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Major Supply Chain Challenges in the Era of Heavily Concurrent Industrial Processes: An Integrated Supply Chain Management 4.0 Framework

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Abstract
This study aims to comprehensively examine the supply chain management concept, starting from its fundamental principles and delving into the primary hurdles hindering its effective implementation alongside exploring the latest emerging trends. Key challenges include fostering innovation and robust partnerships for supply chain management, seamlessly integrating new product development and concurrent engineering processes. Furthermore, current trends underscore the imperative of achieving sustainability within supply chain frameworks, striving to cultivate flexibility and resilience. Supply chain management should be aligned with environmentally conscious practices ("green" initiatives) embracing the transformative potential of Technology 4.0 to usher in the era of Industry 4.0. A review of existing literature regarding the implementation of supply chain management was carried out seeking to identify best practices. Based on the literature analysis and through content analysis methodology notable gaps have been discerned where further exploration is warranted particularly concerning the evolving supply chain management, sustainability, green supply chain management initiatives and the integration of Technology 4.0. These areas present opportunities for deeper investigation to provide pillars for future advancements in supply chain management practices. Research demonstrates that organizations must prioritize the integration of information-based systems to support supply chain management as well as the need for risk assessment. A framework is proposed in six parts bridging the domains of Industry 4.0, concurrent engineering and supply chain management. By aligning technology and process design it is possible to conceptualize and measure the true impact of Industry 4.0 on performance.

Keywords
Supply Chain Management; Industry 4.0; Information Technology; Sustainability; Risk Assessment.

Introduction

Product development requires reliable innovative solutions to deliver sophisticated, yet cost-effective goods. This entails accelerating product release cycles while upholding quality standards (Li et al., 2006; Liao et al., 2017). Achieving optimal product maturity, within agreed timelines, is ensured if all customer needs are met and quality is sustained (Dourado et al., 2013; Yoo et al., 2015).

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When dealing with new product development (NPD), external purchasing requires process analyses, including: (*i*) lead time of purchased component; (*ii*) short life; (*iii*) general *versus* customized components; (*iv*) process variation on suppliers (dimensional/ appearance); and (*v*) alternatives for supplier when facing customized components (Dourado et al., 2013). These considerations are applied not only for standard operating procedure (SOP), but also for mass production.

An effective supply chain management (SCM) is essential to achieve this desired product maturity and quality. However, it is important to overcome the challenges and the transformations that have been propelled by digital technologies and global market dynamics (Cigolini et al., 2014; Yan-Chan et al., 2016). Depending on companies' size and nature, SCM encompasses elements such as suppliers, production systems and distribution networks, all of them interconnected to meet operational demands (Bajdor & Grabara, 2011; Kovács & Paganelli, 2003).

SCM primarily focused on material flow from suppliers to customers, optimizing manufacturing, transportation and inventory management, while minimizing costs and meeting customer needs (Chang & Makatsoris, 2001). Originating from Logistics, SCM evolved from a focus on supplier efficiency to addressing both supplier and customer needs, embracing concepts like "Pull" production to synchronize production with market demand (Treville et al., 2004; Chang & Makatsoris, 2001).

An effective SCM serves as a pivotal means to secure competitive advantage and enhance organizational performance, acknowledging that competition transcends individual organizations to encompass entire supply chains. This viewpoint is shared by other scholars (McFarlane et al., 2016; Ramanathan, 2014; Sabri et al., 2018; Scheuermann & Leukel, 2014). Given the evolving market landscape and SCMs impact on companies' success, a critical analysis of its contemporary roles, functions and challenges, amid current trends, becomes imperative to investigate.

It is also important to note that the "dawn of the heavily concurrent engineering (CE) processes" refers to the historical period when industries began to adopt systems and technologies that allowed multiple processes to operate simultaneously. This marked a significant shift from manual, sequential production methods to automated, continuous, and highly integrated systems (Singhry et al., 2016).

Thus, this paper aims to scrutinize the evolution, transformations and challenges of SCM within the broader context of enhancing organizations' competitiveness. An analysis of how robust the organizations have been establishing a risk management methodology for all potential situations to be handled in SCM is discussed.

The analysis is based on a literary review with an overview of SCM from the 1980s to the present, identifying the best practices proposed for each temporal phase of SCM. Through a content analysis, this research synthesizes the evolution of SCM towards heavily concurrent and Industry 4.0-enabled processes.

The work identifies four main research gaps: (1) the limited empirical implementation studies of Industry 4.0 technologies in SCM; (2) the lack of an integrated upstream–downstream framework linking SCM practices to companies performance; (3) the dearth of maturity models and empirical studies for supply-chain flexibility; and (4) the scarce research on the implementation, control and monitoring phases of supply chain risk management. By mapping these gaps, the paper provides a focused research agenda to guide empirical work that will promote SCM 4.0 implementation.

The paper is structured in seven parts. In Section 2 the fundamentals of SCM are presented, identifying some of the key factors of SCM, focusing on SCM performance. Section 3 presents a brief explanation of the applied research methodology. In Section 4, the main challenges of SCM to adapt to the current times are presented, such as green SCM, sustainability; flexibility; SCM 4.0; resilience and risk management. This is followed by the framework (Section 5), a short discussion on the theme (Section 6) and conclusion (Section 7).

Literature Review

Scope of SCM

Logistics and SCM focus on the efficient flow of materials, information, and value across networks. Christopher (1999) emphasizes that competitive advantage arises from entire supply chains rather than individual organizations. Effective SCM integrates processes, reduces total costs, and enhances customer value through collaboration and responsiveness. Balancing lean efficiency with agile flexibility enables firms to adapt to changing market demands. Christopher (2005) also highlights the importance of risk management, resilience and sustainability, claiming that technology-driven supply chains are key to achieving long-term competitiveness and organizational success. Mentzer et al. (2001) define SCM as a strategic and systemic coordination of business roles across organizations within the supply chain to improve long-term performance for both the individual companies and the supply chain elements.

Lambert et al. (1996) highlight the importance of integrating processes such as sourcing, production, and distribution to enhance efficiency and customer value.

The success of the SCM encompasses planning, synchronization of tasks and the adoption of integrated management methodologies (McLaren et al., 2002; Simatupang et al., 2002).

This foundational framework influences the coordination chain (Naude & Badenhorst-Wiess, 2011), impacting critical facets such as raw material pricing, delivery schedules, supplier financial stability and trust levels within the organization-supplier relationships. From the customer standpoint, issues arise from inadequate communication regarding market demand, order cancellations and sluggish inventory turnover due to delayed orders.

Deshpande (2012) underscores that competition no longer solely resides between organizations but extends to their entire supply chains. However, the existing research often overlooks the interplay between SCM dimensions and performance, particularly on how SCM dimensions correlate with the organizational outcomes (Deshpande, 2012). While dimensions like cost, time and flexibility are recognized in assessing Supply Chain Performance (SCP), few studies explore the relationship between supply chain flexibility and organizational success. Furthermore, there is a call to incorporate customer responsiveness time as a vital dimension in the SCP construct.

Alternative approaches to coordination flow management and SCM, as presented by Kovács & Paganelli (2003), emphasize bilateral supply relationships with individual customers and suppliers, yielding enhanced network visibility, improved coordination and real-time control over material flows. Yet, despite advancements, major Enterprise Resource Planning (ERP) still lack seamless online integration and synchronization with other network elements (Kovács & Paganelli, 2003; McFarlane et al., 2016).

Mohammad et al. (2011) highlight a shift in business focus from singular exchange transactions towards long-term and strategic buyer-seller relationships. When thoughtfully planned and executed, SCM positively influences organizational functions and outcomes, including operations effectiveness, process and product quality, customer responsiveness, manufacturing cost efficiency, market adaptability and overarching performance metrics such as market share and profitability (Linder & Sperber, 2019).

Current Changes and Developments

In today's landscape, SCM has evolved into a realm of heightened complexity, influenced by stakeholders grappling with increasingly stringent time and cost constraints. The multifaceted impact and diverse perspectives of SCM in contemporary contexts are being examined, offering insights into SCM dynamics and future trajectories (Linder & Sperber, 2019; Sabri et al., 2018; Scheuermann & Leukel, 2014). Few perspectives have been explored in detail:

- Partnerships in SCM: Delving into collaborative alliances within SCM networks, emphasizing the critical role of strategic partnerships in fostering resilience and innovation.
- Innovation: Unravelling the nexus between SCM and innovation, highlights how novel approaches drive competitiveness and sustainability within supply chains.
- Integration with NPD and CE processes: Clarifying the symbiotic relationship between SCM and NPD/CE processes, emphasizing the imperative of seamless integration for enhanced efficiency and agility.
- Information technology (IT): Investigating the influence of IT on SCM, underscoring its transformative potential with the integration of information management and performance optimization.
- SCM Performance: Scrutinizing the determinants of SCM performance, from NPD processes to IT integration and their cascading impacts on organizational competitiveness and efficiency.

These perspectives serve as linchpins for driving substantive changes within SCM frameworks, facilitating intra-organizational dynamics, thereby shaping partner selection criteria. Terminology as "Push", "Pull", and "Push-pull" systems elucidates operational strategies, ranging from forecast-driven to demand-driven approaches, with each presenting distinct advantages and limitations. These strategies integrated into hybrid models represent a pragmatic approach to optimize SCP (Janvier-James, 2011).

Emerging research frontiers in SCM encompass diverse domains, from NPD processes fostering competitive advantage (Prasetyo & Dzaki, 2020) to the pivotal role of IT integration (Boubker, 2022) and innovative technologies like blockchain (Reddy et al., 2021; Kopyto et al., 2020).

These endeavours underscore the evolving landscape of SCM, heralding new paradigms and opportunities for organizational growth and competitiveness.

Deepening SCM Integration

SCM is structured across five dimensions, as delineated by Li and colleagues (2006): strategic supplier partnership, customer relationship, level of information sharing, quality of information and postponement.

These dimensions interweave SCM practices, competitive advantage, and organizational performance (Li et al., 2006). Additionally, Janvier-James (2011) distinguishes two primary forms of integration: horizontal and vertical. Horizontal integration consolidates entities at similar production levels, fostering resource-sharing, while vertical integration unifies entities across the entire production spectrum, from raw materials to distribution (Janvier-James, 2011). The evolution of SCM stems from the convergence of two distinct trajectories: purchasing with supply management and transportation with logistics management. From the purchasing and supply management perspective, SCM embodies the integration of the supply base, evolving from traditional purchasing and materials functions.

Conversely, from the transportation and logistics management perspective, SCM embodies integrated logistics systems, prioritizing inventory reduction across organizational boundaries. This integration combines all supply chain activities into a cohesive framework.

Exploring supplier-centric themes, research delves into supplier selection, involvement, manufacturing performance, the impact of supplier alliances and success factors in strategic supplier alliances (Li et al., 2006). Furthermore, case studies conducted by IT service providers such as SAP offer insights into SCM implementations, contributing to a comprehensive understanding of SCM practices. However, a notable gap lies in the absence of an integrated framework encompassing all upstream and downstream supply chain activities, correlated with competitive advantage and organizational performance. Supply integration optimizes manufacturing and delivery efficiency, while demand integration enhances market mediation, by facilitating responsive customer-centric approaches (Treville et al., 2004). Organizations recognize the indispensability of integrated manufacturing and distribution processes, as well as relationships with suppliers and customers for sustained success (Chang & Makatsoris, 2001). Integration within the supply chain creates enhanced flow of goods and information, fostering agility and flexibility, thereby improving customer satisfaction levels (Janvier-James, 2011; Kumar, 2014; Yoo et al., 2015).

Pushing SCM Performance

Efficiency within the realm of SCM has spurred the development of methodologies and techniques to gauge SCM efficiency (Janvier-James, 2011).

These approaches serve as invaluable tools for assessing performance levels across supply chains, empowering supervisors to pinpoint areas for improvement. Recognizing that the performance of the entire supply chain is pivotal for achieving effective SCM, it becomes imperative to use the collective resources of supply chain members in the most efficient manner possible to deliver competitive and cost-effective goods and services (Janvier-James, 2011).

Within criteria used to evaluate SCM efficiency, certain aspects stand out, including reliability, cost and customer satisfaction (Janvier-James, 2011; Linder & Sperber, 2019). Extensive research by Fawcett et al. (2012) provides a comprehensive analysis of achieving effective SCM, elucidating potential benefits, barriers and bridges to strategic SCM. Customer satisfaction is not only achieved by cost savings. Technology, information and control systems need to be considered to reach successful supply chain collaboration (Fawcett et al., 2012; Iwata & Mavris, 2013; Wu & Chiu, 2015).

Globalization has introduced challenges for small and medium enterprises (SMEs), prompting shifts to regions with lower production costs, thereby altering supply chain dynamics. Innovation deficits compel the exploration of methodologies like the Theory of Inventive Problem-Solving (TRIZ) to boost novelty and productivity in NPD and SCM (Lin & Chen, 2021). While TRIZ methods contribute to innovative products fostering, practical implementation may encounter reliability hurdles, potentially leading to customer dissatisfaction. Schiele et al. (2021) emphasize the implication of including professional purchasing agents into the innovation process, supported by strategic measures such as senior management backing, structural differentiation, explicit processes, and collaborative corporate culture (Schiele et al., 2021).

Ellram et al. (2020) employ agency theory combined with Information Processing Theory (IPT) to clarify conflicts in cost reduction during NPD, navigating uncertain environments and accessing diverse information sources to optimize outcomes. Moreover, integration of concurrent product design engineering (CEPD) into advanced manufacturing technology (AMT) emerges as a strong strategy for enhancing SCP, bolstering customer responsiveness, competitiveness and product quality (Singhry et al., 2016). IT assumes a pivotal role, with e-logistics emerging as a linchpin for information sharing and transparency across supply chains, bolstering competitiveness (Erceg & Sekuloska, 2019; Partyka, 2022).

In the quest to enhance logistics SCP within the logistics industry, the integration of blockchain technology is increasingly gaining traction. Blockchain, a decentralized ledger technology, facilitates data storage and sharing in a secure, immutable manner across a network of distributed peer-to-peer members.

By leveraging built-in security measures, blockchain bolsters transaction integrity within the supply chain. One of the key attributes of blockchain is its decentralized and distributed ledger, which harnesses the processing power of all network participants, mitigating single point of failure and scalability concerns. As each block in the ledger references the previous block, creating an unbroken chain, data stored within blockchain remains tamper-proof and immutable, ensuring transparency and data integrity. This transparency is further increased by sharing transaction details among all users, fostering accountability (Reddy et al., 2021; Kopyto et al., 2020; Hye et al., 2020; Kamble et al., 2021; Sarfaraz et al., 2023; Nayak & Dhaigude, 2019).

The adoption of blockchain technology in SCM offers benefits, including enhanced access to data, robust security protocols and improved communication among stakeholders. Also, it unlocks opportunities for performance optimization and the integration of smart devices. However, challenges such as the readiness of supply chain players, regulatory gaps, and concerns about data privacy and identity theft must be addressed to fully capitalize on blockchain's potential (Nayak & Dhaigude, 2019).

Another concept is the supply chain fit. This concept entails aligning supply chain characteristics, such as structure, design and strategies, with product and demand characteristics to achieve an optimal balance between efficiency and responsiveness. While much research has focused on the impact of supply chain fit on financial performance, the nexus between supply chain fit, business performance and innovation is the core (Zimmermann et al., 2020).

The integration of blockchain technology can revolutionize supply chain operations, enhancing transparency, security, and efficiency. Likewise, the strategic alignment of supply chain characteristics through SC fit offers opportunities for optimizing performance and fostering innovation.

Trends in Industry Concurrent Process

The manufacturing, energy and chemical industries are evolving into highly concurrent, interconnected systems. This evolution is driven by Industry 4.0 paradigm, which integrates sensors, connectivity and advanced data analytics throughout production and logistics processes. Internet of things (IoT) devices and cloud-based platforms enable real-time monitoring of plant operations, while advanced automation and robotics facilitate parallel execution of tasks.

By integrating data, organizations achieve end-to-end supply chain visibility, enhancing both decision-making speed and operational agility. Modern supply chains can be made more flexible and adaptable with the help of digital technologies such as cloud computing, Industry 4.0, IoT, big data analytics, blockchain, Artificial intelligence (AI), edge computing and additive manufacturing (Treville & Cosic, 2017). In addition, the digital twins allow creating a virtual replica of physical products, processes, or systems, allowing for simulation and testing of concurrent scenario, demand spikes or supply disruptions, without disrupting physical operations. Event-driven architecture (EDA) uses distributed systems to capture and process streams of data generated by events across the supply chain. This enables decision-making as issues occur. These technologies transform how production systems and networks coordinate activities. Manufacturing lines become "smart" and adaptive, capable of reconfiguring dynamically in response to demand fluctuations or operational disruptions. The outcome is a tighter integration between physical assets and information flows, notably improved responsiveness to market dynamics and greater resilience against shocks such as supply interruptions or equipment failures (Patil el at, 2023).

Industry 4.0 brings connectivity and intelligence to industrial operations. Sensing stream machine data continuously into analytics platforms, and high-speed networks (including emerging 5G) connect distributed assets. Nowadays, manufacturers use embedded sensors and robotics to coordinate assembly and quality checks in real time (Dolgui & Ivanov, 2022).

Digital platforms and cloud-based systems integrate manufacturing execution, inventory, and logistics data to keep the whole network synchronized. In practice, this means production schedules can adjust instantly if a delay occurs upstream, minimizing bottlenecks.

Modern Industry 4.0 assembly lines are equipped with collaborative robots, 3D printers and automated guided vehicles. Similarly, the Pull systems based on Lean Manufacturing principles combine just-in-time production with reconfigurable equipment, letting it rapidly adjust production schedules.

Overall, such smart technologies reduce lead times and raise throughput. As a result, manufacturing lines are no longer isolated sequential processes, but tightly networked systems that self-optimize. Traditional Lean Manufacturing and newer *Agile* practices both underline flexible workflows, allowing a rapid production schedule change. This means that if one production module goes down, others can take place or shift product mix. While cloud data analyse trends and models, edge computing brings intelligence to the shop floor and the field. Edge devices (controllers, industrial PCs, AI) process data locally with minimal latency. By analysing data on-site, edge systems can take immediate action without round-trip cloud delays. Edge computing also enables scale-out concurrency. In large plants or long production lines, each segment can act semi-autonomously, coordinated through local AI agents (Wahlgård et al., 2025).

Finally, the trend of integrated digital supply chains. These trends are reshaping supply chains themselves. The idea of Supply Chain 4.0 is to treat the entire logistics network as one digitally coordinated system. Advanced planning systems merging data from plants, traffic data from logistics, and sales data from suppliers in real time allows the organizations to synchronize all the SCM elements. This result has a net effect and a far tighter integration process (Palacios-Gazules et al., 2024).

Materials & Methods

Two methodological methods were implemented to perform the current study. First, a non-structured literature review was conducted to identify the most relevant approaches for evolution, transformations, and challenges of SCM. Afterwards, a content analysis was conducted, by analysing the selected documents from the literature review process.

Unlike systematic literature reviews, which follow a structured process with predefined search terms, inclusion/exclusion criteria and data extraction methods, literature reviews offer a more flexible and exploratory approach. This method enables in-depth investigation of a subject, involving extensive reading and note-taking. Several sources, such as scientific journals, conference papers, books/book chapters and online databases, can be used to gather relevant information (Saunders et al., 2023).

This methodology is particularly useful for exploratory research, where the primary objective is to gain a comprehensive understanding of a specific subject, identify key discussions, and formulate hypotheses for future investigation. Despite the limitations regarding reproducibility and the susceptibility to the researcher bias in the selection and interpretation of literature, the implemented method was based on transparency principles to ensure the reliability of the findings. Those limitations were mitigated through a rigorous content analysis.

Content analysis is used to analyse qualitative data, predominantly text-based, involving the content comprehension in resources consulted, including scientific articles. It is an organized technique for analysing information, allowing researchers to uncover insights through qualitative methodologies alone (Neuendorf & Kumar, 2016).

The purpose of the research method was to investigate recent developments and innovations in SCM, especially for latest trends and barriers for implementation. This investigation was especially pertinent to understanding the role of SCM in solving the barriers during the different NPD phases. Thus, a main research question was proposed: "*How are emerging trends and concurrent process innovations reshaping the major challenges and risks in SCM?*"

The literature review was conducted by consulting research from the *Scopus*, *Google Scholar* and *Web of Science* databases, focusing on the challenges of SCM. The research design is presented in Table 1.

The review involved a series of sequential searches based on a set of keywords: "SCM Challenges", "SCM trends", "SCM barriers" and "SCM Risk Management".

Table 1
Research design

Criteria	Parametrization
Research Problem Identification	• Define the scope of SCM. • Identify key concerns: Challenges, Trends, and Risks.
Objectives & Sub-Research Questions	• What are the major challenges in SCM today? • What are the emerging trends shaping SCM? • What are the key risks affecting SCM operations?
Methodology Selection	• Qualitative research methods based on Literature Review. • Data Collection based on secondary data.
Data Analysis	• Content analysis. • *VOSviewer*® for bibliometric analysis.

The search was conducted based on the occurrence of the keywords in the "ABS-TIT-KEY", *i.e.*, the occurrence of the keywords on the documents abstract, title and keywords fields. No time frame restrictions were considered, allowing for an examination of how the topic has evolved over the years. The inclusion criteria comprised documents from international journals and conference proceedings, written in English. The search yielded a total of sixty-six documents. These selected documents were then subjected to a content and descriptive analysis.

Content Analysis Results: Insights into Challenges in SCM

In this section, the results from the literature review content analysis are presented. After contextualizing SCM 4.0 coverage, the most important insights into sustainability, resilience, flexibility and risk management of SCM are disclosed.

Era of SCM 4.0

SCM 4.0 represents the convergence and harmonization of the entire product value chain across diverse companies, employing intelligent technologies such as the IoT, Internet of services (IoS). This integration fosters the establishment of an interconnected and transparent system with real-time communication capabilities, facilitating flow management and optimization. Consequently, it engenders an autonomous, adaptive, intelligent, agile, and dynamic network that prioritizes customer needs.

The Supply-chain operations reference (SCOR) model, endorsed by the Supply chain council, is the process reference model. It endeavours to consolidate business processes, metrics, and best practices into a unified framework, enabling communication among different stakeholders (Kunrath et al., 2023).

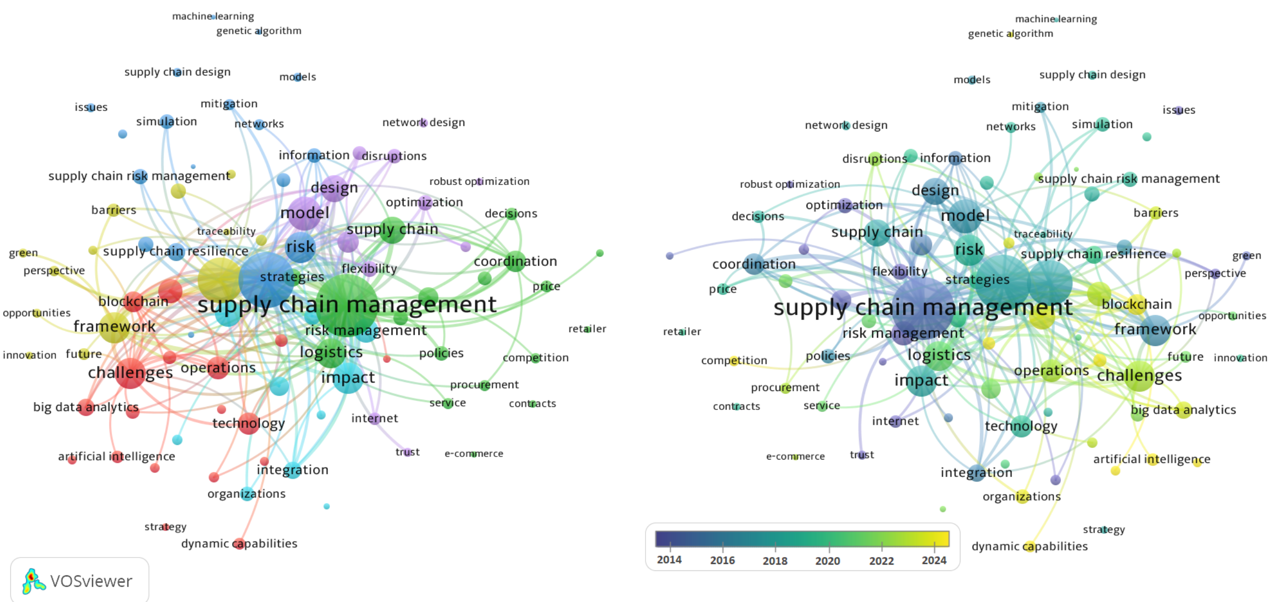
Cloud computing, a cornerstone of modern IT infrastructure, entails the delivery of services over the Internet, encompassing data storage, servers, databases, networking, and software. It has gained widespread adoption among individuals seeking expansive storage solutions and businesses pursuing efficient off-site data backup strategies. In SCM, cloud computing is leveraged for decision-making, training, and collaboration across diverse supply chain entities.

However, challenges such as security risks associated with remote data storage necessitate cautious consideration, as organizations rely on their cloud service providers for data integrity and confidentiality.

Despite the growing interest in Industry 4.0, practical applications in the realm of SCM remain limited. Technologies such as radio frequency identification (RFID), Real-time location systems (RTLS), Cyber-physical systems (CPS), IoT, Big data analytics, data mining, IoS and ERP hold immense potential but require further exploration and implementation (Kunrath et al., 2023; Frazzon et al., 2019). Potential areas of research include investigating how Industry 4.0 technologies can enhance supply chain efficiency and effectiveness, assessing their impact on supply chain risk and resilience, exploring their role in fostering sustainable supply chains, studying their implications on employment and skills within the supply chain sector, scrutinizing the ethical considerations associated with Industry 4.0 and SCM, ensuring robust information/data security in collaborative networks (Kunrath et al., 2023). Fig. 1 presents the bibliometric map of the co-occurrence of indexed keywords regarding the search for SCM challenges and trends.

These *VOSviewer* maps allow users to visualize keywords (nodes) that frequently co-occur in the literature. Each keyword represents a node, which size is related to the frequency of occurrence, meaning that larger nodes represent more central or frequently discussed topics. Node colours in Figure 1a show thematic relationships and co-mentions (clusters), whereas Fig. 1b show the keywords organized by year of publication.

The data is arranged in six keywords clusters (Figure 1a). One of the clusters is related with the challenges deeply related to the technological transition, mostly with the adoption of blockchain, AI and big data analytics. The cluster of the SCM frameworks encompasses the green and resilient supply chain. Another cluster is related to the SCM models which depends on robust optimization, network design and, simultaneously, flexibility. While the smaller cluster corresponds to the SCM impact, which links to the risk



(a) (b)

Fig. 1. Bibliometric map of the co-occurrence of indexed keywords regarding SCM challenges and trends: a) cluster analysis; b) timeline analysis. The map was obtained through *VOSviewer*®software

management analysis, the more comprehensive regards the main aspects of the SCM, namely, the logistics, procurement, contracts, services, policies and decision-making, distribution, contracts, among others.

From a chronological perspective (Fig. 1b), early studies focused on traditional issues such as risk management, logistics coordination and performance optimization. Afterwards, the attention shifted to resilience, sustainability and digital integration, reflecting responses to global disruptions and the growing importance of adaptability.

More recently, works highlight the emerging technologies, including blockchain, data acquisition systems and innovation frameworks. Managerial and technological integration enable real-time, concurrent operations across global supply networks.

Green and Sustainable SCM

The automotive industry has confronted environmental challenges concerning the ecological impact of its products and processes, prompting a shift towards more environmentally and sustainable practices. This transition has prompted the emergence of green supply chain management (GSCM), wherein most of the organizations prioritize environmental considerations throughout operations. This shift towards sustainability has not only transformed supply chain practices but also cultivated a culture of environmental consciousness.

Current studies in this domain focus on three primary objectives: (*i*) identifying prevalent GSCM practices across various industrial sectors globally; (*ii*) evaluating the perception and adoption of these practices within the automotive industry by professionals and researchers; and (*iii*) assessing the impact of these practices on environmental performance within companies and supply chains.

Yet, few challenges persist, including the low enforcement of fines related to environmental violations, ambiguity surrounding the effectiveness of supply chain collaboration, limited prioritization of green procurement and the significance of ISO 14001 certification in facilitating the adoption of GSCM practices (Lopes & Pires, 2020).

Supplier selection for green components assumes paramount importance and requires an approach that involves multi criteria decision making (MCDM).

In this context, a hybrid MCDM method known as DEMATEL-based Analytical Network Process (DANP) coupled with grey relational analysis (GRA), termed as grey DANP (GDANP), has been applied effectively. This methodology aids in discerning key selection factors for green suppliers in the automotive industry, with findings aligned closely with expert opinions. Notably, factors such as technology, delivery time, environmental management systems, and pollution control emerge as pivotal considerations in supplier selection. The successful application of GDANP highlights its efficacy in SCM, offering valuable insights for enhancing sustainability across automotive supply chains (Jiang et al., 2018).

Concerning the sustainability perspective, in today's business landscape, achieving sustainability requires a strategic roadmap geared towards long-term growth in production and service practices. At its core, sustainability entails utilizing products and services in a manner that preserves resources for future generations. Integrating sustainability into SCM should encompass every facet of production, from inception to product lifecycle management.

The objective of sustainable supply chain management (SSCM) is to address environmental, economic and social considerations across all stages of product development and distribution.

This entails diligence in sourcing raw materials, production processes, logistics and product sales. Consequently, supplier selection assumes heightened significance in fostering a SSCM. To effectively evaluate supplier performance and classify sustainable suppliers, a cross-efficiency model has been devised leveraging data envelopment analysis (Tabatabaei & Bazrkar, 2019). While literature on SSCM abounds, studies specifically addressing sustainability within the automotive sector, within the context of the circular economy, remain limited. By identifying and hierarchically structuring barriers to sustainability within the automotive supply chain, organizations can devise targeted strategies to overcome these impediments.

Key barriers identified include a lack of awareness regarding the adoption of reverse logistics, inadequate information sharing on sustainable practices, and the complexity associated with measuring and monitoring suppliers' environmental activities. Moreover, recognizing the imperative of digital transformation in tandem with sustainability goals, organizations are increasingly leveraging Industry 4.0 technologies to address sustainable development challenges and the digital transition (Sonar et al., 2022).

The broader pursuit of sustainability also embraces the circular economy – an economic paradigm premised on sustainable production and consumption practices. The circular economy model embodies principles such as economic permaculture, green economy, reuse, repair and recycling of materials to mitigate waste and resource depletion (Jamwal et al., 2021).

Supply Chain Flexibility

The flexibility of a supply chain encompasses both internal dynamics within the organization and external interactions with customers and suppliers.

A flexible supply chain demonstrates adeptness in swiftly adapting internal capabilities and external ones. The internal capabilities harmonize internal functions to respond to fluctuations or uncertainties, whereas the external capabilities promote interactions with external stakeholders.

Thus, organizational capabilities allow to meet unforeseen demands and expedite the introduction of new products (Nagy-Bota & Moldovan, 2022).

Employing maturity models offers companies valuable insights to evaluate and enhance their supply chain processes by gauging their maturity level and pinpointing areas where flexibility enhancements are warranted. However, literature on the analysis of flexible supply chain maturity and its distinct levels remains sparse, needing further theoretical and empirical investigations. The model dimensions should include flexibility, information sharing, IT, and performance measurement (Mello et al., 2019; Mohammad, 2011).

For instance, information sharing serves as a prerequisite for fostering flexibility, while IT and collaboration function as enablers for achieving internal flexibility across various domains such as machinery, labour, logistics, and supply chains. Subsequently, Performance Measurement assumes a pivotal role in monitoring internal flexibility and assessing the attainment of external flexibility goals (Mello et al., 2019).

Supply Chain Resilience

Companies are increasingly recognizing the importance of developing "leading indicators" to detect emerging vulnerabilities within their supply chains. These indicators encompass several factors, including disruptive political forces, evolving product requirements, critical resource dependencies, and constraints on peak capacity.

To enhance supply chain resilience, tools like the supply chain resilience assessment and management (SCRAM) have been devised. SCRAM serves as a measurement tool designed to pinpoint key aspects of resilience warranting close monitoring. By employing this methodology, supply chain stakeholders can not only identify vulnerabilities but also quantitatively assess risks based on the likelihood of events and the consequences severity. This approach enables organizations to compare vulnerabilities with available capabilities within their supply chains. Furthermore, SCRAM facilitates the delineation of a balanced zone of supply chain resilience, wherein profits are not compromised, and exposure to risk are mitigated. This analysis extends beyond the organization's boundaries to encompass its entire supply chain, spanning from raw material suppliers to end consumers and reverse logistics channels (Kouvelis et al., 2006). By incorporating all relevant stakeholders, companies can effectively safeguard their supply chains against disruptions and optimize their overall performance (Pettit et al., 2019).

Supply Chain Risk Management

Supply chain risk management (SCRM) refers to strategies to deal with risks along the supply chain, considering continuous risk assessment and applying proper tools, either in collaboration with supply chain partners (preferential) or individually, to deal with risks and uncertainties caused by logistics-related activities, product availability (goods and services) or resources. It is an important step within SCM, since it suggests suitable measures and strategies to mitigate and/or eliminate risks along the supply chain, increasing its resilience (Oliveira et al., 2018). Some of those risks are related to the global and dispersed information technology structure, threatening the integrity, reliability and authenticity of goods and services (Emrouznejad et al., 2023). Managing global supply chains get more complex if the risks are not assessed, from natural disasters and geopolitical instability to cyber-attacks and supplier bankruptcies. Thus, organizations need to understand the key aspects and emerging trends in SCRM (Emrouznejad et al., 2023). Typical risks associated with SCRM studies include economic, environmental, political, ethical, manufacturing, storing and shipment, legal, quality, delays, theft, natural catastrophes, weather-related issues and cybercrime. It is also considered a risk the inadequate project management or alterations to the scope of SCM. Also, autonomous mobile robots, distributed ledger technology (DLT) and AI are some of the technologies expected to positively impact SCM in the future, but their adopting can bring new security risks (Emrouznejad et al., 2023).

The strategies for success in SCRM include diversifying suppliers, building strong relationships with suppliers, monitoring supplier performance and investing in technology to develop Supply Chain visibility and resilience (Emrouznejad et al., 2023). Usually, SCRM is described by seven phases: context analysis, risk identification, risk evaluation, strategy selection for risk treatment, strategy implementation, control and monitoring (Gaspar et al., 2020; Oliveira et al., 2018). It is recognized that risks identification and evaluation are the most studied phases, based on scenarios simulation.

Majorities of publications addressed to SCRM show a lack of standardization of SCRM implementation.

Another point to be considered is the existence of a research gap concerning the last three phases (implementation of risk treatment strategy, control, and monitoring). The lack of theoretical and practical studies regarding the implementation of risk strategy, control and monitoring, justifies the low number of proposed tools (Gaspar et al., 2020).

Yet, the future research should focus on developing standardized guidelines for sustainable SCM, exploring emerging technologies' impact on risk management and logistics efficiency (Emrouznejad et al., 2023).

Integrated Concurrent SCM 4.0 Framework

The global shift toward digital transformation has redefined the dynamics of SCM. The dawn of the heavily concurrent process industry has intensified the interest in emerging technologies and how the organizational capabilities and process planning interact to drive resilience, flexibility and sustainability in supply chains. However, as presented in the previous section, existing literature remains fragmented. Research often treats Industry 4.0 technologies, CE and SCM as isolated topics, overlooking their combined influence on companies' performance.

The Integrated Concurrent SCM 4.0 framework suggests that the deployment of Industry 4.0 technologies (*e.g.*, IoT, AI, big data analytics, blockchain and robotics) enables new forms of concurrent process design within supply chains. These technologies empower multiple production and logistics processes to operate simultaneously, supported by real-time data exchange and autonomous control mechanisms.

However, this transformation depends on organizational capabilities, such as IT integration, digital maturity, and governance systems. All of them can be the key in converting technological potential into operational reality.

Thus, the framework (Fig. 2) proposes that heavily concurrent processes modify core SCM practices across sourcing, production, logistics and reverse logistics. This transformation operates through three critical intermediating mechanisms:

(1) Enhanced information sharing.

(2) Reduced decision latency.

(3) Improved process performance, resilience, flexibility and sustainability.

Still, it is important to note that these relationships depend on contextual factors such as industry type, regulatory intensity, network complexity and company size. Thus, the framework definition can be divided into six parts. The first one concerns the adoption and integration of digital among other technologies that facilitate real-time monitoring and autonomous control across supply-chain stages.

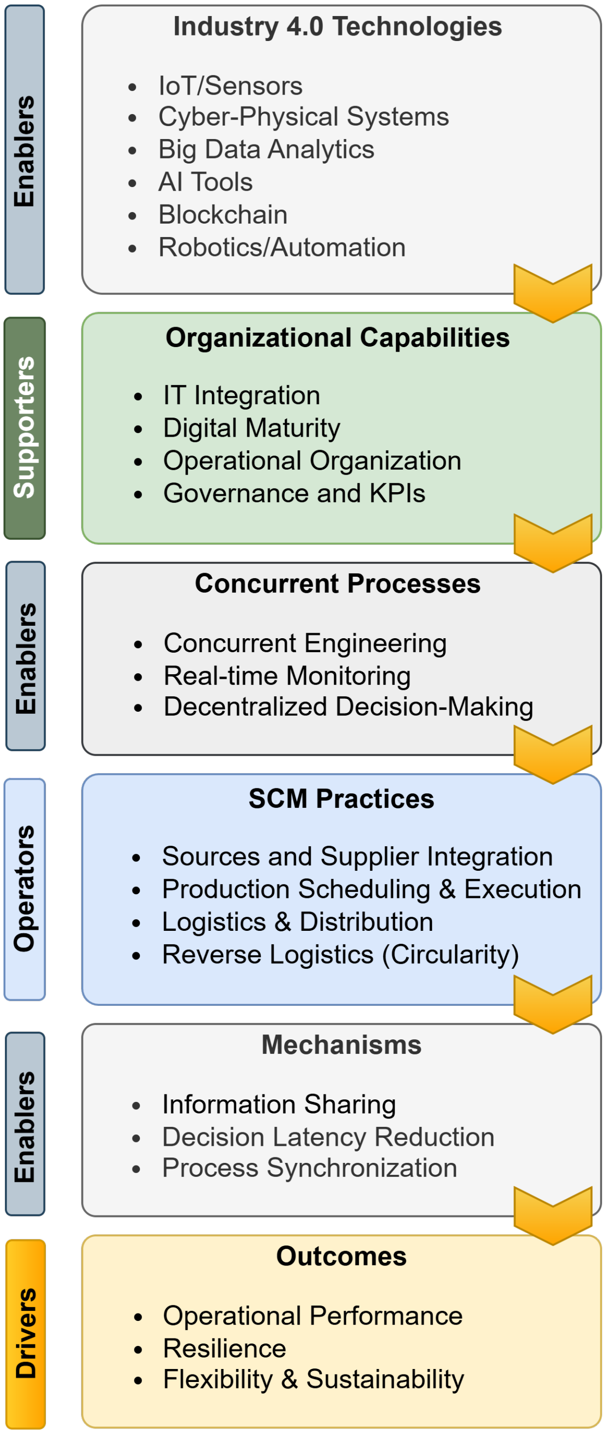


Fig. 2. Integrated Concurrent SCM 4.0 framework

The technology options are the enablers that allow companies to exploit Industry 4.0, including IT infrastructure, cross-functional collaboration and governance systems (second part).

The architectural shift from sequential to overlapping and simultaneous process execution (third part), such as CE, decentralized decision-making and dynamic scheduling enables the SCM practices (furth part) through operational routines across sourcing, production, logistics and circularity that are redefined through concurrency and digitalization.

Information-sharing (fifth part), decision latency and process synchronization are also enablers of the process design, which translate into outcomes (sixth part. The performance results should encompass multidimensional outcomes: operational efficiency, resilience, flexibility, and sustainability.

Therefore, this proposed framework is based on three main Propositions (Ps):

- P1: Adoption of industry 4.0 technologies positively influences the degree of concurrent process design within supply chains.
- P2: Organizational capabilities moderate this relationship, strengthening the impact of technology adoption on concurrency.
- P3: Concurrent process design enhances SCM practices by improving responsiveness, integration and collaboration.

From a managerial point of view, the model emphasizes that companies that only invest in digital technologies might not achieve the desired performance if they do not develop organizational capabilities that enable concurrent processes.

Discussion

Heavily concurrent processes are critical in modern manufacturing supply chains to enable real-time, end-to-end visibility and rapid responsiveness. This is made possible by several advanced technologies that process large amounts of data. CE in industry 4.0 creates an environment where different segments of the production and supply chain can work in parallel, sharing information instantly in order (*i*) to make decisions, (*ii*) to reduce bottlenecks and (*iii*) to increase overall performance.

As depicted by the literature content analysis, several benefits can be identified. First, the increased flexibility, since systems can rapidly switch between different production orders, enabling high levels of productivity. Real-time data analysis and automation reduce bottlenecks and improve visibility across operations, optimizing resource allocation (Singhry et al., 2016).

Downtime reduction since the predictive maintenance, enabled by AI and machine learning analysing real-time data, helps prevent equipment failures before they occur.

Regarding the SCM benefits, the most relevant corresponds to the SCM agility and resilience improvement. Companies can react to market volatility by instantly seeing the impact of a change and running quick "what-if" scenarios to find the best course of action.

Also, concurrent planning helps to balance inventory levels and synchronize production and distribution, leading to reduced waste and lower costs. Efforts to ensure swift transfer of real-time demand information in SCM need to be addressed. This requires that, the SCM facing longer delivery lead times, should concentrate on integrating customer planning and forecasting into their operations.

Robust logistics management systems are essential for timely deliveries and increase the customer service level, warranting significant investment for future enhancements. Real-time logistics information systems are particularly impactful, enhancing communication across the entire value chain.

With a constant, accurate view of the supply chain, companies can provide better customer experience. Decisions are made based on current market trends and customer demand, ensuring product availability and satisfaction (Bonnard et al., 2021; Cao et al., 2021; Haghnegahdar et al., 2022; Kibria et al., 2018).

Managing delivery flexibility can yield inventory cost reductions and improve customer responsiveness. Strategic purchasing emerges as a crucial strategy for enhancing supply chain performance. Key performance indicators (KPIs) are needed to evaluate logistics service performance and estimate associated costs, enabling process mapping and the elimination of non-value-added activities (Gunasekaran & Ngai, 2004).

In assessing SCP, factors like total quality management implementation, postponement, just-in-time practices, supply network coordination, customization and geographic proximity must be considered. Additionally, the influence of SCM tools such as senior management support and IT on these dimensions is paramount (Deshpande, 2012).

Regarding the way that the heavily concurrent processes industry influences the NPD, literature defends that CE must be integrated in the product and process design, through collaborative stakeholder engagement. This integration aims to minimize risk during high production quantities.

Embracing Lean production principles, particularly in automotive industries, is decisive for agility and precision. Disruptions are highly detrimental in such environments, emphasizing the need for seamless processes and high-quality standards across all stakeholders.

Conclusions

The dawn of a heavily concurrent processes industry has transformed SCM, introducing both opportunities and major challenges. Technological advancements such as automation, AI and real-time data systems have enabled greater synchronization and efficiency across the supply chain. However, those technologies have also created complexities in system integration and data management.

Manufacturing challenges and fast delivery times continue to pressure companies to maintain low costs while meeting customer expectations, often straining logistics and resource planning.

Scientific developments in industrial engineering have accelerated production capabilities, yet they require constant adaptation of supply networks to keep pace with innovation. Moreover, global competition intensifies these challenges, as organizations and companies must balance tight lead times, quality and sustainability in increasingly interconnected markets. As industries embrace heavily concurrent processes, supply chains need to ensure coordination, flexibility and resilience amidst growing technological and operational complexity.

Thus, in conclusion, research demonstrates that organizations must prioritize integrative information-based environments to support fully connected networks involving clients and suppliers. KPIs play a crucial role in guiding and controlling the stability of the supply chain, with a particular emphasis on incorporating customer-oriented measures to evaluate satisfaction within SCM strategies.

The proposed "Integrated Concurrent SCM 4.0" framework reframes the understanding of complex supply chains. The framework identifies the enablers supports and operators of the process, based on three main propositions: technology adoption, installed companies' capabilities and the integration of concurrent process design and SCM. By aligning technology, capability and process design, the framework enables practitioners to conceptualize and measure the impact of Industry 4.0 on performance.

Furthermore, this review highlights the importance of improving relative supply lead times over demand information transfer. An effective networking and relationship management with collaborating companies, suppliers and customers drives to performance improvements in SCM. Strengthening these connections allows greater efficiency and responsiveness across the entire supply chain ecosystem.

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