT). Nevertheless, SMEs frequently do not have the infrastructure or knowhow to implement these multifaceted architectures, a fact that further supports the simplified and standardized frameworks with the right balance of cost, scalability as well as interoperability.

Standardization Efforts in Supply Chain Technologies

The objectives of standardization within the supply chain technologies are to develop shared frameworks and data formats and operational models that can facilitate smooth interoperability among varying systems and organizations. With more global and digitized manufacturing networks, visibility, transparency, and efficiency demands that the networks will be interoperated and are using the same protocols (Ahmed *et al*., 2021; Zimon & Madzík (2020). Supply Chain Operations Reference (SCOR) model, GS1 standards, and other ISO-based models have been created to align operations and information flows across businesses. These frameworks provide that the supply chain monitoring tools, including IoT and ERP system-level and blockchain network, conform to the similar principles of data exchange and processes performance to mitigate the fragmentation in digital ecosystems (Ajaz Khan & Abonyi, 2022).

In 1994, the Supply Chain Council introduced a process-based standardization model, which was known as SCOR (Supply Chain Operations Reference) model and developed by APICS and it integrated the following processes: Plan, Source, Make, Deliver and Return processes into quantifiable performance measures. It specifies more than 250 standardized metrics and good practices, allowing companies to compare and optimize supply chain performance (Feizabadi *et al*., 2019)). According to recent research, SCOR 12.0 incorporates digital and sustainability aspects, as was aligned with Industry 4.0 technologies, that is IoT, AI, and Big Data analytics (Rodseth & Hvolby, 2023). Nonetheless, although big companies often use SCOR to be their standard of performance management, small businesses often lack the resources and data maturity to apply them to specific scales or digital monitoring services (Henninger & Mashatan, 2021).

Based on the GS1 framework popular in the logistics and retail markets, the global identification and traceability of products is achieved using unique product numbers like GTIN, GLN and interoperable data exchange formats like EPCIS (Electronic Product Code Information Services). It enables real-time visibility in the supply chain nodes and thus enables uniform traceability of goods (GS1, 2022). Likewise, the ISO standards, including ISO 9001 (quality management), ISO 28000 (supply chain security), and ISO/IEC 27001 (information security) provide a single set of standards of quality assurance and safe information management within organizations (ISO, 2023). Research indicates that big businesses include GS1 and ISO standards in their ERP and PLM systems, but they need to be interoperable, though SMEs are inclined to implement only some of the selected elements because of the certification expenses and the insufficient technical background (Feizabadi *et al*., 2019; Burns *et al*., 2019).

Regardless of these international efforts, there are still large interoperability interfaces between monitoring tools and data standards. According to Ahmed *et al*. (2021) and Burns *et al*. (2019), the work environment of most SMEs is heterogeneous and includes legacy systems and current IoT and analytics systems. This contributes to subdivided data silos and data semantics between applications. The differences in data models, communication protocols and semantic representations are commonly held as the cause of multi-platform interoperability issues. Lacks in harmonized ontologies or standardized APIs prevent real-time flow of data between tools like Manufacturing Execution Systems, ERP and logistics monitoring dashboards (Ajaz Khan & Abonyi, 2022). These loopholes highlight the necessity of global data ontologies and middleware architectures that can be used to facilitate semantic compatibility between heterogeneous technologies.

The contemporary digital supply chains are integrated using API, which links various platforms, including IoT gateways and blockchain nodes, as well as cloud analytics services.

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Nonetheless, Pan *et al*. (2021) state that APIs are not typically governed by a consistent semantic model of data, which leads to non-uniform data interpretation and higher risks of cybersecurity. As an example, one IoT system can be identified as temperature and another as Temp, so automated analytics are complicated without mediated through a standard schema or ontology (Burns *et al*., 2019; Goel *et al*., 2023). To deal with these problems, the technical harmonization and institutional coordination is necessary. This is especially critical to SMEs that aim to be part of global value chains where interoperability and compliance are the determining factors before accessing markets.

New researchers support light, modular standardization systems that are explicitly targeted at the SMEs. These frameworks are made up of simplified process reference models, open-source APIs, and standardized data templates that are cheaper and less complex yet in compliance with global standards (Henninger & Mashatan, 2021). As an example, the Digital Twin Reference Architecture and the Industrial Data Space projects offer interoperability layers that are modular and can be used by small manufacturers. These scalable models help close the divide between international models and the real requirements of the SMEs and result in a greater uptake of standardized monitoring systems. Finally, the intersector of the SCOR, GS1, and ISO principles in open digital ecosystems can be viewed as the avenue, based on which, homogeneous, interoperable, and inclusive supply chain monitoring frameworks are achieved.

Implementation in Small and Medium Manufacturing Enterprises (SMMEs)

The integration of the supply chain monitoring technologies in the Small and Medium Manufacturing Enterprises has been adopted gradually and unevenly as it is to large enterprises. Research persistently shows that SMMEs perceive digitalization as the way to improve efficiency, traceability, and competitiveness in operations but the level of adoption depends on resource constraints and digital maturity discrepancy (Goel *et al*., 2023; Soni *et al*., 2022). An example is the introduction of IoT, AI, and blockchain in the work of SMEs, which tends to be a pilot project without further expansion (Scuotto *et al*., 2021). This leads to the partial digital ecosystems that do not have standard interfaces, interoperability within value chains. Empirical data on Europe and Asia show that less than 40 percent of manufacturing SMEs have already deployed digital monitoring systems beyond the pilot phase (OECD, 2023; Pan *et al*., 2021).

There are various structural and behavioural obstacles to successful technology adoption among SMEs. Digital infrastructure, i.e., IoT sensors and built-in ERP systems, is the most mentioned challenge in cost (Omol *et al*., 2023; Pan *et al*., 2021). Also, the lack of technical skills and cybersecurity issues is a factor that contributes to the reluctance to undergo digital transformation. Slow adoption is also caused by cultural barriers, especially resistance to change and low awareness of managers (Elhusseiny & Crispim, 2022; Hernández-Linares, 2021). Poor internet connectivity and standardized training are also limiting integration in most developing economies. All these put together lead to the occurrence of a digital divide between those companies that are technologically advanced and those that are small manufacturers that produce according to the traditional production models.

Organizational rigidity and ecosystem dependency are also issue with SMEs that restrict the diffusion of technology. Khurana *et al*. (2022) also state that the majority of small firms are restricted to the hard supplier chains of large corporations, where independent innovation is not much possible. Moreover, SME leaders tend to view digital adoption as risky because of the ambiguous ROI particularly at times when cost pressures over the short term are more important than strategic advantages in the long run. The lack of standard frameworks or measures used to assess the results of digital transformation in SMEs is the factor that contributes to this perception (Goel *et al*., 2023). Therefore, the theoretical advantages of digital monitoring are properly recorded, but empirical research indicates the weak transfer to mass adoption.

In spite of these obstacles, a number of facilitating factors have been experienced to facilitate the uptake of technology by SMEs. Digital transformation initiatives, including the Digital Europe Programme by the EU and SME Digital Technology Adoption Fund in Asia, provide financial support and training along with innovation hubs (OECD, 2023; European Commission, 2024). Also, there are digital maturity models, including the IMPULS Industry 4.0 Readiness Index and Smart Industry Readiness Index, two of which offer systematic ways in which SMEs can assess their current state in terms

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of digital capabilities and plan improvements step-by-step (Elhusseiny & Crispim, 2022). The collaborative networks, such as industry clusters, research organizations, and technology transfer alliances, are also crucial in accelerating the process of sharing knowledge and decreasing the barriers to entering the technology (Ghobakhloo, 2020; Khurana *et al*., 2022).

Recent research indicates that hybrid models of adoption exist in the context of SMEs using cloud-based and open-source solutions to attain affordable digital monitoring without significant initial expenditure (Pan *et al*., 2021; Pan *et al*., 2021). As an illustration, ERP-based and IoT-based clouds enable SMEs to pay per modular services instead of investing in full infrastructure. These models encourage slow adoption that allows firms to grow digitally. Nevertheless, despite the fact that hybrid systems should follow data standards and interoperability principles (Soni *et al*. (2022), standardized but adaptable structures adjusted to SMEs are still necessary.

Although the literature provides a lot of information on the digital adoption barriers and enablers, there still is a significant gap in terms of practical implementation frameworks of supply chain monitoring standardization at the SME level. The current models (SCOR, ISO-based) are developed based on big businesses with highly developed digital systems. Lack of context-sensitive, scalable and resource-efficient structures hinder the involvement of SMEs in global digital supply chains (Goel *et al*., 2023). Future studies thus need to be done to come up with standardized but adaptive models that are in tandem with the realities of SMEs in their operations- affordability, interoperability and performance measurement in digital monitoring adoption.

Research Gaps and Limitations

Although the publication of literature on supply chain digitalization and monitoring technologies is growing at a blistering pace, a substantial percentage of the literature contains a methodological weakness. The majority of studies are cross-sectional, where the analysis is performed based on a single time and does not involve continuous and longitudinal monitoring of the diffusion and performance results of technologies (Soni *et al*., 2022; Goel *et al*., 2023). Empirical research tends to use small and geographically restricted samples that are usually restricted to developed economies like Germany, South Korea or the United States. Due to that, the results might not be sufficient to reflect the situation of manufacturing SMEs in developing countries and their challenges. Also, the fact that survey-based and conceptual research predominates over field experiments or implementation case studies decreases the usefulness of the existing frameworks in a practical sense (Scuotto *et al*., 2021; Pan *et al*., 2021).

The other significant gap comes about because of the disproportional attention given to big, digitally mature companies in literature. The majority of the currently available models, including SCOR, ISO-based models, and GS1, are available to organizations that have a significant financial, technological, and human basis (Feizabadi *et al*., 2019); Ajaz Khan & Abonyi, 2022). In turn, such frameworks tend to ignore structural and functional facts of small and medium manufacturers as well as their resource limitations and data fragmentation. The literature on the topic of SME typically only goes as far as the descriptive analysis, which offers only a partial understanding of the implementation strategies, step-by-step models, or integration toolkits that are specific to SME settings (Goel *et al*., 2023; Khurana *et al*., 2022). Such bias creates a discrepancy between theoretical propositions of digital monitoring and their practice in resource constrained contexts.

There are a few research gaps that are not explored sufficiently, namely, cross-country comparative studies, SMEs interoperability standards, and longitudinal research of digital maturity evolution. There has been limited research on understanding the effects that national policies, culture or infrastructure preparedness can have on the capacity of SMEs to use standardized supply chain monitoring tools (OECD, 2023; European Commission, 2024). Also, the issue of interoperability and data standardization is reported to be among the core problems, but there has been no research to connect technical integration with the frameworks of organizational readiness. Such fragmentation creates gaps in the process of determining how to create lightweight, flexible, adaptive standardization models that optimize flexibility, scalability, and compliance across SME networks (Henninger & Mashatan, 2021; Ahmed *et al*., 2021).

The literature synthesis indicates that although significant strides have been witnessed on the development of supply chain monitoring

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technologies, there is imbalance and lack of uniformity in terms of and among the size of firms and the geographical location of firms. It is evident that there is a necessity of integrated, SME-oriented structures that integrate technological interoperability with process standardization and institutional support systems. The second section expands those gaps by developing a conceptual framework of the supply chain monitoring tool standardization in small and medium manufacturing enterprises.

DISCUSSION

The overall literature review indicates that there is a distinct overlap of digital transformation and supply chain monitoring, which are caused by Industry 4.0 technologies and technologies including IoT, Big Data analytics, AI, and blockchain. The overall direction is the transition to reactive, paper-based systems to proactive, data-driven monitoring ecosystems to improve visibility, traceability and responsiveness. Research always indicates that companies that implement digital monitoring solutions have better agility in decision-making, risk anticipation, and transparency in operations (Shrestha Pundir *et al*., 2024; de Koning *et al*., 2024). Nevertheless, the adoption of these technologies has been rather unequal, with big businesses being on the frontline and SMEs being the last adopters due to the lack of resources and disjointed standards (Goel *et al*., 2023). Another trend illustrated by the literature is the increased recognition of the necessity of standardization models that will guarantee the interoperability of a variety of digital tools.

There is also a difference that arises between conceptual research that tends to postulate idealized digital architectures and empirical studies, which report actual adoption and challenges. Conceptual works also tend to put digital transformation into theoretical perspective, focusing on frameworks like SCOR, RAMI 4.0 and ISO-based models of interoperability ((Feizabadi *et al*., 2019); Ajaz Khan & Abonyi, 2022). These papers propose structured and layered architectures as a means to integrate the supply chain processes. Conversely, empirical research indicates that the reality of implementation, in particular in SMEs is much more complicated, with obstacles such as cost, low IT expertise, and legacy (Khurana *et al*., 2022; Soni *et al*., 2022). Therefore, whereas conceptual models are establishing what should be, empirical research illustrates what can be, and in many cases the ideal of theoretical standardization and realities found in manufacturing ecosystems are vastly different.

One of the main inconsistencies in the literature is whether or not standardization increases or limits the flexibility of supply chain. According to some authors, standardization can also make agile work possible, as it promotes the interoperability of data and eliminates ambiguities in processes (Ahmed *et al*., 2021; Burns *et al*., 2019). Others warn that too much standardization can produce inflexibility and less responsiveness, especially in the case of SMEs whose work processes depend on customized flexibility (Henninger & Mashatan, 2021). This dualism implies that the procedure of standardization is not to be conceived as a one-size-fits-all approach but rather as a scalable and modular approach. Adaptive frameworks, in which the core data formats and communication protocols are standardized, but the operational models are free to evolve, are the new consensus of the recent literature.

Supply chain standardization has a theoretical basis in supply chain frameworks like SCOR, ISO 9001, ISO/IEC 27001 and GS1 which are aimed at enhancing process coherence, data integrity, and interoperability. But practice shows incongruities. SMEs often have no regulations, technical skills and finances to implement these systems (OECD, 2023; European Commission, 2024). Practically, most SMEs use disjointed digital solutions that do not share data or analytics with limited capabilities. Literature therefore suggests that there is no consistency between theory on global integration and reality on the ground that require local, incremental implementation strategies.

Technological evolution in monitoring of supply chains has changed the trend towards not individualized, but network-based digital ecosystems supported by the IoT, cloud computing, and AI. The concept of integration such as Digital Twins and Cyber-Physical Systems is a new paradigm where data can flow smoothly among the suppliers, manufactures and distributors (Ahmed *et al*., 2021; Moshood *et al*., 2021). The migration to these ecosystems, however, is slowed down by the unavailability of affordable integration standards and modular digital solutions in the case of SMEs. The idea of platform-based ecosystems in which SMEs are able to implement standardized APIs and shared digital infrastructures in order to reduce the technical

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complexity but maintain operational autonomy is increasingly promoted by scholars.

In the case of SMEs, the possible advantages of standardization are also beyond technical compatibility. Standardized monitoring tools have the potential to enhance the visibility of data, predictability of operations and coordination of suppliers therefore reducing the cost of transactions, as well as improving competitiveness (Goel *et al*., 2023; Khurana *et al*., 2022; Guarin, A. Y. L. 2024). Standardization further gives SMEs an opportunity to engage in global supply chains which will satisfy compliance and traceability mandates by bigger partners. Nevertheless, it is emphasized in the literature that these advantages depend on tailored implementation models that match standards to the specific capabilities of SMEs, making compliance not an excessive administrative cost (Henninger & Mashatan, 2021; Ajaz Khan & Abonyi, 2022).

Operationally speaking, standardized monitoring frameworks have far reaching efficiency, cost management, and sustainability implications. Interoperable systems decrease the repetition of information entry, and increases the accuracy of predictive maintenance, as well as simplifying the procurement process with traceable and transparent digital transactions. In addition, standard data protocols make it easy to track sustainability, e.g. track carbon emissions or waste reduction in the supply chains (de Koning *et al*., 2024; Sahoo *et al*.,2022). However, the problem of cost-effectiveness is also a major obstacle: lacking the economies of scale or state support, the SMEs might struggle to explain their investments in standardization. Therefore, the policy makers and industry organizations should focus on common digital infrastructures and public- private collaboration towards lower cost of adoption.

The interpretation of the literature shows that the future of supply chain monitoring in SMEs is in modular standardization, which is a hybrid system that would integrate the strength of a global model with the flexibility that small firms need. The evidence indicates that the sustainability of adoption is based on the alignment of three interdependent pillars such as technological alignment, organizational readiness, and collaborative ecosystems. Technological alignment also focuses on the implementation of IoT, AI and Big Data technologies that are combined and interoperated with interoperable standards to guarantee efficient data sharing and monitoring. The organizational preparedness pays attention to in-house skills in terms of governance models, workforce education, and digital maturity advancement so that SMEs can progressively embrace sophisticated systems. Lastly, collaborative ecosystems: These systems include networks of SMEs, larger organisations and institutional participants that enable the sharing of digital infrastructures and resource pooling, thereby cost-reduction and promoting interoperability. All these components create the prerequisites of a coherent conceptual framework which enables step-by-step standardization, which enables the SMEs to improve on competitiveness, visibility, and sustainability without sacrificing flexibility. This synthesis preconditions the next part that forms a visual and theoretical model of the modular standardization implementation in the SME supply chains in a practical and scalable way.

PROPOSED CONCEPTUAL FRAMEWORK

The review of the available literature shows there is an ongoing discrepancy between the theoretical level of development of supply chain standardization models and its use in small and medium manufacturing businesses. Although giant corporations have been able to employ internationally accepted models like SCOR, ISO, and GS1, SMEs are still experiencing structural and resource-related problems that do not allow them to integrate completely. To counter these shortcomings, the proposed study is the conceptual framework of the standardization of supply chain monitoring tools adapted to SMEs. The framework will also offer a scalable modular and adaptive model that will incorporate technological, organizational and collaborative dimensions, so that standardization will be a scalable enabled, but not a limiting factor.

The given model is based on three pillars that are connected with each other Technological Alignment, Organizational Readiness and Collaborative Ecosystems and each of them reflects a pressing dimension of SME digital transformation. Technological Alignment entails the implementation of interoperable digital tools including IoT sensors, AI analytics, and Big Data platforms that are based on common standards and open data architecture. Organizational Readiness focuses on the internal enablers such as organizational commitment to leadership, digital skills of the workforce, governance frameworks, and custom of continuous improvement in the

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support of the adoption of digital standards. Collaborative Ecosystems are external enablers like industry networks, digital supply chain consortia and government initiatives which enhance common infrastructure and interoperability standards. A combination of these factors is the basis of SMEs slowing shifting towards fragmented digital operations to completely integrated standardized monitoring systems.

The framework assumes that there is a circular and reinforcing relationship between its elements. In Technological Alignment, there is an increase in data visibility, traceability, which creates real-time intelligence that assists decision-making in the firm. Such technological capacity, in its turn, enhances Organizational Readiness since it proves the actual benefits of digital integration and, thus, makes employees more engaged and managers more likely to buy in. Over time, SMEs gain confidence and capacity to participate in Collaborative Ecosystems in which they share common standards and best practices to enhance their technological and operational maturity. The influence of the feedback of collaborative networks on technological decisions and the organization process creates a virtuous circle of continued improvement. Therefore, the framework represents standardization as a dynamic process that develops and grows by the interplay of these three dimensions.

In theory, this framework will add to the mounting literature on digital transformation and supply chain standardization in SMEs by unifying the scattered views into a cohesive, dynamic concept. In contrast to the current models, which concentrate exclusively on one of the two domains of technology and governance, this model introduces a socio-technical approach within the digital infrastructure that connects it to organizational behavior and inter-firm cooperation. It is consistent with systems theory and resource-based views in that the theme of competitive advantage is that firms do not develop technological resources, institutional competencies, and network relationships in a vacuum but through co-development. Moreover, it expands the theory of digital ecosystem to place SMEs in the role of not only passive adopters but also active co-creators of interoperable value networks, in which standardization is a strategic resource shared.

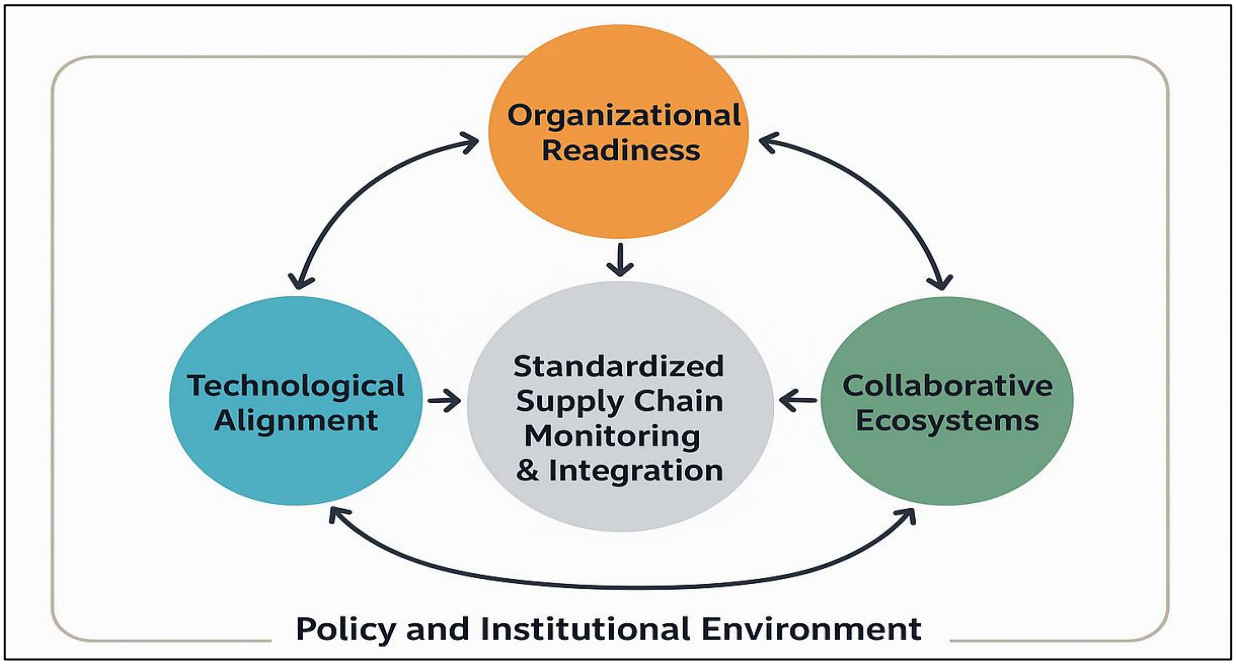

Figure 1: Conceptual Framework for Standardizing Supply Chain Monitoring Tools in SMEs

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Regarding the management perspective, the framework can offer a tangible guide to the leaders of SMEs that want to utilise standardised supply chain monitoring instruments but not to stretch their financial and technical resources. It promotes small-scale deployment - interoperable data formats and low-cost cloud infrastructure should be deployed first and then expanded to full integration. This framework allows policymakers and industry associations to develop specific mechanisms of assistance, including data standardisation and open-source, and shared digital hubs, subsidies on the adoption of ICT services. The framework will result in inclusiveness in global supply chains by encouraging collaboration among SMEs, technology providers and standardization bodies to ensure that digital transformation is affordable, sustainable, and fair to all the sizes of enterprises.

FUTURE RESEARCH SUGGESTIONS

Future studies should be based more on comparative studies across various industrial sectors and countries in order to gain a better insight into the various avenues that SMEs follow in adopting and standardizing supply chain monitoring tools. The existing body of work is still too much focused on manufacturing industries in developed countries like Germany, Japan, and South Korea, which do not provide a comprehensive understanding of the emerging economies with quite different levels of digital preparation, policy facilitation, and infrastructural availability. Comparative analysis of the low- and high-tech manufacturing sectors and/or of the regions of differing industrial maturity can shed light on context-modulated enablers and obstacles to standardization.

The next important step that is required by scholars is designing and testing standardization toolkit specifically targeting SMEs. These toolkits are expected to incorporate practical guidelines, modular templates and open-source digital protocols that can be used by resource constrained enterprises to deploy incremental interoperable monitoring systems. In contrast to the current models which presuppose the developed infrastructure, the SME-oriented models should consider cost-efficiency, scalability, and easy deployment. The potential usage of AI-brokered configuration tools and cloud-based integration platforms to automate compliance with standards such as ISO 9001, ISO/IEC 27001, and GS1 should be considered by researchers. Additionally, it can be expanded through the creation of industry-specific digital maturity indexes to gauge advancement in standardization activities, especially in manufacturing hubs where SMEs emphasize bigger supply chain participants.

The theoretical frameworks of the last several years need to be empirically tested with the help of longitudinal and mixed-method research designs. The long-term research is able to record the evolutionary character of the SME digital transformation, and individuals should note how the technological adoption, organizational learning, and collaboration develop together over the time. Cross-case comparisons between the SMEs having different levels of digital maturity should also be conducted to empirically validate the dynamic interrelations between technological alignment, organizational readiness, and ecosystem collaboration. Through quantitative performance indices and qualitative insights, future research can make evidence-based improvements to theoretical frameworks to change the theoretical propositions into actionable schemes that can be applied by practitioners and policymakers.

Lastly, the research in the future must concentrate on the incorporation of sustainability and resilience measures into SME supply chain monitoring and standardization models. Despite the increased visibility of operations provided by the digitalization, the number of studies that focus on how the monitoring systems could be used to trace the carbon emissions, energy efficiency, circular flows of resources, or social compliance indicators is quite small. Similarly, the COVID-19 crisis highlighted the importance of resilient supply chains that can absorb shocks due to flexible supply chains based on data and standard communication. Incorporating ESG (Environmental, Social, Governance) and resilience-focused indicators into standardized digital systems will allow SMEs to work in line with the sustainability objectives worldwide and enhance their adaptability. In this way, multi-objective models that combine economic

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performance, sustainability, and resilience should be the defining trend of the next research that will offer a comprehensive blueprint to the next generation of SME-based supply chain monitoring systems.

CONCLUSION

This review has depicted that standardization of the supply chain monitoring tools is not just a technical requirement but a strategic facilitator of digital inclusion, competitiveness and sustainability among Small and Medium-sized Enterprise. Based on the literature, it can be concluded that a patchwork system, data heterogeneity, and the absence of interoperable structures are major challenges to the involvement of SMEs in global digital ecosystems. The suggested conceptual model, which is based on the pillars of technological alignment, organizational preparedness and collaborative ecosystems, provides a scaled method of making it through these challenges. It fills the divide between theory and practice through the illustration of how interoperability standards, combined with capacity building and shared infrastructures on digital, can democratize access to Industry 4.0 technologies.

In conclusion, standardization is not just harmonization of procedures; it is the basis of fair digital transformation (Guarin, A. Y. L. 2024). Standardization promotes innovation, efficiency, and resilience in the whole industrial environment since it allows SMEs to become a part of bigger supply networks. This review has its theoretical contribution as it brings together scattered evidence in a dynamic socio-technical model and its practical contribution, where it has been used to present a roadmap that policymakers, industry regulating organizations, and the managers of SME can use to synchronize technology and governance in scalable forms. Going forward, a coordinated, global, and national policy that encourages modular and cost-effective standards will be essential to make sure that digital transformation is inclusive, sustainable, and helpful to every level of the manufacturing ecosystem.

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