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Industrial Engineering and Management

Volume 14

Aims and Scope of the Series

Industrial Engineering and Management (IEM) is a discipline that focuses on optimizing complex processes and systems within various industries. It involves the integration of engineering, business, economics, mathematics, and behavioral sciences to improve efficiency, productivity, quality, and overall performance in organizations. Key aspects of Industrial Engineering and Management include: Process Optimization; System Analysis and Design; Quality Control and Management; Supply Chain Management; Operations Management; Human Factors and Ergonomics; Project Management; Cost Analysis and Financial Management; Decision Analysis.

Overall, Industrial Engineering and Management aims to optimize resources, improve processes, enhance productivity, and ensure the effective and efficient utilization of all elements involved in the production or delivery of goods and services. It is crucial in today's competitive business environment for organizations to stay efficient and competitive.

Production Engineering and Operational Excellence are fields of study and practices that focus on optimizing and improving the manufacturing and production processes within an organization. It combines principles from engineering, management, and operational strategies to enhance productivity, efficiency, quality, safety, and sustainability in the production of goods and services.

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Production Engineering and Operational Excellence are crucial for organizations aiming to stay competitive in the global market by achieving high levels of efficiency, quality, and customer satisfaction while optimizing resources and minimizing waste. It is a multidisciplinary approach that encompasses engineering principles, management strategies, and the effective use of technology to drive operational success.

Meet the Series Editor

Fausto Pedro Garcia Marquez is a Full Professor at UCLM, Spain, with accreditation since 2013. He also holds the position of Honorary Senior Research Fellow at Birmingham University, UK, and serves as a Lecturer at the Postgraduate European Institute. In addition to these roles, Fausto has experience as a Senior Manager at Accenture from 2013 to 2014. He earned his European Ph.D. with the highest distinction. Throughout his career, Fausto has received numerous awards and honors. These include the Nominate Prize (2022), Gran Maestre (2022), Grand Prize (2021), Runner Prize (2020), and Advancement Prize (2018), as well as Runner (2015), Advancement (2013), and Silver (2012) by the International Society of Management Science and Engineering Management (ICMSEM). He was also the recipient of the First International Business Ideas Competition 2017 Award. Fausto's contributions extend to academic publishing, with over 242 papers to his name. Notably, his work has been recognized in journals like "Applied Energy" (Q1, IF 9.746, Best Paper 2020) and "Renewable Energy" (Q1, IF 8.001, Best Paper 2014). His affiliations include the editorial and authorship roles in more than 50 books, with publications through respected publishers such as Elsevier, Springer, Pearson, Mc-GrawHill, IntechOpen, IGI, Marcombo, and AlfaOmega. He has authored over 100 international chapters and holds 6 patents. Fausto serves as the Editor of 5 International Journals and is a Committee Member for more than 70 International Conferences. His research portfolio encompasses being the Principal Investigator in 4 European Projects, 8 National Projects, and participating in over 150 projects involving universities and companies. His areas of expertise and research interests span Artificial Intelligence, Maintenance, Management, Renewable Energy, Transport, Advanced Analytics, and Data Science. Fausto is a recognized Expert in the European Union in AI4People (EISMD) and ESF. He also serves as the Director of www.ingeniumgroup.eu, holds the status of Senior Member at IEEE since 2021, and has been honored as an Honorary Member of the Research Council of the Indian Institute of Finance since 2021. Fausto is also the Committee Chair of The International Society for Management Science and Engineering Management (ISMSEM) since 2020.

Meet the Volume Editor

Dr. Pengzhong Li is a professor at the School of Mechanical Engineering, Tongji University, Shanghai, China. He received his Ph.D. in Mechanical Engineering from Tongji University in 2004. From 1995 to 2001, he served as a manager in the Business Department and Warehousing Management Department of Guilin Daewoo Bus Co., Ltd. He is a Director of the Intelligent Manufacturing and Services Branch of the China Creative Studies Institute and the Director of the East China Branch of the National College Institute of Manufacturing Automation.

Contents

Preface

With the development of globalization and information technology, supply chain management in modern manufacturing has become a key factor for enterprises to enhance competitiveness and adapt to market demands. Manufacturing enterprises must modernize their supply chain management to meet the challenges of market fluctuations and evolving customer needs.

Modern manufacturing supply chain management can improve production efficiency, reduce costs, enhance product quality, accelerate time-to-market, and increase enterprise flexibility by integrating suppliers, manufacturers, and sales channels. However, the modernization of supply chain management in manufacturing faces several challenges. Poor information flow between different stages of the supply chain leads to delays and inaccuracies in information transmission; manufacturing enterprises struggle with slow supply chain responsiveness to rapidly changing market demands, hindering timely adjustments to production scale and delivery cycles; and insufficiently close collaboration between different segments of the supply chain results in resource waste and inefficiency.

To address these problems, manufacturing enterprises must adopt a series of measures to achieve modernized supply chain management, which includes introducing information technology to establish a digital supply chain network enabling real-time information sharing and communication across all stages, strengthening collaborative partnerships within the supply chain to build long-term, stable relationships for jointly formulating and implementing supply chain strategies; and enhancing internal management to optimize supply chain processes, thereby improving production efficiency and product quality.

This book compiles recent articles from academia, researchers, and engineers on the latest advancements, emerging trends, and applications in modern manufacturing supply chain management. The book is divided into five chapters, encompassing methods for improving supply chain maturity, the application of supply chain visualization technology, an approach to production and supply chain integration, and supply chain performance improvement supported by innovative tools. This book serves as a valuable reference for professionals in the fields of modern manufacturing and supply chain management, including undergraduate and postgraduate students, researchers, and practising engineers.

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Chapter 1

Introductory Chapter: Supply Chain Management in Modern Manufacturing

Pengzhong Li

1. Introduction

With the development of globalization and information technology, supply chain management has become a critical factor for modern manufacturing enterprises to enhance competitiveness and adapt to market demands. To meet the challenges posed by market fluctuations and customer needs, manufacturing enterprises must strengthen their modernized supply chain management. By integrating suppliers, producers, and sales channels, modern supply chain management in manufacturing can improve production efficiency, reduce costs, enhance product quality, accelerate time-to-market, and increase operational flexibility [1].

However, supply chain management in modern manufacturing faces several challenges. Poor information flow across different segments of the supply chain leads to delays and inaccuracies in data transmission. When confronted with rapidly changing market demands, manufacturing enterprises often experience slow supply chain responsiveness, hindering timely adjustments to production scale and delivery cycles. Additionally, weak collaboration among various stakeholders within the supply chain results in resource waste and inefficiency. To address these issues, manufacturing enterprises must implement a series of initiatives to achieve modernized supply chain management.

2. Characteristics of modern manufacturing supply chains

2.1 The modern manufacturing supply chain has evolved into a new organizational form

Its scope of collaboration extends beyond partial coordination of processes between individual enterprises. Instead, it has developed into an integrated organizational model that prioritizes customer demand, centers on data as the core element, and leverages modern information technology and organizational methods to efficiently consolidate, optimize, and synchronize upstream and downstream enterprises along with the related resources. This enables end-to-end coordination across product design, procurement, production, sales, and service [2].

2.2 Digitalization, networking, and intelligence define its distinctive features

The rapid advancement and application of modern information technologies have propelled supply chains into a new phase of smart supply chains deeply integrated with the internet and the Internet of Things (IoT). Digitalization empowers supply chains with big-data support, networked sharing, and intelligent collaboration, significantly enhancing coordination efficiency and reducing costs. Statistics indicate that effective digital supply chains can boost corporate revenue by 10%, lower procurement costs by 20%, and reduce overall supply chain expenses by 50%.

2.3 Greater emphasis on macroeconomic operational quality and efficiency

While traditional supply chains focus on internal management or inter-enterprise coordination, modern manufacturing supply chains prioritize cross-industry collaboration and integration within the national economic system. This shift places stronger emphasis on optimizing resource allocation and improving economic efficiency.

3. Development trends in modern manufacturing supply chains

Modern manufacturing emphasizes digitalization, networking and intelligence, end-to-end integration, and horizontal-vertical collaboration. Beyond manufacturing itself, the transformation and upgrading of supply chains are integral to modern manufacturing. Advanced manufacturing requires modern supply chains to achieve lean, stable, efficient production and reliable delivery. Without synchronized and well-matched supply chains, modern manufacturing would remain confined to laboratory prototypes [3].

3.1 Intelligentization

Rapid advancements in IoT, internet, cloud computing, big data, and blockchain have propelled supply chain management toward informatization, data-driven operations, networking, integration, intelligence, flexibility, and visualization. Previously siloed manufacturing, sales, and logistics are now converging through information and advanced manufacturing technologies. Business flow, logistics, information flow, and capital flow are being integrated to holistically—rather than partially—respond to end-user demands. Traditional supply chain strategies no longer meet enterprise needs in this new landscape. Modern supply chain management is evolving toward digital, intelligent, and networked systems, building dynamic, visible, and interconnected smart supply chains for greater agility and adaptability.

3.2 Networking

The organizational structure of modern supply chains shifts from multinational corporation dominance to platform-centric models. Platformization has become a defining feature of contemporary supply chains. Cross-industry, cross-regional, and transnational industrial supply chain platforms—centered on platform enterprises—synergize resources across nations, regions, industries, and businesses. They establish tightly knit global supply chain networks for integrated operations, driving upstream and downstream partners toward scale, clustering, and specialization.

Simultaneously, enterprises across tiers coalesce into boundary-spanning, platform-sharing ecosystems under supply chain platforms, propelling platform-based organizations to evolve into ecosystem-based frameworks.

3.3 Globalization

Economic globalization fundamentally drives the continuous upgrading of global value chains (GVCs), ushering in an era of deep global resource integration. Globalization enables cross-border flows of production factors, allowing enterprises to distribute R&D, material sourcing, manufacturing, logistics, sales, and services across countries and regions. This has spurred new models such as service outsourcing and modularized production. Concurrently, globalization demands higher supply chain management capabilities. Enterprises must design and build optimized global supply chains through process reengineering, risk mitigation, and performance evaluation—fostering partnerships to reduce costs while creating greater value. Mastery over global supply chains has become a core competency in international competition.

3.4 Greening

Global economic development faces tightening resource constraints, severe pollution, ecosystem degradation, and strained human-nature relationships. Accelerating green growth is now a universal consensus. Traditional supply chain management prioritized optimization and synergy but overlooked environmental impacts. Under urgent developmental imperatives, modern supply chains increasingly emphasize environmental sustainability and resource efficiency—reducing consumption and enhancing energy conservation across management, collaboration, and service processes. This shift enables industrial structures and production methods characterized by high technology, low resource use, and minimal pollution. Green supply chains have emerged as a critical direction for modern supply chains [4].

3.5 Strategic prioritization

As supply chains grow in strategic importance, their management is escalating from the corporate to the national level. Economic globalization has transformed inter-enterprise competition into supply chain-versus-supply chain rivalry, making supply chains pivotal to national competitiveness. The maturity of modern supply chains influences a nation's economic openness, determines its position in global value chains, shapes its institutional voice in global economic governance, and impacts the formation of broad-based interest alliances. Complex international dynamics and pandemic disruptions have challenged global industrial and supply chains, prompting growing strategic realignments of supply chain configurations worldwide.

4. Enhancement measures for modern manufacturing supply chain management

4.1 Strengthen multidimensional supply chain collaboration

Enterprises should enhance multidimensional coordination—including organizational alignment, process interoperability, information synchronization, resource sharing, and supply-demand matching—to mitigate information asymmetry risks, improve market responsiveness and customer value, and boost supply chain quality, cost-efficiency, and productivity.

4.2 Implement lean supply chain management

Precisely identify redundancies across the supply chain network. Redesign end-to-end processes from product design to customer use, eliminate unnecessary costs and waste through upstream-downstream collaboration, shorten business cycles, and maximize customer satisfaction with minimal resources [5].

4.3 Accelerate digital transformation of supply chains

Leverage next-gen technologies (IoT, 5G, blockchain, big data, industrial IoT, AI) to integrate quantified operational data across all supply chain segments. Achieve data-driven, model-based, and visible supply chain operations, enhancing predictive analytics, decision support, and risk control while reducing operational costs and improving production efficiency.

4.4 Build comprehensive supply chain networks

Establish end-to-end collaborative supply chains spanning product design, procurement, production, sales, and services across national and global dimensions. This is critical for manufacturing firms to reshape competitive advantages, reduce operational costs, and strengthen core competitiveness.

4.5 Integrate green practices into supply chains

Embed environmental and resource-conservation principles across the entire supply chain lifecycle—from product design, material sourcing, and manufacturing to packaging, warehousing, transportation, sales, and end-of-life recycling. Identify and manage environmental attributes at each stage to minimize ecological impact and maximize resource efficiency [6].

4.6 Enhance supply chain resilience and security

Resilience and security are interconnected and mutually reinforcing. Resilience focuses on resisting disruptions and enabling rapid recovery; security emphasizes reducing disruption risks and maintaining stable operations under crises [7].

5. Conclusion

Amid ongoing technological revolution and industrial transformation, the deep integration of modern services and advanced manufacturing has positioned the sector at a critical juncture of intelligent upgrading. To align with supply chain evolution and embed modern supply chains into manufacturing ecosystems, stakeholders must collaborate to elevate supply chain management through innovative approaches that support high-quality industrial development.

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Chapter 2

Quantitative Methodology for Improving the Maturity of Modern Supply Chain Management

Alberto Molina Ossa

Abstract

The competitiveness of the modern goods and services industry depends on the maturity of supply chain management (SCM). However, there is little applied research on quantitative methodology to improve it. The objective of this chapter is to develop the quantitative methodology for process improvement (QMPI), designed to improve SCM maturity through the influence of integrated development projects (IDP). The conceptualization and operation of IDPs is determined from hypothetical models, qualitatively and quantitatively adjusted to the needs of stakeholders, through continuous process improvement in accordance with the international standards. The QMPI methodology was validated by the applied research Molina, according to which, an average improvement of 27% in three critical IDP processes in the Latin American electricity sector with influences between 60 and 97%, improved the maturity of SCM-GI:2011-2021 by 14.3%, with an effectiveness greater than 85%.

Keywords: SCM maturity, continuous improvement, management system, applied research, integrated projects

1. Introduction

With the consent of the company Grupo ISA (GI) [1, 2], the quantitative methodology for process improvement (QMIP) was designed through applied research "Implementation of supplier development to improve the maturity of the SCM-GI supply chain: 2011-2021" [2]. Around this statement, the following is presented: (1) background of SCM, (2) basic concepts associated with SCM, and (3) chapter content structure.

1.1 SCM background

Since 2010, the international market has presented the following circumstances in SCM systems: (1) high level of international standardization of management systems (ISO) [3]. (2) High level of SCM standardization with reference to the framework for supply chain operations (SCOR) [4]. (3) The level of SCM maturity is inadequate to meet contractual commitments [5]. (4) High risk of imminent loss of company competitiveness due to unavailability of suppliers [6]. (5) Lack of knowledge of the influence of supplier development on SCM maturity [7]. (6) Inadequate levels of supplier capacity and performance [8, 9].

1.2 Basic concepts

First, "modern SCM" is a procurement and supply system, standardized according to the following references: (1) the SCOR model [4], (2) the SCM maturity model [10], (3) the ISO management standards [3], and (4) the contractual commitments between the company and suppliers [11]. According to the ASCM "Supply Chain Dictionary," 17th edition, 2022, page 199, the SCM concept consists of "the design, planning, execution, control and monitoring of supply chain activities with the objective of creating net value, building a competitive infrastructure, taking advantage of global logistics, synchronizing supply with demand and measuring performance globally."

In this system, strategy and governance determinations are made based on risks identified in the sourcing, purchasing, supplier, and performance processes. The corporate strategic direction flows into sourcing, where basic operations are optimized for emergent and predetermined planning processes. Next, the plans go through the supplier process to manage their competencies, and the purchasing process to manage the contracting, contract administration, risk control, and performance evaluation processes [2].

Secondly, "SCM maturity" is a concept that indicates the level of development and implementation of the qualities and capabilities of the SCM processes: definition, predictability, reliability, planning, control, opportunity, compliance, effectiveness, efficiency, performance, structuring, precision, systematization, and integration. This concept implies that of "SCM maturity assessment," which consists of the assessment, interpretation and diagnosis of the maturity levels of the SCM processes, using as a reference the best procurement practices, standardized by an "SCM maturity model" which characterizes five levels of maturity of the SCM processes [10].

Third, "improving SCM maturity" is increasing the development and use of SCM qualities, which implies: (1) Explicitly defining, documenting and structuring strategies, objectives, practices, procedures, processes, and responsibilities. (2) Focusing on customers, the foresight, planning, and functional cooperation between the company and suppliers. (3) Reducing risks and costs; maximizing mutual trust, team spirit, and customer satisfaction. (4) Sharing efforts, investments, and benefits. (5) Intervening in SCM processes through a coordinated effort with suppliers, led by the company. (6) Implementing a supplier development program (PDP), focused on the appropriation of SCM management practices, and on the adjustment of the skills and attitudes required in suppliers [2].

Fourthly, a "quantitative methodology for process improvement" (QMIP) is a numerical data-based research procedure designed to predeterminedly plan and to control in a detailed and concomitant manner the improvement of SCM process maturity through integrated development projects (IDP), coordinated by means of the implementation of a PDP program. It allows to determine, describe, explain, and predict the behavior of a set of independent variables managed as integrated development projects (IDP), through the analysis of the earned value and the continuous improvement approach, articulated with the descriptive and relational statistical analysis [2].

1.3 Content structure

This chapter is structured into eight sections: (1) Introduction describes an overview of the QMPI methodology. (2) The research approach on which the QMPI methodology is developed. (3) The theoretical framework on supplier development and SCM maturity. (4) Previous research. (5) QMPI methodology designed to solve the research problem. (6) Discussion of the findings, corroboration, and contrast of the research results. (7) Conclusion. (8) References.

2. Research approach

This approach begins by identifying the need to develop a quantitative methodology to improve SCM processes, and then explains the methodological components.

2.1 Need to develop QMPI

The evolution of techniques, practices, knowledge, and problems of management systems implies the need to adopt a QMPI methodology to improve SCM maturity to the level required by international ISO management standards, the standards defined by the SCM maturity model, the satisfaction expectations of the company, its customers, and other stakeholders [2]. According to academic literature, it is possible to improve SCM maturity through integrated development projects (IDP) of supplier management processes, led by the company and executed through a PDP program [12].

2.2 Research line

SCM is the thematic axis or line of research in which the QMPI was originally designed. The hypothesis, objective, and procedures to solve the problem and generate new knowledge are focused around this axis. SCM focuses on two specific themes. The first is "SCM maturity," which seeks to develop and apply research methodologies at the application level, when companies are at high risk of losing competitiveness, due to an inadequate level of SCM maturity. The second is "integrated projects" because the study focuses on the development of a solution, generating synergy between the areas of business development project management [13].

2.3 Research scenario

The social environment involving the participants in this research is the SCM-GI:2011-2021 supply chain of seven GI group companies operating in Latin America: ISA (GI parent company) [1] and the following six GI subsidiary companies: ISA Intercolombia, ISA Transelca, Expertos en Mercados (XM), and Internexa, which operate in Colombia; ISA Companhia de Transmissão de Energia Elétrica Paulista (ISA CTEEP), which operates in Brazil; and ISA Perú, which operates in Peru [14].

2.4 Research problem

Considering the SCM problem [15], the researcher identifies the general problem (GP) that he intends to solve with this study: How can the implementation of the PDP-GI program improve the maturity of SCM-GI:2011-2021? This indicates a lack of specific, empirical, and analytical knowledge of the relationship and influence of a PDP program on SCM maturity [13]. Therefore, it is appropriate to disaggregate this GP into subsidiary problems, which specifically identify the convenience of empirically studying the implementation of the PDP-GI program, and analytically the effect of the PDP-GI program on the maturity of SCM-GI:2011-2021.

Therefore, the five specific subsidiary problems are: (PE1) How to diagnose the SCM maturity level at the initial moment of the implementation of the PDP program? (PE2) How to implement the first stage of the PDP program to improve SCM maturity? (PE3) How to implement the second stage of the PDP program to improve SCM maturity? (PE4) How to diagnose the SCM maturity level at the end of the PDP program? (PE5) How to measure and analytically test the effect of the implementation of the PDP program on SCM maturity?

2.5 Research hypothesis

Considering the SCM problem [15], the theoretical framework of the variables involved, the acquired experience, and the research problem, the researcher proposes the supposed solution to the research problem. Therefore, the general hypothesis (HG) of the study is: "The implementation of the PDP-GI program improves the maturity of SCM-GI: 2011-2021." Considering the magnitude of this supposed general solution, the researcher breaks it down into five specific subsidiary supposed solutions, which involve the analysis of a controlled intervention of the relationship and the effect of the PDP-GI program on the maturity of SCM-GI [13].

The specific HE hypotheses are: (HE1) There is a strong linear trend relationship with direct and positive impact between supplier development (DP), supplier capacity (CP), supplier performance (DP), and SCM maturity; (HE2) There is a strong linear trend relationship with direct and positive impact between the components of the SCM maturity effort and the components of the DP management effort; (HE3) DP management has a direct and positive impact on SCM maturity; (HE4) CP has a direct and positive impact on SCM maturity; (HE5) DP has a direct and positive impact on SCM maturity; (HE6) DP planning and control has a direct and positive impact on SCM maturity planning and control; (HE7) DP improvement has a direct and positive impact on SCM maturity planning and control; (HE8) DP improvement has a direct and positive impact on SCM maturity improvement. (HE9) The implementation of the first stage of the PDP program improves SCM maturity; (HE10) The second stage of the PDP program improves SCM maturity.

2.6 Research objective

In accordance with the PG problem and the HG hypothesis, the general objective (GO) is raised that will fulfill the purpose of the research: "To measure and verify in practice and analytically, the direct and positive influence of the implementation of the PDP-GI program, in the improvement of the maturity of SCM-GI: 2011-2021." Likewise, in accordance with the specific subsidiary problems, and the respective specific hypotheses, the general objective OG is broken down into five specific subsidiary objectives (OE1, OE2, OE3, OE4, and OE5): (OE1) Diagnose the level of SCM maturity at the initial moment of the implementation of the PDP program. (OE2) Implement the first stage of the PDP program, to improve SCM maturity. (OE3) Implement the second stage of the PDP program, to improve SCM maturity. (OE4) Diagnose the SCM maturity level at the end of the PDP program. (OE5) Analytically measure and test the impact of the implementation of the PDP program on SCM maturity.

2.7 Relevance of the research

The QMPI methodology of this research provides an understanding of the theoretical, conceptual and operational knowledge that can be adapted and applied to solve problems and situations of inefficiency and ineffectiveness in the SCM processes of companies from various sectors of the economy [2]. Specifically, QMPI is useful when seeking to: (1) Ensure economic viability in free competition markets. (2) Improve business relationships with suppliers. (3) Improve the power and capacity to purchase goods and services. (4) Comply with international standards of: occupational health, safety, environmental protection, and quality (HSEQ). (5) Comply with contractual commitments. (6) Adopt standard SCM practices. (7) Develop or continually improve SCM processes.

3. Theoretical and conceptual framework

The theoretical foundations and conceptual bases provide an understanding of the topic of this research because they focus on: the structuring of the problem, the hypothesis, the objective, the methodological design, and the adaptation of the SCM maturity model [10]. In accordance with the research approach, the conceptual theoretical framework is broken down according to the specific objectives: (1) Conceptual framework of objectives OE1 and OE4. (2) Conceptual framework of objectives OE2 and OE3. (3) Conceptual framework of objective OE5.

3.1 Conceptual framework of objectives OE1 and OE4

The academic literature establishes the foundations for diagnosing the maturity of SCM processes [10]. The SCM maturity profile provides an overview of the status and changes of processes over a given period [5]. To improve SCM maturity, processes are developed according to a normative approach [7]. To this end, models classify the maturity levels of SCM processes in stages [10]. SCM diagnostics are performed periodically because logistics risks are more likely to materialize when the SCM maturity level is low [16].

3.2 Conceptual framework for objectives OE2 and OE3

It includes the following concepts: (1) Management [17]. (2) International management standards [18, 19]. (3) Management system practices [18]. (4) SCOR model [19]. (5) SCM maturity models [10]. (6) Supplier performance management [20]. (7) Supplier development [21]. (8) Implementation of supplier development programs [22]. (9) Management of supplier development programs [23, 24]. (10) Integrated supplier development projects [22, 25, 26].

3.3 Conceptual framework for objective OE5

In this framework, it is important to adopt the conceptual bases that have been used to study the relationship between supplier development factors and SCM maturity [5], and the impact of supplier relationship management on procurement performance [26].

4. Previous research

Research from recent years is used to corroborate and contrast the results and findings of this research with the results of other studies developed in the following areas of knowledge: (1) SCM management models [4, 10, 20, 27–32]. (2) SCM maturity and performance [7, 28, 31]. (3) PDP program [7, 12, 22, 24, 25]. (4) Supplier performance [8, 11, 21, 33, 34]. (5) Effect of SCM on organizational performance [7].

5. Methodology

This systematic framework indicates the methods, criteria, techniques, and procedures that the researcher determines to solve the research problem in a rigorous and scientific manner, using as reference the research approach, the conceptual theoretical framework, and previous research [2]. This research is at the application level, because the first four specific objectives seek to implement a PDP program; and it is at the relational level, because the fifth specific objective seeks to measure and test the relationship and influence of the PDP program on SCM maturity.

5.1 Research design

It is the planning of the research strategy that allows to fulfill each purpose declared in the study statement. The research design constitutes the planned and organized work scheme that the researcher assumes in order to be able to argue the hypotheses posed. The adapted framework for choosing the research design facilitates the choice of the research method [8, 35]. This framework considers 10 relevant characteristics of the research requirements, which are related to four research methods (axiomatic, surveys, case studies, and action research).

5.1.1 Choice of research method for each specific objective

Table 1 presents the research design for each specific objective. This design reflects the work scheme that is planned and organized in an appropriate manner to compare the results with the hypotheses raised.

5.1.2 Stages of field activities

In operations management research, the behavior of phenomena is analyzed iteratively because their characteristics are not revealed in a single experience. Therefore, to discover the relevant characteristics of the PDP-GI program, this study is conducted into two stages [8, 30]. The first stage of the PDP-GI program runs from 2011 to 2015, and the second stage runs from 2016 to 2021. The PDP-GI program begins with the periodic assessment of the management levels of four project-managed processes, of which three are subprocesses of supplier management, development, capability, and performance; and the fourth level indicates the maturity of SCM-GI [2].

In each assessment, the maturity gaps of the procurement system are analyzed using the SCM maturity model [10] as a reference. The integration of PDP-GI projects is ensured by means of: (1) The strategic direction of supply. (2) The PMBOK® Guide (Project Management Institute). (3) The GI company's supplier development model [1].

Specific objective OE1: Diagnose the SCM maturity level before the PDP program. *Specific result RE1:* Approved diagnosis of the "maturity of SCM-GI processes" before the implementation of the PDP program. Design: Qualitative, descriptive, transversal. Reasons for the choice: Numerical and graphical presentation of the data. Statistical descriptive analysis of the specific result. Diagnosis of SCM maturity. Qualitative analysis of the specific result.
Specific objective OE2: Implement the first stage of the PDP program, to improve SCM maturity. *Specific result RE2:* Positive variation in SCM maturity V3, attributable to the positive variation in supplier management levels ("development" V1, "capacity" V2, and "performance" V3), implemented through the first stage of the PDP program. Design: Qualitative, descriptive, action research, longitudinal. Reasons for the choice: Numerical and graphical presentation of the data. Statistical descriptive analysis of the specific result. Qualitative analysis of the specific result.
Specific objective OE3: Implement the second stage of the PDP program, to improve SCM maturity. *Specific result RE3:* Positive variation in SCM maturity V3, attributable to the positive variation in supplier management levels ("development" V1, "capacity" V2, and "performance" V3), implemented through the second stage of the PDP program. Design: Qualitative, descriptive, action research, longitudinal. Reasons for the choice: Numerical and graphical presentation of the data. Statistical descriptive analysis of the specific result. Qualitative analysis of the specific result.
Specific objective OE4: Diagnose the level of SCM maturity at the final moment of the PDP program. *Specific result RE4:* Standardized diagnosis of the "maturity of SCM-GI processes," at the final moment of the PDP program. Design: Qualitative, descriptive, transversal. Reasons for choice: Numerical and graphical presentation of data. Statistical descriptive analysis of the specific result. Diagnosis of SCM maturity. Qualitative analysis of the specific result.
Specific objective OE5: Measure the impact of the implementation of the PDP program, on SCM maturity V3. *Specific result RE5:* Statistical verification of the impact of "development management" V1, "capacity" V2 and "supplier performance" V4, on SCM maturity V3. Design: Qualitative, quantitative, longitudinal Reasons for choice: Numerical and graphical presentation of data. Relational statistical analysis of the specific results. *General objective OG:* Measure and verify in practice and analytically, the direct and positive influence of the implementation of the "PDP-GI:2011–2021 program," on the improvement of SCM maturity. *Overall RG result:* (1) The positive variation of SCM V3 maturity, attributable to the positive variation of the supplier management levels ("development" V1, "capacity" V2, and "performance" V3), implemented through the PDP program. (2) The measurement and statistical verification of the impact of "development management" V1, "capacity" V2, and "supplier performance" V4," on SCM V3 maturity. (3) The practical and statistical verification of the general hypothesis: The implementation of the PDP program improves SCM maturity. Design: Qualitative, descriptive, action research, longitudinal. Reasons for the choice: Presentation and analysis of the data. Discussion. Conclusions

Table 1.
Choice of research method for each specific objective.

5.2 Population and sample

The determination of the population and the sample of the study variables is aimed at ensuring the homogeneity of the characteristics and the statistical equivalence of the sample, required to generate empirical knowledge of the PDP-GI and its impact on the maturity of SCM-GI [2]. The main purpose of this study is to improve the maturity of the SCM-GI. Therefore, for this main purpose, the population is the SCM-GI, which is made up of all the parties affected by the research problem.

However, this study also has a subsidiary purpose, which consists of implementing a PDP program. The statistical population of the suppliers of a PDP program is the set of suppliers that are required to be developed, and in this research, they are the 130 suppliers that are classified in the critical, restrictive, and relevant categories of the SCM-GI [36]. However, to ensure the validity of the sample of suppliers, four concepts are considered: (1) The convenience sampling method is the one that allows for an adequate selection of suppliers to meet the objectives of the PDP-GI program. (2) To implement the PDP-GI program, a non-probabilistic sample of 50 suppliers that fully meet four eligibility criteria is used. (3) This sample size is representative of the population of 130 suppliers. (4) The sampling error or difference between the sample and the supplier population is admissible to make the study viable. (5) Statistical significance of the data. For the analysis and statistical interpretation of the data and results of the PDP-GI program, the researcher adopts a limit between significance and lack of significance based on probability. This limit is set with a p value = 0.05, where p means the 5% probability that a finding of interest was reached by chance. It also means that the 95% confidence interval in the research is the range of values that contain the population parameter with a confidence level of 95%.

Therefore, for the subsidiary purpose of implementing the PDP-GI program, the supplier population is the set of 130 suppliers classified in the critical, restrictive, and relevant categories of the SCM-GI. The non-probabilistic sample is 50 suppliers selected according to four eligibility criteria: (1) The first criterion is to have legal status and legal representation registered in the SCM-GI Single Contracting Registry System (SCRS). In this SCRS system, 1000 registered suppliers with legally constituted representation are identified. (2) The second criterion is to have sufficient technical and operational capacity. Of the thousand suppliers registered in the SCRS system, 230 are classified as active with sufficient technical and operational capacity to be contracted. (3) The third criterion is segmentation. This criterion indicates that of the 230 active suppliers, 130 are from the three highest risk categories. Of these 130 suppliers, 30 are classified in the critical category, because the contracts are of a larger value and present a high risk of complexity in the contracting processes; 50 suppliers are classified in the restrictive category, because although they are of a smaller value, they also present a high risk of complexity in the contracting processes; and 50 suppliers are classified in the relevant category because they are of a larger value and present a low risk of complexity in the contracting processes. (4) The fourth criterion is potential, in the sense that the suppliers voluntarily agree to participate in the PDP program with an attitude of cooperation, and has the greatest potential for development, value capture, continuous improvement, and competitive advantage. Consequently, from the population of 130 suppliers that simultaneously meet the first three eligibility criteria, the 50 suppliers that fully meet the fourth eligibility criterion are selected for convenience, as they have the greatest potential for development, value capture, continuous improvement, and competitive advantage.

5.3 Variables

Considering that the study consists of implementing a PDP program to improve the maturity of an SCM, the QMPI aims to verify in practice and analytically, the direct and positive influence of the efforts of the PDP-GI program managed as independent variables, to improve the maturity of SCM-GI, managed as a dependent variable. Therefore, the four variables of the study are: “supplier development” V1; “supplier capacity” V2; “SCM maturity” V3; “supplier performance” V4. The periodic measurement of each variable is carried out with an indicator of the degree of compliance with the goals and objectives of each effort planned with the PDP-GI program, expressed in percentage (%) [2]. Each of these four variables is measured through the weighted evaluation of three dimensions. Likewise, each of the three dimensions of each variable is quantified through the weighted evaluation of five specific subdimensions of each dimension. These efforts are coordinated, continuous, observable and quantifiable, and measurable in terms of time, cost, and quality. Therefore, these four variables are numerical and continuous.

Furthermore, the effort for each variable is structured using the Plan-Do-Check-Act (PDCA) cycle. This structure is an interactive strategy that applies the trial and error principle, and is adapted to this research in a particular way. First, the planning steps "P" and verification "V" of the PDCA cycle act in a coordinated manner as a component of the reactive effort of continuous management "PV." Initially, planning "P" plans the organization, integration, and direction of a process or resource seeking to ensure compliance with SCM objectives. Subsequently, verification "V" reviews the conformity of the process with respect to a reference model.

In addition, the steps of execution "H" and action "A" operate in a coordinated manner as an active effort component of continuous improvement "HA." This effort component begins with execution "H," which materializes the planning produced by planning "P." Finally, action "A" rectifies the anomalies that may have occurred in planning "P" or in execution "H," to optimize the maturity of each process. These two complementary effort components "PV" and "HA," continuously integrate the management and improvement efforts represented by each variable "V." Therefore, V1 = PV1 + HA1; V2 = PV2 + HA2; V3 = PV3 + HA3; V4 = PV4 + HA4.

Under these conditions, the researcher intervenes and controls in an intentional, direct, and predetermined manner, the reactive effort component "PV," seeking to produce the desired effect on variable "V" through the active effort component "HA." Therefore, in each variable, the reactive effort of "continuous management" is measured with a PV indicator. The complementary part, the active effort of "continuous improvement," is measured with an HA indicator [2].

5.3.1 Operationalization of the variable V1 "supplier development"

In V1, the first dimension is V1.1 "Strategic alignment," and it has five subdimensions: V1.1.1 Direction. V1.1.2 Value offer. V1.1.3 Trust. V1.1.4 Strategic alliances. V1.1.5 Development plan. The second dimension is V1.2 "Continuous improvement," and it has five subdimensions: V1.2.1 Technical and financial resources. V1.2.2 Systemic management. V1.2.3 Joint efforts. V1.2.4 Capacity and performance. V1.2.5 Business development. The third dimension is V1.3 "Integrated capacity management," and it has five subdimensions: V1.3.1 Integrated management systems. V1.3.2 Risk management. V1.3.3 Integrated development. V1.3.4 Communication. V1.3.5 Alignment of company areas.

5.3.2 Operationalization of the variable V2 "supplier capacity"

In V2, the first dimension "Critical capacity" is the competitive capacity of suppliers managed with "full contractual formalities." The second dimension "Restrictive capacity" is the capacity of suppliers participating in contracting processes managed with "moderate formalities." The third dimension, "Relevant capacity" is the competitive capacity of suppliers managed with "basic formalities." Each of these three component dimensions comprises five subdimensions. (1) Registration capacity. (2) Operational capacity. (3) Pre-contractual capacity. (4) Contractual capacity. (5) Post-contractual capacity.

Each subdimension is weighted with a value that reflects its importance in supplier capacity according to the company's criteria. The "supplier capacity level" is the average of the capacity levels obtained by suppliers in the category in the last period. A supplier's capacity level in a category is the capacity obtained by the supplier in the category in the last period.

5.3.3 Operationalization of the variable V3 "SCM maturity"

In V3, the SCM-GI:2011–2021 supply chain is configured with 11 management processes: (1) Strategy and governance. (2) Planning. (3) Strategic sourcing. (4) Contract management. (5) Supplier management. (6) Purchasing process. (7) Human resources, skills, and knowledge. (8) Technology. (9) Structure. (10) Performance management. (11) Risk management.

Therefore, the "SCM maturity level" V3 is the average of the maturity levels of these 11 processes. The first dimension "Critical maturity" is to manage the critical goods and services supply chain processes. The second dimension "Restrictive maturity" is to manage the restrictive goods and services supply chain processes. The third dimension, "Relevant Maturity," is managing the processes of the supply chain of relevant goods and services. Each of these three dimensions comprises five subdimensions: (1) Design. (2) Planning. (3) Execution. (4) Control. (5) Monitoring.

5.3.4 Operationalization of the variable V4 "supplier performance"

In V4, the first dimension "Performance in critical category supplies" is the performance of suppliers managed with "full contractual formalities." The second dimension "Performance in restrictive category supplies" is the performance of suppliers managed with "moderate contractual formalities." The third dimension "Performance in relevant category supplies" is the performance of suppliers managed with "basic contractual formalities." Each of these three dimensions comprises five subdimensions: (1) Risk management performance. (2) Quality performance. (3) Schedule performance. (4) Relationship performance. (5) Document management performance.

Each subdimension is weighted with a value that reflects its importance in supplier capacity according to company criteria. The "supplier performance level" of a supplier category is the average of the performance levels achieved by the suppliers in the category in the last period. The performance level of a supplier in a category is the capability achieved by the supplier in the category in the last period.

5.4 Data collection and analysis scenario

To limit and clarify the data collection and analysis scenario of this research, the following units are defined: (1) Study unit. (2) Information unit. (3) Analysis units. (4) Observation units. (5) Intervention units [2].

5.4.1 Study unit

The SCM-GI:2011–2021 supply chain, which constitutes the study population, is the study unit of this research, considered integrally with all its content of suppliers and processes. This unit is composed of four parts: (1) Information units. (2) Analysis units. (3) Observation units. (4) Intervention units. As a member of this "study unit," the researcher has the possibility and the capacity to intervene directly to influence, modify, and help change its conditions, make observations, and measurements of the variables involved during the implementation period of the PDP program.

5.4.2 Information unit

The corporate information system of the GI company (SIC-GI) is an organized information unit that aims at the production, analysis, conservation, and dissemination of corporate documentation. This is the digital platform that facilitates the operational processing of information and data recorded in the "central corporate documentation file of the company." This central file physically stores the documentary records of the contracting and contract administration processes, including the evaluations of supplier performance, recorded, and validated with the signatures of the contract administrators and the director of the corresponding area.

The information and data recorded in this SIC-GI system constitute the information unit of this research, because it is managed in a controlled manner, in accordance with legal regulations and the international information security standard ISO 27001. The management indicators for supplier development, supplier capacity, and SCM maturity are archived and controlled by the team responsible for procurement. This company's documentary registration and consultation system is of a scientific and legal nature. The file folders have controlled access. Physical and digitalized contractual documents that require legal support are signed by administratively authorized persons responsible for recording, validating, and storing the information and data in a secure and controlled manner.

5.4.3 Analysis units

An analysis unit is the minimum part of the study unit that is needed to perform a measurement. The first analysis unit (UAV1), of the "supplier development management level" V1, is the area of the company responsible for managing the PDP program. The second analysis unit (UAV2), of the "supplier capacity level" V2, is the set of suppliers involved in the PDP program. The third analysis unit (UAV3), of the "SCM-GI maturity" level V3, is the set of documents describing SCM processes, duly approved. The fourth analysis unit (UAV4), of the "supplier performance level" V4, is the set of documents of the current contracting processes, related to the set of suppliers involved in the PDP program.

Since these analysis units are different, protocol rules are applied to the measurement of variables V1, V2, V3, and V4, in order to ensure that the information and data lead to conclusions representative of the study unit.

5.4.4 Observation units

The measurements are obtained by direct or indirect observation of the activities of the supplier development management, supplier capacity development, supplier performance management, and SCM processes. Each of these processes constitutes an observation unit. Therefore, for each period of execution of these processes, data is collected for monitoring, control, and calibration purposes.

5.4.5 Intervention units

The intervention is the implementation of the PDP program in the SCM-GI chain. The focus is the variation of V1, V2, V3, and V4 in each intervention period of the PDP program. The intervention unit of Variable V1 is the area of the company responsible for supplier management and the PDP program. This work team has a coordinator and a group of analysts who manage the supplier management processes.

The intervention unit of Variable V2 is the set of suppliers that participate in the PDP program and in the "contract management," "purchase management," and "supplier performance management" processes. The intervention unit of Variable V3 is the area responsible for the SCM-GI processes, made up of work teams specialized by supply chain processes, each with a coordinator and a group of analysts. Each team specializes in an SCM-GI process. The intervention unit of Variable V4 is the group of suppliers that develop their performance through monitoring and control activities of the processes "contract management," "purchase management," and "supplier management."

5.5 Information and data collection instruments

These are "ad hoc" formats or templates developed by the GI company to collect the measurement and control data for the study [2]. These data are the indicators of the component efforts of the subdimensions of the four variables (from PV1.1.1 and HA1.1.1 to PV4.3.5 and HA4.3.5), with which the measurements of the dimensions and variables of the study are calculated. The validation and implementation of these instruments is part of the "process control system" of the "integrated management system." Each documented SCM process is controlled with a consecutive code and release date. Each of the four instruments has a header that identifies the variable, the variable indicator, the measurement unit, the evaluation period, and the type of format.

The content of each format relates to the variable, the three dimensions, and the five subdimensions of each dimension, with the spaces to record the data collected for each subdimension. Example: from PV1.1.1 and HA1.1.1 to PV1.3.5 and HA1.3.5, for the case of variable 1. The responsibilities for collecting information and data for variables V1, V2, V3, and V4 are assigned by the SCM-GI director. Compliance with these functions ensures that the data is assessed and recorded by authorized, competent, and trusted personnel of the company's management and administrative staff.

The relevance of the data collection instruments is verified and validated through periodic audits by external certification agencies in accordance with international management standards; external fiscal audits by government agencies; and internal management audits on information security, occupational health, industrial safety, environmental management, risks, and quality.

5.5.1 Instrument F1 "supplier development management"

This is a format used to periodically record indicators for the dimensions and subdimensions of variable V1 in the SIC-GI. The indicators for the first dimension, V1.1, are: PV1.1 and HA1.1. The indicators for the second dimension, V1.2, are: PV1.2 and HA1.2.

The indicators for the third dimension, V1.3, are: PV1.3 and HA1.3.

The five subdimensions of V1.1 and their indicators are: V1.1.1 (PV1.1.1 and HA1.1.1); V1.1.2 (PV1.1.2 and HA1.1.2); V1.1.3 (PV1.1.3 and HA1.1.3); V1.1.4 (PV1.1.4 and HA1.1.4); V1.1.5 (PV1.1.5 and HA1.1.5). The five subdimensions of V1.2 and their indicators are: V1.2.1 (PV1.2.1 and HA1.2.1); V1.2.2 (PV1.2.2 and HA1.2.2); V1.2.3 (PV1.2.3 and HA1.2.3); V1.2.4 (PV1.2.4 and HA1.2.4); V1.2.5 (PV1.2.5 and HA1.2.5). The five subdimensions of V1.3 and their indicators are: V1.3.1 (PV1.3.1 and HA1.3.1); V1.3.2 (PV1.3.2 and HA1.3.2); V1.3.3 (PV1.3.3 and HA1.3.3); V1.3.4 (PV1.3.4 and HA1.3.4); V1.3.5 (PV1.3.5 and HA1.3.5).

5.5.2 Instrument F2 "supplier capacity"

This is a format in which the indicators of the dimensions and subdimensions of the variable V2 are periodically recorded in the SIC-GI. The indicators of the first dimension, V2.1, are: PV2.1 and HA2.1. The indicators of the second dimension, V2.2, are: PV2.2 and HA2.2.

The indicators of the third dimension, V2.3, are: PV2.3 and HA2.3.

The five subdimensions of V2.1 and their indicators are: V2.1.1 (PV2.1.1 and HA2.1.1); V2.1.2 (PV2.1.2 and HA2.1.2); V2.1.3 (PV2.1.3 and HA2.1.3); V2.1.4 (PV2.1.4 and HA2.1.4); V2.1.5 (PV2.1.5 and HA2.1.5). The five subdimensions of V2.2 and their indicators are: V2.2.1 (PV2.2.1 and HA2.2.1); V2.2.2 (PV2.2.2 and HA2.2.2); V2.2.3 (PV2.2.3 and HA2.2.3); V2.2.4 (PV2.2.4 and HA2.2.4); V2.2.5 (PV2.2.5 and HA2.2.5). The five subdimensions of V2.3 and their indicators are: V2.3.1 (PV2.3.1 and HA2.3.1); V2.3.2 (PV2.3.2 and HA2.3.2); V2.3.3 (PV2.3.3 and HA2.3.3); V2.3.4 (PV2.3.4 and HA2.3.4); V2.3.5 (PV2.3.5 and HA2.3.5).

5.5.3 Instrument F3 "SCM-GI maturity"

It is a format in which the following indicators are periodically recorded in the SIC-GI: (1) The indicators of the profile of the maturity levels of the SCM-GI processes, which are used to diagnose the maturity of SCM-GI based on the SCM maturity model adopted as a reference. (2) The indicators of the dimensions and subdimensions of the variable V3, which are used to plan and control the maturity of SCM-GI in each stage or period of the PDP program. The indicators of the SCM-GI process maturity level profile are: V3.1, V3.2, V3.3.

The V3.1 indicator is the average of the maturity of the 11 SCM-GI processes for critical goods and services, and S3.1 is its standard deviation. The V3.2 indicator is the average of the maturity of the 11 SCM-GI processes for restrictive goods and services, and S3.2 is its standard deviation. The V3.3 indicator is the average of the maturity of 11 SCM-GI processes for relevant goods and services, and S3.3 is its standard deviation. These indicators of the SCM-GI process maturity level profiles for critical, restrictive, and relevant chains are used to build the SCM-GI maturity level profile at the start times of each period in which the SCM-GI process description documents have been updated. Thus, the SCM-GI maturity level at this time is: $V3 = V3.1 + V3.2 + V3.3$. The indicators of the first dimension, V3.1, are: PV3.1 and HA3.1. The indicators of the second dimension, V3.2, are: PV3.2 and HA3.2. The indicators of the third dimension, V3.3, are: PV3.3 and HA3.3.

The five subdimensions of V3.1 and their indicators are: V3.1.1 (PV3.1.1 and HA3.1.1); V3.1.2 (PV3.1.2 and HA3.1.2); V3.1.3 (PV3.1.3 and HA3.1.3); V3.1.4 (PV3.1.4 and HA3.1.4); V3.1.5 (PV3.1.5 and HA3.1.5). The five subdimensions of V3.2 and their indicators are: V3.2.1 (PV3.2.1 and HA3.2.1); V3.2.2 (PV3.2.2 and HA3.2.2); V3.2.3

(PV3.2.3 and HA3.2.3); V3.2.4 (PV3.2.4 and HA3.2.4); V3.2.5 (PV3.2.5 and HA3.2.5). The five subdimensions of V3.3 and their indicators are: V3.3.1 (PV3.3.1 and HA3.3.1); V3.3.2 (PV3.3.2 and HA3.3.2); V3.3.3 (PV3.3.3 and HA3.3.3); V3.3.4 (PV3.3.4 and HA3.3.4); and V3.3.5 (PV3.3.5 and HA3.3.5).

5.5.4 Instrument F4 "supplier performance"

This is a format in which the indicators of the dimensions and subdimensions of the variable V4 are periodically recorded in the SIC-GI. The indicators of the first dimension, V4.1, are: PV4.1 and HA2.1. The indicators of the second dimension, V4.2, are: PV4.2 and HA4.2. The indicators of the third dimension, V4.3, are: PV4.3 and HA4.3.

The five subdimensions of V4.1 and their indicators are: V4.1.1 (PV4.1.1 and HA4.1.1); V4.1.2 (PV4.1.2 and HA4.1.2); V4.1.3 (PV4.1.3 and HA4.1.3); V4.1.4 (PV4.1.4 and HA4.1.4); V4.1.5 (PV4.1.5 and HA4.1.5). The five subdimensions of V4.2 and their indicators are: V4.2.1 (PV4.2.1 and HA4.2.1); V4.2.2 (PV4.2.2 and HA4.2.2); V4.2.3 (PV4.2.3 and HA4.2.3); V4.2.4 (PV4.2.4 and HA4.2.4); V4.2.5 (PV4.2.5 and HA4.2.5). The five subdimensions of V4.3 and their indicators are: V4.3.1 (PV4.3.1 and HA4.3.1); V4.3.2 (PV4.3.2 and HA4.3.2); V4.3.3 (PV4.3.3 and HA4.3.3); V4.3.4 (PV4.3.4 and HA4.3.4); V4.3.5 (PV4.3.5 and HA4.3.5).

5.6 SCM-GI maturity model

It is a specific adaptation of the SCM maturity model proposed by Lockamy and McCormack [10] to improve SCM performance [2]. It was adopted by the GI company as a reference to homologate the maturity of SCM-GI processes. The SCM-GI maturity model specifies five stages: (1) Ad hoc-GI: An SCM scheme has not been implemented. (2) Defined-GI: Transactional purchasing process with some SCM topics implemented in an isolated manner. (3) Linked-GI: An SCM scheme has been formally implemented, which is not systematically executed. Some success stories in strategic contribution of purchasing are presented. (4) Integrated-GI: The SCM scheme works systematically. The supply area adds value mainly in the categories of greatest impact. (5) Extended-GI: The supply area is recognized throughout the organization as a strategic business partner and as a provider of innovative supply solutions and commercial expertise [14].

5.7 Scope of information and data collection

It is determined by the scope of the expected results. The scope of the RE1 and RE4 results is: (1) Statistical description of the SCM V3 maturity level corresponding to the start and end times of the PDP program. (2) Qualitative description of the RE1 and RE4 results.

The scope of the RE2 and RE3 results is: (1) Qualitative description of RE2 and RE3. (2) Statistical description of the dimensions, subdimensions and components of the variables V1, V2, V3, V4, and their variations in RE2 and RE3. (3) Maturity gaps of the variables V1, V2, V3, V4 at the beginning of each period. (4) Maturity level of each variable V1, V2, V3, V4, approved according to the SCM-GI maturity model.

The scope of the RE5 result is: (1) Graphic and tabulated presentation of the statistical measures of data quality, correlation, and influence of variables V1, V2, V4 on variable V3. (2) Statistical verification of the hypotheses. The scope of the RG result is: 1. Synthesis of the integration of the specific results. 2. Agreement between the hypotheses, objectives, and results [2].

5.8 Method of information and data collection

The method of information and data collection is the "review of existing records." This procedure is supported by the "Participant Consent" issued by the company GI [2]. Using this technique, the researcher selectively extracts from the SIC-GI information system the information and data required to develop the research objectives.

The "review of existing records" allows obtaining a general view of: 1. The SCM-GI maturity level (V3) approved according to the SCM-GI maturity model. This view constitutes the reference point to analyze the improvement of SCM maturity. 2. The variation of the SCM-GI maturity level V3, and its relation to the variation of three factors: (1) The "management of supplier development" V1. (2) The "capacity of suppliers" V2. (3) The "performance of suppliers" V4. This insight is essential to verify whether the three supplier management factors ("development" V1, "capability" V2, and "performance" V4) have a direct and positive influence on SCM maturity V3.

This systematic approach to data collection ensures the integrity and fulfillment of the development objectives of this research. Additionally, it ensures the relevance, validity, quality, and reliability of the study data.

5.9 Presentation of data

The data are "high level" and describe: (1) For the RE1 and RE4 results: the SCM maturity profile based on the maturity of 11 procurement management processes. (2) For the RE2 and RE3 results, the periodic behavior of the "supplier capacity," classified by categories [1, 2].

5.9.1 Presentation of data for RE1 and RE4 results

Based on a descriptive statistical analysis of the maturity levels of the SCM V3 processes, the data are presented in three supply categories: (1) Critical. (2) Restrictive. (3) Relevant. The dimensions and subdimensions of V3, on the one hand, present the efforts corresponding to the "planning and verification" PV activities, which are complemented by the records of the efforts corresponding to the "continuous improvement" HA activities.

The data presented with the "SCM-GI maturity indicators" recorded at the beginning (RE1) and at the end (RE4) of the PDP program are: description of the variable (DV); dimensional and subdimensional weighting coefficient (CP); planned final value of the variable (BACds); planned final value in the program (BACpdp); V3 start value; start max. Gap; start maturity level; stage of maturity overcome; start gap.

5.9.2 Presentation of RE2 and RE3 outcome data

These high-level data describe the periodic behavior of SCM maturity V3, and "supplier capability" classified by category [1, 2]. Through descriptive statistical analysis of the RE2 and RE3 outcomes, an examination of the variations of "supplier development" V1, "supplier capability" V2, and "supplier performance" V4, against the variation of SCM maturity V3, is presented.

The RE2 and RE3 outcome data presented with the “SCM-GI maturity indicators” recorded at the start and end times of each stage of the PDP program, include the following indicators: variable description (DV); dimensional and subdimensional weighting coefficients (CP); start value (EV0 in the first stage; EV1 in the second stage); planned value at the end of the stage (VP.1 in the first stage; VP.2 in the second stage); final planned value in the PDP-GI (BACpdp); schedule variation at the end of each stage (SV1; SV2); schedule performance index for each stage (SPI1; SPI2); variation at each stage (Var.1; Var.2).

5.9.3 Presentation of the data for the RE5 result

These data reveal the SCM-GI represented by the variables V1, V2, V3, and V4, each broken down into three dimensions, and each dimension into five subdimensions, which represent the maturity of the PDP program processes and the maturity of the SCM processes. These activities are structured with two components of the PDCA cycle: the first registers the “planning and control” (PV) efforts; the second registers the “continuous improvement” (HA) efforts.

These PV and HA activities, being structured according to the PDCA cycle, allow administrative control of the effort invested in management and resources. The effort of the “planning and verification” activities is complemented by the effort of the “execution and action” activities. The data are presented expressed in percentages (%), tabulated, and sorted by periods of the PDP program, classified by variables (V1, V2, V3, and V4), dimensions (critical, restrictive, and relevant categories) and subdimensions (design, planning, execution, monitoring, and control).

5.9.4 Presentation of the data of the RG result

This is the “synthesis and integration of the specific results,” which describes the sequence of the specific results of this research, RE1, RE2, RE3, RE4, RE5, through an integrated description that relates, unifies and interprets the analysis and findings of these results. This description has the purpose of: (1) Verifying compliance with the general objective OG of this research. (2) Verifying the general hypothesis HG of this study. For this purpose, two parts are presented: (1) Synthesis and integration of the specific results. (2) Agreement between objectives, hypothesis, and results.

5.10 Methods of analysis of numerical data

The evaluation of the results RE1, RE2, RE3, RE4 is carried out by the method of “statistical descriptive analysis,” articulated with the method of “earned value analysis” (EVA) (ISO 21508:2018, Earned value management). The statistical verification of the result RE5 is carried out by means of the “statistical analysis of correlation and linear regression” to check the effect of positive variation of V3 by association and direct influence of the positive variations of V1, V2, and V4 [2].

5.10.1 Scope of the descriptive statistical analysis method

Apply descriptive statistics to examine the quality, accuracy, and behavior of the data: (1) Examine each specific result to synthesize it into a few data, organize, simplify, and present the content through tables and visual aids. By numerically representing the most significant statistical characteristics, the interpretation of the information contained is facilitated, the accuracy is verified, and the behavior trends of the SCM V3 maturity are described. (2) Homologate the maturity levels, with reference to the SCM-GI maturity model, to determine the maturity stage in which the SCM-GI and its management processes are at the beginning and end of each stage of the PDP program. (3) Determine the central tendency measures of the SCM maturity level, as a reference base for performing the following predictive analyses: 1. Proportional analysis of the maturity and management efforts of the SCM processes, by category. 2. Earned value analysis (EVA). 3. Analysis of the SCM-GI process profile gaps. The measures of central tendency and variability of the data are: the mean, the weighted mean, the median, and the standard deviation. These data indicate the center around which the data set is located, and are used to summarize the information. This summary of data in a single value for each variable synthesizes the analysis of the information and provides an overview of the specific result. (4) Determine the proportions in which the activities and subsidiary components of design, planning, execution, control, and monitoring of the management processes contribute to the maturity of SCM-GI" in each category. (5) In the results RE1 and RE4, the frequency distribution analysis method is not used, because the data series of these results correspond to unique (non-periodic) observations of the diagnosis of the maturity level of each process or category. On the other hand, in the result RE5, prior to the correlation and linear regression procedures, the normality of the data of the results RE2 and RE3 is verified. (6) In the RE2 and RE3 results, identify the variation of V3 versus the variation of V1, V2, V4, between the start and end times of each stage of the PDP program. This variation analysis provides an understanding of the direct and positive influence of the supplier development factors V1, V2, and V4, in the improvement of the SCM V3 maturity. (7) Identify the management gaps for each variable at the beginning and end of each period. These gaps constitute the possibility of improving the SCM-GI maturity, through improvement actions in the PDP-GI program, in stages, to make viable the planning and control of the growth of the level of the supply management processes, in the PDP program of integrated projects, through the planned effort and the program schedule.

5.10.2 Scope of the earned value analysis (EVA) method

It uses the statistical data of the central tendency measures of each variable, V1, V2, V3, and V4, to plan and control the growth of the SCM-GI process level, as an integrated project program, through the planned effort and the execution schedule of the PDP program. The periodic observations of the variables are organized in ascending order, and an integrated graph of the magnitudes of the events is drawn. At the end of each stage of the program, the accumulated values of planned effort PV, effective effort EV, and invested financial effort AC in each project, determine the accumulated variations of the schedule variation SV of the effective effort EV with respect to the planned effort PV, and the cost variation CV of the invested effort AC in each project.

The data are visualized as a whole by means of a graphical representation of the earned value analysis. This two-dimensional graph shows the periodically accumulated values of the variables V1, V2, V3, and V4 on the vertical axis. On the horizontal cross axis, the behavior of these variables is illustrated over time in the implementation stages of the PDP program. This graph provides an approach to analyze the variations, evaluate the trends, and formulate forecasts of the variation of the SCM-GI maturity V3, against the variations of the supplier development factors V1, V2, and V4.

This analysis focuses on describing the control of the effective effort completed (EV) against the previously planned effort (PV) for the integrated projects represented by the variables V1, V2, V3, and V4. In each project V1, V2, V3, and V4, the management effort carried out and validated (earned value EV) is periodically compared with the estimate previously planned at the beginning of the period (VP). Based on the variation (EV-PV) = SV, the following is determined by extrapolation: (1) The management effort pending to be carried out in V1, V2, and V4, to achieve the planned improvement goals in V3. (2) The estimated time required to achieve the planned goals, according to the conditions and performance criteria of the schedule. 3. The estimate of the resources required to complete the planned effort until the end of the PDP program.

The planning and control lines for the management efforts of variables V1, V2, V3, and V4, each considered as an integrated project of the PDP program, begin with the start values and end with the values at the end of each stage of the program. These lines describe the analysis of earned value. The coordinate axis represents the stages of the program, and the ordinate axis represents the management efforts of the variables.

This method has the following scope: (1) The PDP program is made up of the implementation of four integrated projects: "supplier development management" V1, "supplier capacity development" V2, "supply chain management" V3, "supplier performance management" V4. (2) Measurement baseline. The scope, schedule, and cost of each of these management efforts (V1, V2, V3, V4) integrate a measurement and control baseline for the implementation of the PDP program. Each baseline projects the planned effort to compare it with the effort executed and validated in the first stage. This comparison determines the variation and performance of each project. (3) Basic measurement elements. The analysis of variations and performance of each variable V1, V2, V3, and V4 is carried out for each stage based on four basic elements: the management effort planned for the first stage (PV); the cost of the management effort carried out (AC); the effective management effort (EV); and the planned effort to achieve the objectives determined until the completion of the PDP program (BACpdp). (4) The variations, performance indices, and forecasts with respect to the original plan of each management project are obtained from the four basic measurement elements: Cost variation, CV = EV-AC; Schedule variation, SV = EV-PV; Effort performance, CPI = EV/AC; Schedule performance, SPI = EV/PV; Estimated performance to complete the program, TCPI = (BAC-EV)/(BA-AC); Variation at completion, VAC = BAC – EAC; Estimated total effort forecast, EAC = AC + BAC-EV; Estimated total effort forecast with CPI, EAC=BAC/CPI; Estimated total effort forecast with CPI and SPI, EAC = (AC + BAC-EV)/(CPI*SPI); Forecast of the estimated effort with ETC, EAC = AC + ETCupward; Forecast of the estimated effort until the end of the planned program: ETC = EAC-AC. (5) The planning and control of the variables V1, V2, V3 V4, at the start and end times describes the progress of each stage or period of implementation of the PDP program. (6) At each stage of the program, the initial and final gaps of the management levels of the program processes and SCM-GI are determined, in order to verify the possibility of mitigating them through the implementation of the PDP-GI program. (7) The management levels of VI, V2, V3, V4 at the beginning and at the end of each stage of the PDP-GI program, approved according to the SCM-GI maturity model, determine the stage of maturity exceeded by each process.

Based on this information, the parameterization of the PDP-GI program processes is projected aimed at improving the SCM-GI maturity. The approved maturity level at a time t is: Mt = [(EV.t*5)/BACpdp], where EV.t is the value reached at the end of period t, and BACpdp is the final planned value of the project in the PDP program.

5.10.3 Scope of the relational statistical analysis method

The correlation quantifies the relationship between the variables V1, V2, V3, V4, and the linear regression generates an equation (model) based on the relationship between two variables, which allows predicting the value of V3 from V1, V2, and V4. This method has the following scope: (1) Validate the proposed conceptual model using correlational links between supplier management factors and SCM maturity to determine the correlation between variables V1, V2, V3, V4. (2) Examine, evaluate, and verify the type of relationship and influence between supplier management factors and SCM maturity. (3) Quantify the stability and consistency of the measurements and the reliability of the measurement scale of the instruments for each variable based on the dimensions observed. (4) Determine the appropriate test to calculate the correlations between the variables under study, based on the normality test of the scores of the consolidated variables. (5) Identify the correlations that exist between the consolidated variables (V1, V2, V3, V4), determine how strong the associations are, and in each case verify whether the reliability value of the estimates is acceptable. (6) Contrast the normality of the data set. (7) Interpret how strong the correlation is. (8) Interpret the meaning of the correlations, the type of association that exists between the variables, the degree of linearity, the direction of the relationship, the strength of the relationship, the trend of the variables, and the dispersion that exists in the points around this trend. (9) Determine the relationship between the variables using the linear regression technique. (10) Verify the linearity between the variables (dispersion diagrams). (11) Using V1-V3 and V2-V4 regressions: interpret the correlation and determination coefficients; explain the behavior of the variables; rate the intensity of the relationship; verify the statistical significance of the model, and the existence of the linear relationship. (12) Using regressions and correlations with component variables: examine the effect of the planning and control effort compared to the continuous process improvement effort, and identify which of these factors has the greatest influence on SCM maturity.

6. Results

Table 2 presents the periodic indicators of variables V1, V2, V3, and V4 collected by the researcher during the implementation of the PDP-GI program.

The discussion of the results RG, RE1, RE2, RE3, RE4, and RE5 focuses on four elements of analysis: (1) Variation in the maturity profile of the SCM-GI processes between RE1 and RE4 (**Figure 1**). (2) The analysis of the earned value of V1, V2, V3, and V4 of the specific results RE2 and RE3 of the PDP-GI program (**Figure 2**). (3) The RE5 result of statistical verification of the relationship and the influence of the PDP-GI supplier management on the SCM-GI V3 maturity (**Figure 3**). (4) The findings with their respective treatments, the corroboration, and the contrast of the results (**Table 2**).

First, **Figure 1** shows the maturity profile of the SCM-GI processes at the beginning (RE1) and at the end (RE4) of the PDP-GI program. The specific result RE1 is the first diagnosis of the SCM-GI V3 maturity, before implementing the PDP-GI program. The result RE2 is the second diagnosis and corresponds to the final moment of

	Period													
Variable	**1**	**3**	**5**	**7**	**9**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
V1	430	468	523	557	580	600	609	665	703	713	770	767	729	800
V1.1	200	220	265	290	300	305	309	350	369	355	383	390	371	400
PV1.1	84	59	92	125	87	140	142	81	85	124	134	105	100	184
HA1.1	116	161	173	165	213	165	167	269	284	231	249	285	271	216
V1.2	150	160	165	170	180	190	193	205	217	220	238	230	219	250
PV1.2	41	74	48	73	83	67	68	48	51	101	109	106	101	87
HA1.2	109	86	117	97	97	123	125	157	166	119	129	124	118	163
V1.3	80	88	93	97	100	105	107	110	117	138	149	147	139	150
PV1.3	28	31	27	41	46	48	49	46	49	37	40	52	49	35
HA1.3	52	57	66	56	54	57	58	64	68	101	109	95	90	115
V2	198	205	233	243	250	288	259	299	358	330	397	357	336	369
V2.1	198	206	230	242	248	292	263	301	360	336	404	365	342	372
V2.2	195	200	234	242	247	292	263	306	367	337	405	355	334	376
V2.3	201	210	234	245	254	280	252	290	348	318	381	352	331	360
V3	481	489	539	557	576	583	565	588	570	606	588	616	629	627
V3.1	434	443	503	520	544	548	531	553	537	560	543	568	580	577
V3.2	518	527	558	579	595	603	585	617	598	641	622	651	664	669
V3.3	491	498	555	571	590	598	580	594	576	618	599	629	642	636
V4	653	667	700	758	770	780	808	808	792	855	828	875	888	956
V4.1	717	728	786	808	818	828	858	867	850	903	875	909	922	991
V4.2	669	680	690	760	770	780	808	786	770	841	814	860	873	939
V4.3	573	594	623	707	722	732	758	771	756	821	795	856	869	939

Source: ISA Intercolombia S.A. ESP. Participant consent: GLVA 2019.10.20.

Table 2.
PDP-GI implementation data and SCM-GI maturity.

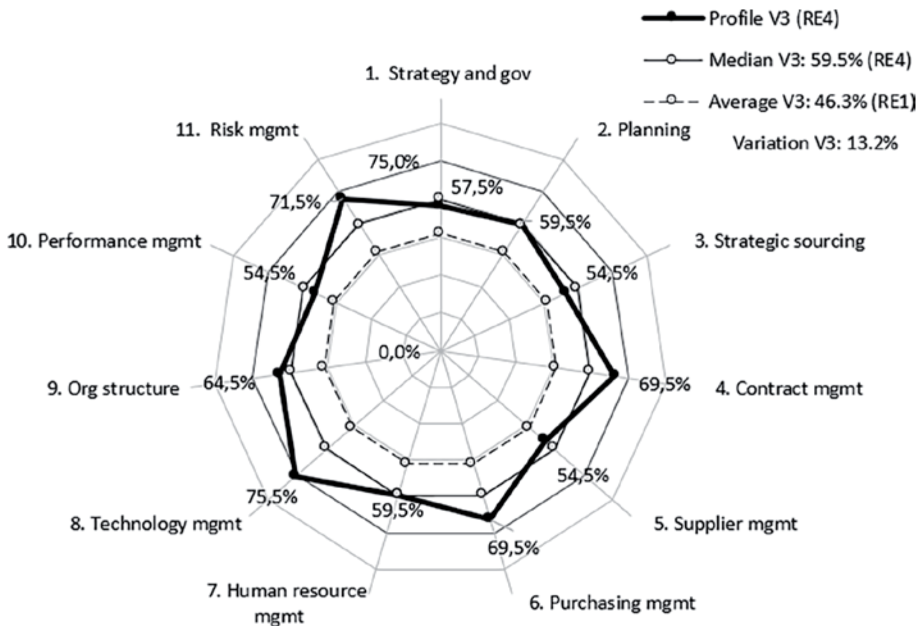

Figure 1.
Maturity profiles of SCM-GI processes, at the beginning and end of the second stage of the PDP-GI.

the implementation of the PDP-GI program. These diagnoses provide the most recent and complete information on the improvement of the SCM-GI maturity, representative of the Latin American electric sector.

Secondly, **Figure 2** illustrates the earned value analysis of variables V1, V2, V3, and V4 of the RE2 and RE3 results of the supplier management and development program PDP-GI [2].

Third, **Figure 3** illustrates the RE5 result of statistical verification of the relationship and the direct and positive influence of PDP-GI supplier management on SCM-GI V3 maturity. This model verifies the statistical significance of the relationships between the variables, and the correlation measure between SCM-GI V3 maturity, and the independent variables: development management V1, supplier capability V2, supplier performance V4. Additionally, it calculates the prediction error of the dependent variable V3.

Although this measurement determined small coefficients for V1 and V2, the standardized coefficient for supplier performance management was very high, 0.93. In addition, the non-standardized coefficients indicated that supplier performance management V4 effectively influenced the CS-GI V3 chain maturity, because its P value was less than 0.05 (<0.001), and this influence is in direct relationship because its coefficient is positive (0.543). This regression also indicated that about 85.8 percent of the V3 supply chain maturity results are explained by the set of V1, V2, and V4 supplier performance and capability development factors, which were made effective through the PDP-GI program.

Fourth, **Table 3** presents the relationship between findings and their treatments, corroboration, and contrast of the results: (1) For each specific result, the concatenation between the hypotheses, objectives, and evidence of the research results as a product of real effects is verified. (2) For each of the specific results, the findings or anomalies of the SCM-GI maturity and the treatment planned to be developed with

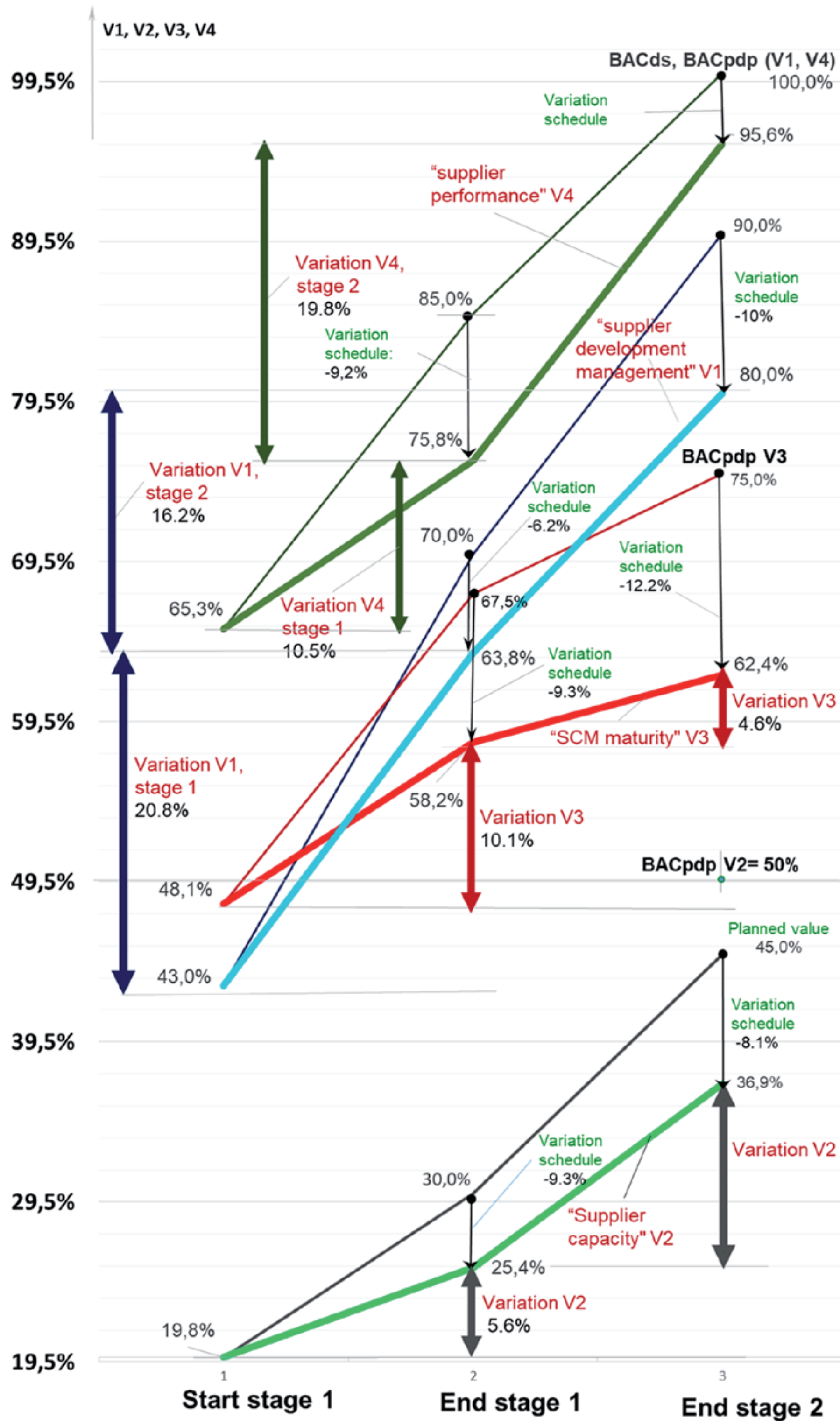

Figure 2.
Analysis of the earned value of the results RE2 and RE3 of the PDP-GI program.

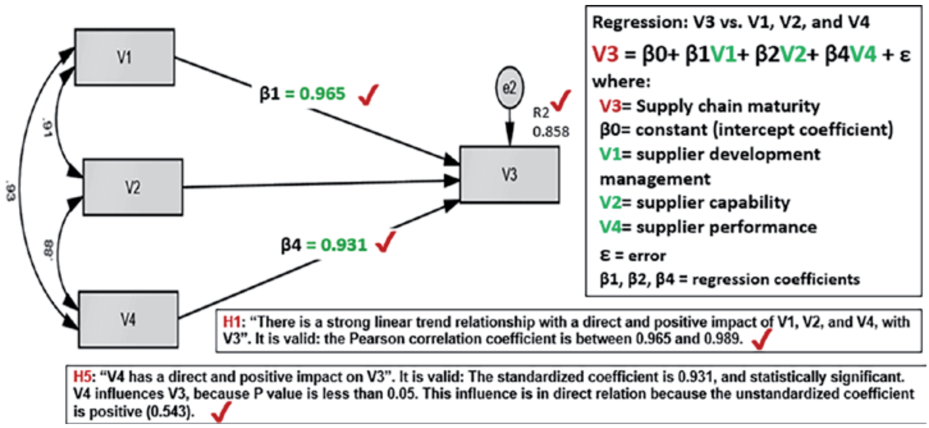

Figure 3.
Direct and positive influence of PDP-GI supplier management on SCM-GI maturity V3.

Concatenation of the hypotheses, objectives and results of the research
General hypothesis HG: The implementation of the PDP program improves SCM maturity.
General objective OG: To measure and verify in practice and analytically, the direct and positive influence of the implementation of the PDP program, in the improvement of SCM maturity.
Overall Result RG: Practical measurement and analytical verification of the direct and positive influence of the implementation of the "PDP-GI program" on the improvement of SCM maturity. *Evidence No. 1.* The practical measurement in the implementation of the PDP program shows the improvement of: 1. The "management of supplier development" V1, by 37%; 2. The "capacity of suppliers" V2, by 17.1%; 3. The "performance of suppliers" V4, by 30.3%; 4. The maturity of SCM V3 by 14.3%. 85.8% of this improvement ΔV3 = 12.27% is attributable to the implementation of the "PDP-GI." *Evidence No. 2.* Analytical verification of the influence of the PDP-GI program on SCM-GI maturity indicates the following: 1. "Capacity developed by suppliers" V2, explains 96.5% of the changes in "contractual performance of suppliers" V4; 2. "Continuous improvement of SCM maturity" HA3, is explained 61.7% by "supplier performance" PV4 and HA4; 3. "SCM maturity planning and control" PV3, is explained 65.8% by "supplier performance" PV4 and HA4; 4. The correlation and determination coefficients measured for the "consolidated variables" model V1, V2, V3, V4, and the "component variables" model PV1PV2, HA1HA2, PV4, HA4, PV3, HA3, analytically validate the specific hypotheses HE1, HE2, HE5, HE6, HE7, HE8, HE9, and HE10; 5. The practical measurement of V1, V2, V3, and V4 during the implementation of the PDP program, and the analytical verification of the direct and positive influence of the "PDP-GI program," in improving SCM maturity, validate the general hypothesis HG. Consequently: The implementation of the PDP program improves SCM maturity V3, with an effectiveness of 85.8%.
Specific objective OE1: Diagnose the SCM maturity level before the implementation of the PDP.
Specific result RE1: (1) The diagnosis of the "maturity of SCM-GI processes," before the implementation of the PDP program, the SCM V3 maturity level was valued at 46.3%. (2) This V3 level can increase up to 51.9% = 100% - 46.3%, through the implementation of a PDP program, in stages.
Finding and treatment of RE1: 1. Diagnosis of SCM-GI maturity before the PDP-GI program. 2. SCM-GI V3 process maturity gaps. 3. PDP-GI program aimed at improving SCM-GI maturity, in the first and second stages.
Corroboration and contrast of RE1: The findings of RE1 complement the previous research with a practical methodology for managing numerical data of SCM-GI, based on the articulation of the descriptive statistical analysis of V3, with the *ex ante* analysis of the earned value of the integrated PDP-GI projects.
Specific hypothesis HE9: The implementation of the first stage of the PDP program improves the maturity of SCM-GI.
Specific objective OE2: Implement the first stage of the PDP program, to improve the maturity of SCM.

Concatenation of the hypotheses, objectives and results of the research
Specific result RE2: The positive variation of SCM maturity V3, attributable to the positive variation of the levels of supplier management ("development" V1, "capacity" V2, and "performance" V3), of the first stage of the PDP program. *Evidence No. 1:* The practical measurement in the implementation of the first stage of the PDP program, shows the improvement of: 1. The "management of supplier development" V1, by 20.8%. (2) The "capacity of suppliers" V2, by 5.6%; 3. The "performance of suppliers" V4, by 10.5%. (3) The maturity of SCM V3, improved by 10.1%. Around 85.8% of this improvement ΔV3 = 8.67% is attributable to the first stage of implementation of the PDP program. *Evidence No.2.* Analytical verification of the influence of the first stage of the PDP-GI program on SCM-GI maturity indicates the following: 1. "Capacity developed by suppliers" V2 explains 96.5% of the changes in "contractual performance of suppliers" V4. 2. "Continuous improvement of SCM maturity" HA3 is explained 61.7% by "supplier performance" PV4 and HA4. 3. "SCM maturity planning and control" PV3 is explained 65.8% by "supplier performance" PV4 and HA4.
Finding and treatment of RE2: 1. V3 variation, attributable to the variation of V1, V2, V4, in the first stage. 2. Final gaps of V1, V2 and V4 in the first stage.
Corroboration and contrast of RE2: The findings of RE2 complement the previous research with the following contributions: 1. Practical demonstration of the positive variation of SCM maturity V3, attributable to the positive variation of the levels of supplier management (V1 development, V2 capacity, and V3 performance), achieved in the first stage of implementation of the PDP-GI program. 2. Implementation of the first stage of the PDP-GI program intentionally aimed at improving SCM-GI maturity.
Specific hypothesis HE10: The second stage of the PDP program improves SCM-GI maturity.
Specific objective OE3: Implement the second stage of the PDP program, to improve SCM maturity.
Specific result RE3: The positive variation of SCM maturity V3, attributable to the positive variation of the levels of supplier management ("development" V1, "capacity" V2, and "performance" V3), during the second stage of the PDP program. *Evidence No. 1:* The practical measurement in the implementation of the second stage of the PDP program shows the improvement of: 1. The "management of supplier development" V1, by 16.2%; 2. The "capacity of suppliers" V2, by 11.5%; 3. The "performance of suppliers" V4, by 19.8%; 4. The "maturity of SCM" V3, improved by 4.6%. Around 85.8% of this improvement ΔV3 = 3.95% is attributable to the implementation of the second stage of the PDP program. *Evidence No. 2:* Analytical verification of the influence of the second stage of the PDP-GI program on SCM-GI maturity indicates the following: 1. "Capacity developed by suppliers" V2 explains 96.5% of the changes in "contractual performance of suppliers" V4. 2. "Continuous improvement of SCM maturity" HA3 is explained 61.7% by "supplier performance" PV4 and HA4. 3. "SCM maturity planning and control" PV3 is explained 65.8% by "supplier performance" PV4 and HA4.
Finding and treatment of RE3: 1. V3 variation, attributable to the variation of V1, V2, V4, in the second stage. 3. Final gaps of V1, V2, and V4 in the second stage.
Corroboration and contrast of RE3: The findings of RE3 complement the previous research with the following contributions: 1. Practical demonstration of the positive variation of SCM maturity V3, attributable to the positive variation of the levels of supplier management (V1 development, V2 capacity, and V3 performance), achieved in the second stage of implementation of the PDP-GI program. 2. Implementation of the second stage of the PDP-GI program intentionally aimed at improving SCM-GI maturity.
Specific objective OE4: Diagnose the level of SCM maturity at the final moment of the PDP program.
Specific result RE4: Diagnosis of the "maturity of SCM-GI processes" at the end of the PDP program: (1) At the end of the second stage of the PDP program, the SCM V3 maturity level was valued at 62.8%. (2) This V3 level can continue to increase up to 37.2% = 100% - 62.8%, by implementing new stages of the PDP program.
Finding and treatment of RE4: 1. Diagnosis of SCM-GI maturity at the end of the second stage of the PDP-GI program. 2. SCM-GI V3 process maturity gaps. 3. PDP-GI program aimed at improving SCM-GI maturity in a new stage.
Corroboration and contrast of RE4: The findings of RE4 complement the previous research with a practical methodology for managing numerical data of SCM-GI, based on the articulation of the descriptive statistical analysis of V3, with the ex-post analysis of the earned value of the integrated PDP-GI projects.

Concatenation of the hypotheses, objectives and results of the research
Specific objective OG5: Measure the impact of the PDP program on SCM maturity.
Specific result RE5: Measurement of the impact of "development management" V1, "capability" V2, and "supplier performance" V4, on SCM maturity V3: (1) The improvement in SCM maturity V3, attributable to the implementation of the "PDP-GI," was ΔV3 = 12.27% (equivalent to 85.8% of the total variation achieved by V3 in the two stages of the PDP-GI program, ΔV3total = 14.3%). (2) The "continuous improvement of SCM maturity" HA3, is explained by 61.7% by the "supplier performance" PV4 and HA4. (3) The "SCM maturity planning and control" PV3, is explained by 65.8% by the "supplier performance" PV4 and HA4. (4) For every 10 units that the variable V2 "supplier capacity" increases, the variable V4 "supplier performance" increases by approximately 15 points (V4 = PV4 + HA4). (5) The correlation, linear regression, and statistical significance analyses of the data from the RE2 result validate the specific hypotheses HE1, HE2, HE5, HE6, HE7, HE8, and HE9. (6) The correlation, linear regression and statistical significance analyses of the data from the RE3 result confirm the validation of the specific hypotheses HE1, HE2, HE5, HE6, HE7, HE8, and HE10.
Finding and treatment of RE5: Statistical evidence of the direct and positive influence of supplier management implemented with the PDP-GI program on SCM-GI V3 maturity.
Corroboration and contrast of RE5: The findings of RE5 complement previous research with the following contributions: 1. Methodology for data collection and statistical analysis, in accordance with the objectives. 2. Conceptual model of the relationship between research variables, using correlational links between SCM-GI V3 maturity and the determining factors of PDP-GI supplier management. 3. Procedure for relational statistical analysis and influence of V1, V2, and V4 on V3.

Table 3.
Discussion of research results (findings, treatments, corroboration, contrast).

the subsequent specific objective are identified. (3) Likewise, the corroboration and contrast of the results and findings with reference to previous research are indicated, to determine the feasibility of the research results.

7. Conclusion

The overall RG result of this study complements the previous research with a quantitative methodology for process improvement (QMPI) for practical and analytical demonstration of the positive impact on SCM maturity produced by a supplier development and performance management program PDP, planned and controlled as a set of integrated projects.

This methodology consists of the articulation of statistical analytical procedures with the analysis of earned value of integrated management projects, focused on the predetermined, detailed, and effective planning and control of the improvement of SCM maturity.

The QMPI methodology complements the previous research with the following contributions: (1) The practical demonstration of the improvement of SCM maturity as a result of the implementation of a PDP program, plannable, and controllable through the articulation of statistical analysis with the analysis of earned value of projects. (2) Statistical verification of the specific hypotheses HE1, HE2, HE5, HE6, HE7, HE8, HE9, and HE10, which support the confirmation of the general hypothesis HG: The implementation of the PDP program improves the maturity of the SCM.

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Chapter 3

Enhancing Vaccine Distribution Networks: The Synergy of Supply Chain Visibility for Traceability and Resilience

Karthik Kalyan Raj Kumar Yesodha, Prabhakaran Rajendran, Arunkumar Jagadeesan and Nitin Agarwal

Abstract

Vaccine management refers to the proper handling of vaccines with a view of disbursing them at the right time, which is very crucial, especially during the pandemic. Although the supply chains for vaccines are far more developed than those of other goods, there are often barriers, such as a slower delivery rate, a lack of transparency, or even general ineffectiveness in distributing vaccines. These factors reduce the ability to respond to and compound inequities. This work examines utilizing supply chain visibility technologies, including RFID, IoT, and blockchain technologies, to optimize visibility in vaccine distribution logistical chains. Focusing on the practical applications of the analyzed technologies, this work demonstrates how they enhance vaccine inventory management, resource utilization, and minimization of logistical mistakes. The findings suggest that supply chain visibility improves decision-making, costs, and the necessary transparency, especially during pandemics. The study reveals that enhancing supply chain transparency may be critical in addressing distribution issues, enhancing population health, and unlocking fair, accelerated vaccine distribution. It also presents a discussion of the application of the findings, the ability and scope of the study, and directions for more development in the use of new and efficient technologies in the distribution of vaccines.

Keywords: vaccine distribution, supply chain visibility, RFID, IoT, blockchain technology

1. Introduction

1.1 Overview

The efficient distribution of vaccines is a key component in guaranteeing that people get vaccines at the Right Time in proportion to the disease burden in the world today, especially where there is an epidemic such as COVID-19 [1]. However, to the present, smooth vaccine distribution is a problem that many networks encounter, including delays, inefficiencies, poor traceability, and a general inability to track batches of vaccines as they move along the supply chain. These challenges make vaccine distributions ineffective, slow the response to emergencies, and further increase inequalities when it comes to vaccines [2].

Effective vaccine administration plays a crucial role in ensuring that vaccines are delivered promptly and equitably, especially in the context of global health crises like the COVID-19 pandemic [3]. Despite its importance, numerous supply chain issues persist, including logistical delays, inefficiencies, and inadequate tracking systems that hinder the ability to monitor vaccine batches as they move through the distribution network [4]. These challenges undermine the effectiveness of vaccination campaigns, slowing emergency response times and exacerbating disparities in vaccine access. Addressing these barriers requires innovative solutions to streamline distribution, improve traceability, and ensure timely delivery, especially in regions with high disease burden [5].

Figure 1 highlights four key strategies for enhancing supply chain visibility and transparency. These include implementing advanced tracking technologies (to monitor real-time movement of goods), collaborating with suppliers and logistics partners (to ensure seamless coordination), utilizing cloud-based supply chain management systems (for centralized data management and process optimization), and embracing blockchain technology (to ensure secure, tamper-proof data sharing, and traceability). Together, these approaches aim to build a more efficient and trustworthy supply chain network.

1.2 Problem statement

The obscurity in the distribution networks leads to disorganization, loss/delay in shipment, and little control over the storage of sensitive vaccines, which consequently affects the goal of providing vaccines in a timely and fair manner [6]. To correct these problems, improving supply chain visibility might help increase traceability, resiliency, and overall decision-making in the distribution of vaccines.

The lack of transparency in vaccine distribution networks leads to significant challenges such as disorganization, shipment delays, and insufficient control over the storage of temperature-sensitive vaccines [7]. These issues ultimately hinder the goal of delivering vaccines efficiently and equitably. To address these problems, enhancing supply chain visibility is crucial. By improving traceability, strengthening the resilience of the distribution system, and enabling more informed decision-making,

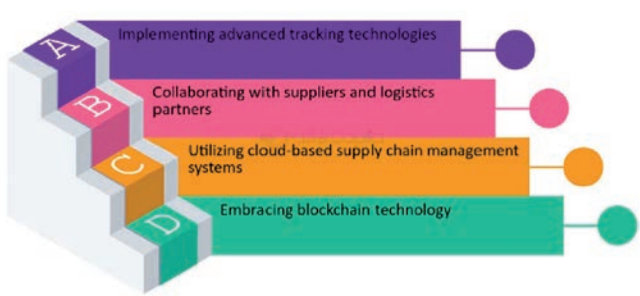

Figure 1.
Enhancing supply chain visibility and transparency [3].

supply chain visibility can ensure that vaccines are delivered in a timely and fair manner, reducing delays and improving overall effectiveness in addressing public health needs [8].

1.3 Technical challenges in vaccine distribution networks

Despite advancements in vaccine supply chains, several technical challenges persist, affecting the efficiency and reliability of distribution networks. Key issues include temperature monitoring failures, traceability limitations, and data silos within healthcare IT systems.

1.3.1 Temperature monitoring failures

Cold-chain logistics rely on IoT-enabled temperature sensors to ensure vaccines remain within the required temperature range. However, calibration inconsistencies in these sensors have led to failures in temperature monitoring. For instance, during the COVID-19 vaccine rollout in rural India, frequent power outages disrupted refrigeration systems, leading to significant vaccine spoilage. Such failures highlight the need for more robust temperature control mechanisms and real-time alert systems to mitigate the risk of wastage.

1.3.2 Traceability limitations

Ensuring proper vaccine tracking is essential for preventing batch mismanagement. However, fragmented RFID and blockchain-based traceability systems across multi-stakeholder networks have created inefficiencies. A notable example is the Pfizer-BioNTech vaccine distribution, where discrepancies arose between shipments allocated to the European Union and those destined for Africa due to inconsistencies in batch tracking. These gaps in traceability reduce accountability, increase the likelihood of mismanagement, and hinder equitable vaccine distribution.

1.3.3 Data silos in healthcare IT systems

The integration of legacy healthcare IT systems with modern supply chain visibility (SCV) tools remains a significant challenge. Many healthcare institutions still operate on outdated systems that lack interoperability with newer digital tracking solutions. In Case Study 2, a Tehran hospital experienced delays in vaccine stock updates due to system incompatibility, leading to inefficiencies in stock replenishment and distribution. Addressing these data silos requires the adoption of standardized data exchange protocols to enhance real-time visibility across the vaccine supply chain.

By identifying these technical barriers, this study aims to explore advanced AI-driven solutions to enhance vaccine distribution efficiency and resilience.

1.4 Research objectives and scope

The study pursued in this chapter discusses the peculiarities of how supply chain visibility tools will help enhance traceability and supply chain protection within vaccine distribution channels. This work outlines the technologies and best practices that can help minimize the time necessary for vaccine distribution and track the vaccine's route while ensuring it remains safe throughout the process.

This study explores the unique role of supply chain visibility tools in enhancing traceability and strengthening the security of vaccine distribution networks. It highlights the technologies and best practices that can streamline the vaccine distribution process, minimizing delays and ensuring vaccines are effectively tracked from origin to delivery. By focusing on maintaining the safety and integrity of vaccines throughout their journey, this work emphasizes the importance of real-time monitoring, data-driven decision-making, and secure handling procedures to optimize the efficiency and reliability of vaccine distribution systems.

1.5 Research questions

In what ways is supply chain visibility helpful in enhancing the efficiency and reliability of the distribution of vaccines?

1.6 Significance of the study

This study is important as it details the prospect that increased visibility within supply chain systems used in delivering vaccines can decrease costs and serve as a key inspiration to enhance public health during crises. Greater transparency helps in decision-making, allocation of resources, and response to calls for vaccines in a way pivotal for extensive immunization programs like COVID-19.

This study is crucial as it emphasizes the potential of enhanced supply chain visibility in vaccine delivery systems to reduce costs and improve public health outcomes during crises. Increased transparency within the supply chain facilitates more informed decision-making, efficient allocation of resources, and quicker responses to vaccine demands. Such improvements are essential for the success of large-scale immunization programs, such as those during the COVID-19 pandemic, ensuring equitable access and timely distribution to the populations in need. The findings of this research offer valuable insights for strengthening future vaccine distribution frameworks.

2. Literature review

2.1 Supply chain visibility (SCV)

SCV means the actual visibility of products, processes, and key metrics for supply chain partners in real time at every stage of the extended supply chain [9]. Therefore, SCV helps deliver results on time or even earlier and minimizes various risks while using analytical data for decision-making. It helps logistics increase accountability and accuracy while accessing, managing, and distributing stocks and other resources while at the same time promoting communication between associated parties [10].

2.2 Challenges in vaccine distribution

Certain key hurdles unique to vaccines concern vaccine distribution. These are some of the challenges: temperature-sensitive goods, time-sensitive goods (most vaccines have a certified shelf life), multiple batches, multiple stakeholders, and multiple locations. Lack of accountability and supervision is evident in the fact that vaccines are misplaced and the challenge of reaching remote areas of the country.

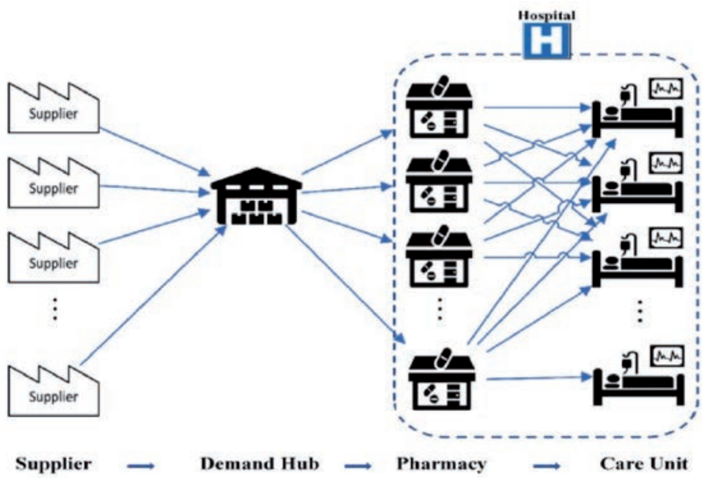

Figure 2.
Flow of medical supplies [2].

Figure 2 illustrates a supply chain model for a hospital, showing the flow of medical supplies and medications. Suppliers deliver resources to a centralized Demand Hub, which then distributes them to multiple pharmacies within the hospital. These pharmacies supply the required medications and equipment to the corresponding Care Units, ensuring that patients receive appropriate care. The structure highlights a systematic approach to streamline inventory management and ensure efficient delivery of medical necessities.

2.3 Emerging technologies for enhancing supply chain visibility

- *Radio frequency identification (RFID)* allows real-time tracking of vaccines and their conditions, such as temperature. **Figure 3** explains enhancing supply chain visibility with RFID technology.

- *Internet of Things (IoT)* devices enable continuous monitoring of the supply chain's environmental conditions (e.g., temperature, humidity). Below **Figure 4** explains the understanding of IoT in supply chain management.

- *Blockchain* ensures tamper-proof records of vaccine transactions, improving transparency and accountability in the supply chain. Though applied more extensively in other sectors, such as pharmaceuticals and food, these technologies have great potential to enhance vaccine distribution visibility. **Figure 5** explains enhancing supply chain visibility with blockchain.

2.4 Supply chain vaccine distribution efficiency

Supply chain visibility is now widely accepted to be an essential pillar of contemporary supply chain management especially in industries such as the pharmaceutical where products such as vaccines may require protection. SCV is the capability of tracking the flow of materials, information, and KPIs from suppliers through distributors to customers. SCV also brings positive change to all the rules that use it to

Figure 3.
Enhancing supply chain visibility with RFID technology [3].

Figure 4.
IoT in supply chain [4].

Figure 5.
Enhancing supply chain visibility with blockchain [3].

monitor the status of goods and processes in real time, which reduces risks and makes the businesses decision-making efficient. Even more important in the case of vaccines, SCV facilitates the safe, efficient, accurate distribution of vaccines to intended users, avoiding the consequences that arise from storage conditions and/or theft and/or any other circumstance that may delay distribution of vaccines.

2.5 Main aspects of SCV in vaccines distribution

Vaccines are to some extent distinctive from other classes of supply chains driven by numerous factors including temperature and time sensitivity of vaccines. The supply chain for most general merchandise operates with standard handling, a stark contrast to the specialized requirements of vaccine, which are a bit unique in that they need to be handled in a particular way that includes ideal temperatures under which most if not all vaccines should be transported and stored. This is far more important when working with new vaccines, for example, vaccines created to counter the COVID-19 disease, which have extreme low storage temperatures.

In order to meet these challenges, stakeholders in the overall supply chain of the vaccine must establish a visibility of the product location, environmental sensitiveness, and condition of the product at every transport node or link in the chain. Through SCV, one is able to keep track of various parameters including temperature, humidity, and expiry dates; hence, vaccines will always be in the right conditions. For instance, RFID capability in tracking vaccines makes it possible to detect early problems such as variation in temperature or a delay in delivery.

Also, through the SCV, collaboration is achieved between manufacturers, wholesalers, distributors, healthcare providers, and other regulatory authorities. It makes it possible for one party to know whether the vaccine is available or not at any time is not only efficient, but also saves the parties from the health and safety regulations.

2.5.1 Emerging technologies: RFID, IoT, and blockchain

It was found that several emerging technologies are helping to track and improve the vaccine logistic chain. Such technologies are RFID, IoT, and blockchain that all enhance SCV and the distribution of vaccines.

2.5.1.1 Communication technology: The RFID technology

Of all the available technologies, RFID is considered to have the most potential to improve SCV in vaccine distribution. RFID is captured through electromagnetic fields as they contain tags to place on containers that give real time details of stock circulation of vaccines. RFID technology eliminates the need to scan barcodes directly, unlike conventional barcodes that make the RFID especially useful in large organizations where time is of the essence.

The idea of installing RFID tags in vaccine consignment makes it possible through monitoring consignment location and state of vaccines starting with production up to the delivery point. This makes it possible for stakeholders to check on climatic conditions that may be favorable for vaccines, storage and transportation facilities and identify cases where vaccines may have been lost or delayed hence making it possible to increase chances of loss, damage, or spoilage. RFID can also interface with other systems to offer data analysis, which means that the stakeholders are able to forecast disruption so that they may contain disruption.

For instance, real time temperature tracking of vaccines using cables such as RFID tags, the stakeholders involved are able to track and monitor the temperatures at which store vaccines at the required temperatures during transportation and storage of the vaccines. Any vaccine delivery that is not within the right storage conditions, the stakeholders are notified so that they can correct it before the vaccine gets expired.

2.5.1.2 Internet of Things (IoT)

IoT stands for Internet of Things, which is a connection of physical objects with sensors and software to enable its functionalities to capture and share information. Regarding the distribution of vaccines in IoT devices, some examples in recording environmental data include temperature, light exposure, and humidity etc., and this occurs at different stages of distribution chain. RFID tags are complimented by IoT sensors to facilitate constant and real-time tracking of vaccine shipments.

Another advantage of IoT in vaccine distribution is its capability to provide full visibility of vaccine temperature. IoT sensors can be placed in refrigerated containers, vehicles, and storage facilities to ensure that data on the temperature and other conditions that might compromise vaccines quality is constantly collected in order to ensure that these vaccines are safely delivered to the target population. This constant supervision enables stakeholders to monitor vaccines condition without exposing them to damaging conditions that would reduce their effectiveness.

Secondly, IoT sensors and devices can be connected to cloud networks thus allowing for monitoring and data logging from a remote location. The integration also makes sure that decision-makers including policy makers and health care providers are always in the loop in terms of the progress about the shipment of the vaccines so that they can always be ready to take action if there is a delay.

2.5.1.3 Blockchain technology

Distributed ledger technology for storing records of transactions with an unprecedented level of decentralization and inaccessibility is gradually being considered to boost the credibility of the process of vaccine distribution. The most important benefit of the blockchain is that it enables creating the tamper-proof and transparent records of the flow of vaccines [7].

Through blockchain technology, all participants in the supply chain have an opportunity to develop a transparent record of all transactions of vaccines from the time they are manufactured to the time that they are delivered [9]. This increases transparency so that stakeholders can ensure that the vaccines have not been compromised by inadequate storage and transportation, handling among the chain of supply. Also, transparency created by blockchain helps to say that vaccines cannot be forged or altered in any way, which means that fraud is minimized while the proper certification of the vaccine stock is guaranteed [10].

Blockchain helps to bring together many interested parties, including manufacturers, distributors, and healthcare organizations, by providing everyone with equal access to a distributed record of transactions within the network. This is especially the case within the healthcare system large and complex vaccine supply chain network where several stakeholders are often involved in the process of moving vaccines from the manufacturers to the end users.

In addition, the application of blockchain can improve the compliance with regulatory requirements since temperature, light, humidity, time and other essential characteristics of vaccine's shipment will be strictly controlled to meet the appropriate standards of storage. The authorities can engage the blockchain ledger to check and ensure that storage, transport and distribution have been conducted in a right and proper manner as required to reduce compromise and make the vaccine safe and effective.

2.6 Gaps in literature

A literature review has elucidated the effect of supply chain transparency and the importance of visibility on healthcare operations and specific pharma Logistics Companies [9]. Overall, from these studies, it is seen that visibility helps in many ways, such as in the management of inventory, reduction of stock-out situations, and good compliance with regulations. Thus, the literature review of studies related to vaccine distribution is scarce, especially about incorporating IoT and blockchain implementation [3]. These gaps can be closely filled in this study by establishing the applicability of these technologies within vaccine distribution networks.

Despite the theoretical and empirical literature that aims to illustrate the significance of supply chain transparency and visibility in health care management, and especially with regard to inventory management, minimized stock-out times, and compliance with regulations, the present research question simmers with the subject of vaccines distribution [1]. Many works investigate conventional SCM strategies without considering the inclusion of emerging technologies such as IoT and blockchain to the evaluated solutions [4]. These are technologies that have the capability of transforming the status of vaccine distribution because of the provision of tracking, regulation of temperature, and accurate documentation.

3. Methodology

For this research, a case study approach is quite suitable since it facilitates an analysis of vaccination supply chain networks that employ visibility tools. Case studies illustrate specific applications using particular technologies or strategies and the effects of these applications within an overall system.

3.1 Case study analysis

Two distinct case studies are analyzed:

3.1.1 Case Study 1: AI technologies in the improvement of vaccine supply chain visibility

This case briefly revolved around the idea of interpretable AI systems in the context of vaccine distribution amidst the COVID-19 pandemic. This study explains the positive impact of an AI-based predictive model in enhancing decision-making regarding the forecasts of vaccine deliveries, vaccination trends, and demand at different geographical locations. Due to the AI system's capability to analyze large and presumably sophisticated datasets, decision-makers could allocate their efforts and the distribution structures for vaccines where they were needed most. Organization stakeholders, especially during a crisis, realized effective coordination and use of resources because of the interpretable outputs provided by the AI model.

3.1.2 Case Study 2: Supply chain planning of vaccine and pharmaceutical clusters under uncertainty

This paper proposes a mathematical approach for inventory management, distribution, and supply of pharmaceuticals and vaccines during epidemic crises with special reference to the COVID-19 pandemic. The model incorporates the cold and non-cold chain and leverages the K-means clustering for temperature sensitivity, shelf life, and vaccine priority decision-making. To respond to pharma management challenges under uncertainty, a four-echelon supply chain integrating the Mixed-Integer Linear Programming (MILP) model was utilized. Through evaluating the case study's details, the model is applied and validated using Tehran hospital data to show that an acceptable service rate can still be achieved with low costs during the epidemic.

3.2 Comparison of case study results

The two cases are similar in some ways as both examine the possibilities and challenges of efficient vaccine distribution in crises. However, the strategies used and the research methods applied are quite distinct.

- *Technological focus*: In Case Study 1, interpretable AI technologies help forecast the delivery of the different vaccines and, hence, the different resources. This approach is focused on the fact that it is crucial to be able to describe AI decision-making in order to trust AI during an emergency.

- *Modeling approach*: New techniques in Mathematical Modeling: Case Study 2 discussed the application of mixed-integer linear programming (MILP) and K-means clustering for uncertain management of pharmaceutical supply chains. This model focuses on how cold chain and non-cold chain should be integrated such that the distribution considers the characteristics of these vaccines, for instance, their sensitivity to temperature fluctuations.

- *Data handling*: Case Study 1—A case in point is where real-time decisions are made using TMHs through predictive modeling, while Case Study 2 utilizes statistical and clustering methods to ensure that data is structured for simplicity in uncertain conditions.

In terms of purpose, while both of these works serve to improve vaccine distribution and make it more efficient in emergency situations, our Case Study 1 was used primarily as a tool more geared toward real-time modeling and decision-making, as compared with the Case Study 2, which was employed primarily as a tool for supply chain modeling and optimization.

3.3 Model construction framework

To better understand the methodologies applied in each case study, we detail the model construction approaches used in AI-based decision-making and supply chain modeling.

3.3.1 AI model architecture

- *LSTM networks*: Used for vaccine demand forecasting based on historical vaccination rates and disease spread patterns.

- *SHAP values*: Applied to improve interpretability by identifying *key features affecting AI decisions* (e.g., seasonality, population density).

4. Results

4.1 Case Study 1: AI-driven supply chain enhancement

4.1.1 Effectiveness of predictive AI

All these were solved by the AI system that accurately forecasted the demand for vaccines, deliveries, and the rate of vaccinations, which helped optimize the distribution of vaccines and the general utilization of resources. Implementing the AI model helped the decision-makers focus on delivering in areas of high demand as other data were analyzed in large volumes.

4.1.2 Trust and transparency

The model was designed to be explainable so that it became 'trustable' in the eyes of the various healthcare providers, thereby facilitating cooperation in case of coordinated action.

4.2 Case Study 2: An analysis of pharmaceutical supply chain management

4.2.1 Mathematical model success

The MILP model applied in this paper helped design an efficient four-echelon supply chain with a lower cost and satisfying service level overall. Where uncertainty played a role, supply and demand fluctuations during the epidemic were considered in the model adaptation process.

4.2.2 Cold and non-cold chain integration

The integration of cold and non-cold chains was especially essential in ensuring the vaccines arrived in the right physical state. Further, the problem-solving scale was also decreased due to the clustering method, which led to faster model-solving and greater efficiency in offering information.

4.3 Findings of case study results

The findings from both case studies highlight several key aspects of how technology can improve vaccine distribution during crises:

4.3.1 Enhanced decision-making

AI and mathematical modeling technologies enhance organizational decision-making about vaccines by increasing perceptions of need and forecasts about distribution. This is more important in crises where every minute counts and informed decisions must be made.

4.3.2 Optimized resource utilization

In Case Study 1, AI models play the same role of resource utilization enhancement as in Case Study 2 MILP models. The former achieves this through geographical and population-oriented approaches, while the latter achieves the objective *via* economizing on cost.

4.3.3 Addressing uncertainty

In Case Study 2, uncertainty in the distribution of vaccines is mentioned; therefore, adaptive modeling techniques are applied to guarantee the efficient supply chain can respond to flexibility requirements. This capability is vital in a crisis where sudden shifts in demand or disruptions to the supply chain are common.

4.3.4 Cost efficiency

The two examples further show that more innovative technologies can help lower costs, in this case, about vaccine distribution. By applying AI in forecasting the number of vaccines needed and MILP to schedule timely and accurate vaccine distribution, those vaccines are delivered on time and in the right quantity and quantity; hence, there is no wastage and costs that may be incurred from delay in delivery and inaccurate quantification.

4.3.5 Improved traceability and transparency

In both cases, the most frequently mentioned goal is the issue of vaccine traceability at the distribution stage. Whereas Case Study 1 focuses on the interpretation aspects of interpretable AI, Case Study 2 draws on the cold and non-cold chain and data clustering to also concern itself with traceability.

Therefore, incorporating visibility tools in supply chains—whether through AI or complex mathematical mapping—greatly boosts vaccine distribution's robustness, effectiveness, and accountability during threshold phases like the one occasioned by the COVID-19 pandemic. These results support the importance of increasing the applicability of technology in handling and decision-making, specifically in healthcare logistics during emergencies.

4.4 Answer to research questions

The two cases provide direct solutions to the problem of using supply chain visibility to enhance the distribution of vaccines. In detail, this is exemplified in Case Study 1 which presents how interpretable AI systems, can improve vaccine supply chain transparency. With the help of such an AI system, it is possible to predict when vaccines will be delivered, monitor the rate of vaccination, as well as understand the demand for it in different locations, and thus make more accurate decisions for distribution to guarantee effectiveness. Enhanced visibility of distribution requirements results in better distribution fulfilling the purpose of increasing the rate of vaccine distribution and also the efficiency of delivery that strengthens the supply chain adequacy during such an exigent situation as a pandemic.

Case Study 2 is focused on how MILP and other models make a huge difference in proposing a more expansive and informed view of supply chains and how such aspects as temperature sensitivity, shelf life, and priorities of vaccines can be incorporated into it. By applying K-means clustering, vaccines are distributed differently according to their respective supply chain management, so that the handling of vaccines will be better and respective to the requirements of vaccines. With this increased transparency of such essential parameters along with the mathematical endeavor to exploit the distribution, there ensue enhanced decision-making and decreased costs leading to the optimization of the circulation infrastructure of vaccines, including stressful, unpredictable circumstances such as those surrounding the COVID-19 pandemic.

Observing the real-life implementations of both platforms from the case studies, it is seen that transparency in supply chain, be it AI forecasts or mathematical models, increases the reliability of delivering vaccines to the right places.

5. Discussion

5.1 Interpretation of results

These case studies amplify the importance of supply chain visibility in increasing the traceability and response to vaccine distribution networks. AI technologies in Case Study 1 show how forecasts provide real-time decision support by predicting the demand and delivery of vaccines. In this process, there is an enhanced prioritization, thus enhancing resource utilization, which is a crucial consideration during emergencies such as the current COVID-19 pandemic. On the other hand, Case Study 2 presents how mathematical models, like Mixed–Integer Linear Programming and/or clustering strategies, can enhance the distribution of vaccines, even in conditions of high volatility.

These findings support the extant literature on supply chain visibility, which has received considerable research attention in the recent years. These findings have important practical implications for vaccine distribution. The next-generation technologies of supply chain visibility, like AI and advanced modeling, solve many of these fundamental issues that arise in vaccine logistics. These technologies effectively ensure that vaccines are delivered on time and safely, a factor that is extremely important in dealing with vaccines that may have a very short shelf life and are extremely sensitive to temperatures.

For example, in Case Study 1, accurately predicting vaccine demand patterns would enable supply chain strategies to reduce time and ensure the first delivery of vaccines to target areas. The same is the situation of cold and non-cold chains in Case Study 2; vaccines are moving in a proper environment so that they will not spoil or degrade.

5.2 Limitations

However, some limitations need to be discussed. First, the study participants were selected from different universities and colleges in their sophomore and junior years. Lack of data could have contributed to such findings, particularly in Case Study 1, where reliance on history narrows the model's ability to anticipate future interruptions or odd cases. Also, the study suffers from limited external validity because the case studies concern only regions (France and Tehran). Countries or regions with distinct healthcare infrastructures or logistical challenges may yield different results. Furthermore, the complexity of the technologies used—AI and MILP models—may present implementation challenges for organizations lacking the necessary resources or expertise. These factors limit the broader applicability of the findings.

6. Conclusion

6.1 Summary of findings

This research demonstrates the *value of supply chain visibility* in enhancing the resilience and traceability of vaccine distribution networks. Both case studies highlight how integrating advanced technologies like *AI and mathematical modeling* can optimize vaccine logistics, improve resource allocation, and mitigate risks during high-pressure scenarios such as the COVID-19 pandemic. The ability to predict demand and adjust supply chains dynamically ensures timely and efficient vaccine delivery, a crucial aspect in public health emergencies.

6.2 Recommendations

Based on the findings, several recommendations can be made for stakeholders involved in vaccine distribution:

- Policy-makers should invest in infrastructure and regulations that promote the integration of advanced visibility technologies such as AI, RFID, and blockchain. This can streamline vaccine logistics and improve transparency.

- Healthcare providers should adopt digital tools that allow for better tracking and prioritization of vaccine deliveries. Using technologies that offer real-time data can help ensure vaccines reach those who need them most, particularly in high-risk areas.

- Logistics companies should enhance collaboration with technology providers to implement real-time monitoring systems that track vaccine conditions (e.g., temperature and storage) to reduce spoilage and wastage.

6.3 Future research

Future research could expand on this study by exploring several avenues:

- *Testing other visibility technologies*: While AI and modeling techniques were explored in this study, other technologies, such as blockchain and IoT, could be tested for their effectiveness in improving vaccine supply chains.

- *Expanding case studies*: Future research could broaden the scope by investigating different regions or countries, especially those with less developed healthcare infrastructures, to examine how supply chain visibility impacts vaccine distribution in diverse contexts.

- *Integration of AI and predictive analytics*: A deeper investigation into how predictive analytics and AI can be integrated into supply chain management across various phases of the vaccine lifecycle—from production to delivery—would offer valuable insights into enhancing vaccine logistics.

- *Long-term impact studies*: Future studies could also focus on the long-term impact of implementing visibility technologies in vaccine distribution, assessing their role during emergencies and in routine healthcare supply chains.

In conclusion, the research underscores the essential role of supply chain visibility in enhancing vaccine distribution networks, making them more resilient, efficient, and responsive to emerging global health challenges.

Acronyms

RFID	radio frequency identification
IoT	Internet of things
MILP	mixed-integer linear programming
AI	artificial intelligence
SCV	supply chain visibility

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Chapter 4

Production Excellence: Synchronizing Manufacturing and Supply Chain Strategies in Biotech Companies

Varun Choudhary, Anirudh Mehta and Moazam Niaz

Abstract

Biotechnology companies operate under strict rules that call for perfectly timed connections between their manufacturing and supply chain operations to meet all performance targets and meet customer needs quickly. This chapter examines how companies deliver excellent production results through various methods, such as strategy linking and using lean and agile principles in combination with integrated technology systems. It also discusses ways to manage risks and sustainability goals plus outlines what the future holds for companies. Biotech companies achieve better production results by linking their manufacturing and supply chain processes. This practice reduces production waste while handling upcoming challenges. Both lean and agile systems help us adapt, while technology capabilities like automation, AI blockchain, and digital twins improve our ability to react quickly and see what happens in our supply chain. Biotech companies need to spread their supply sources and have backup plans while securing online systems to keep their business running. Biotech companies take sustainability seriously when they use environmentally friendly production methods and supply chain techniques to lower their impact on the earth. Industry 4.0 and blockchain technology lead the way in forming new production and logistics systems for biotech industries. On top of adopting technology and sustainable methods plus good risk planning, biotech companies build better production systems and safer supply chains to win business in their competitive future.

Keywords: biotechnology, manufacturing, supply chain, automation, risk management, sustainability, blockchain, industry 4.0

1. Introduction

Biotech companies need production excellence to effectively bring safe, innovative products to market in their controlled industry. Because biotech differs from the normal manufacturing industry, it faces tough processes and strict regulations in a fast-changing technology environment. Biotech companies must combine their production plans with supply chain operations to build better performance and protection through this sensitive sector [1]. Biotech production needs more than just better plant operations since it calls for companies to bring together their production methods and reliable supply chain plans. Companies can better handle supply variations and protect their business while staying ready for changing market needs when production and supply chain directions line up. The rising challenges of global supply chains demand that biotech firms depend on technology to make smart choices and move fast to succeed in their industry [2].

Biological processes naturally behave unpredictably, which creates major production difficulties for the biotech industry. Biotech production with living organisms causes tougher management of reliability and stability compared to standard chemical plants. A company needs flexible supply chain strategies to handle manufacturing output variations and regulatory enforcement requirements. Biotech firms need to abide by FDA and EMA GMP standards during their operations [3]. Production must align exactly with GMP standards since any mistakes bring manufacturing to a stop and lead to financial penalties. This proves why all operations must work together. Biotech manufacturers who combine supply chain planning with production protect themselves better from safety standards violations [4].

Technical solutions drive systems towards better performance as new technology tools advance our understanding of supply chain management in biotech businesses. AI forecasting and blockchain technology help companies detect customer trends early and control their product supply to lower the chance of unsafe counterfeits reaching the market. Smart factories that use the Internet of Things technology (IoT) monitor production factors in real time to support quality control requirements. The COVID-19 outbreak revealed weak points in worldwide biotech supply chains, which made companies reassess their business methods [5]. They now focus on setting up local factories and finding multiple suppliers, plus enhancing their digital systems to handle future risks better. Biotech businesses need to improve their practices regularly to create production excellence that effectively meets logical supply chain performance goals [6]. This chapter analyzes essential methods and obstacles in connecting supply chain and manufacturing operations for biotechnology companies to succeed in their dynamic industry.

2. Key challenges in biotech manufacturing and supply chains

Biotech companies operate under strict rules while handling many production and supply chain management difficulties. Biotech manufacturers need to handle both efficiency goals and total adherence to laws because their product creation process requires deep knowledge, and their product passes through many global systems. To reach production excellence and provide customers with safe, high-quality products on time, we need to solve these supporting challenges [7].

Biotech manufacturers must follow rigorous Good Manufacturing Practices (GMP) set by the FDA and EMA, along with their quality standards. Biotech producers need to fulfill every requirement of strict medical safety and effectiveness tests through their complete manufacturing process. Any production mistakes through Minute pollution can force us to stop operating our facility and make us pay penalties or experience product recall. New rules demand that biotech firms build powerful quality monitoring systems and validate their methods (**Figure 1**) [8].

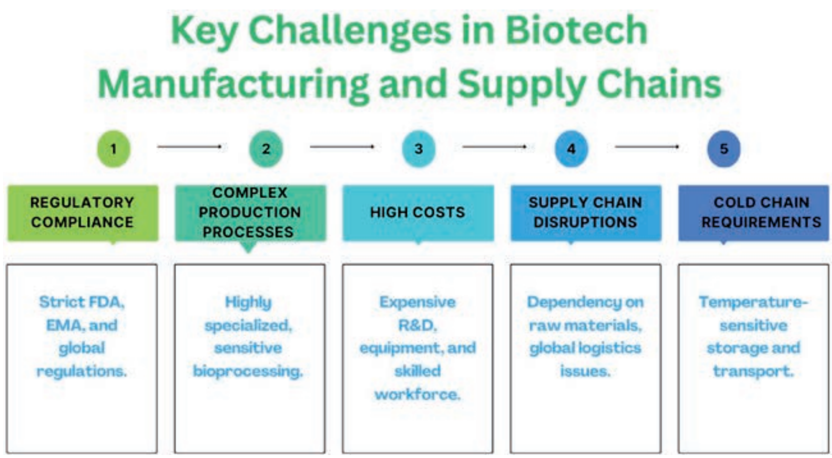

Figure 1.
Shows key challenges in biotech.

Biotech companies need suppliers worldwide for their essential materials, such as raw ingredients and pharmaceutical components. The industry needs specific items such as cell culture media and enzymes from tiny supplier networks that pose high risks to supply chain stability. Disruptions from political conflicts, natural disasters, or health crises push back product production, which reduces patients' options for vital medical treatments [9]. Companies should balance their supplier base by using multi-celestial purchasing sources and tracking supply status in real-time to reduce supply chain risks.

Biotech products require biological organisms like bacteria and yeast as well as cells from mammals to produce them, which differs from synthetic pharmaceutical manufacturing. Biological systems create fluctuations within production processes that make it hard to achieve both consistent standards and large-scale operation. Regular checks on cell development, along with improvement of fermentation methods and protein production, help to keep yield levels steady and control product quality. Modern technology tools allow us to solve production problems in biotech [10].

Specialized cleanroom and bioreactor systems demand significant investment to create and scale biotech products. From small-scale lab experiments to producing products at a commercial level, it is hard because it must follow the standard validation steps that ensure consistent results. Organizations need to combine affordable production methods with proper regulations while adding single-use systems and portable equipment to produce more while saving money. The biotech industry needs a business strategy that joins up manufacturing quality with supply chain strength to achieve success both today and in future market competition [11].

3. Strategic alignment of manufacturing and supply chain

Biotechnology firms need to perfectly link their production plans and supply chain movements to stay ahead in their industry. Biotech production's complex regulations need both functions to work together smoothly for better results and market delivery.

Strategic alignment protects companies from risks and helps them find savings while making their production system stronger [12].

The materials supply and production process for biotech companies needs to connect smoothly together to avoid delays and make better use of supplies. The intricate nature of biological production causes delays in obtaining basic materials like cell cultures and growth media, which affect schedule timing. Manufacturing teams follow Sales & Operations Planning (S&OP) methodologies to match production schedules with supply chain constraints so they can act quickly against changes in the system [13]. All departments that handle procurement production quality and delivery work together well to achieve success. Synching production performance with supplier data helps the team make early changes to maintain production quality despite supply and inventory limitations.

Modern biotech companies base their supply chain and production decisions on processed large-scale data plus artificial intelligence predictions. Companies can predict supply issues and improve inventory control by processing real-time production line updates with network suppliers and market sales figures. AI systems help biotech businesses predict consumer needs to avoid production issues and supply problems. Digital twins of manufacturing and supply chain operations let organizations test various situations before making better business choices [14].

Biotech companies have to achieve both high production speed and the capacity to change their approach without traditional manufacturing standards. Regulatory processes, market changes, and biological output fluctuation make supply chains need the ability to change directions quickly. Bioprocessing systems made for single-use help companies switch processes fast while stopping germs from entering their equipment. Companies should partner with many suppliers to prevent total reliance on a single supplier [15].

Biotech companies need to develop adequate storage supplies of vital materials yet keep small amounts of fast-expiring bioproducts from spoiling. Biotech companies achieve better business results when they join their production processes with supply chain operations while remaining compliant and growing in today's changing industry [16].

4. Lean and agile manufacturing in biotech

Companies in biotechnology need to operate efficiently under strict rules while staying able to adapt crosswise different products and handling materials with high-quality standards. Biotechnology firms that use lean and agile production methods enhance their operations by managing resources better and reacting swiftly to market requirements [17]. Biotech companies encounter specific difficulties of biological variations and strict rules plus intricate supply systems, so they need stronger lean and agile methods than regular production industries (**Figure 2**).

Companies apply automotive industry-based lean manufacturing methods to reduce waste and enhance product outcomes in biotechnology. Biotech production generates different forms of waste, including quality problems, production overruns, materials delays, and physical movements [18]. Product failures happen when harmful substances mix with raw materials during processing errors. When factories make too many products, this creates a storage problem that raises extra holding costs. Products need to wait because of required regulatory clearances, plus delays in getting raw materials. Unnecessary motion and transportation within production facilities to deal with these

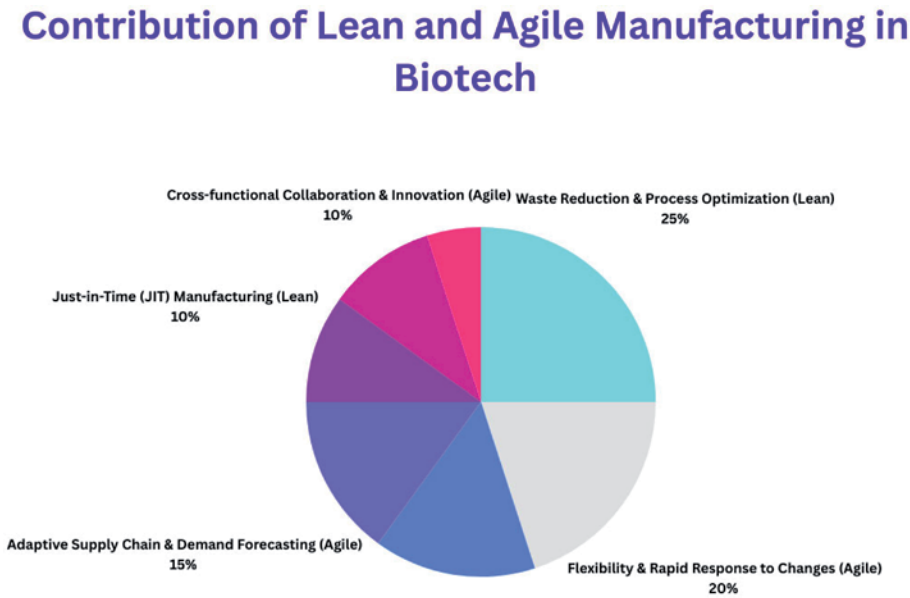

Figure 2.
Shows the contribution of lean and agile manufacturing in biotech.

unproductive methods, biotech companies use lean practices such as value stream mapping (VSM), just-in-time (JIT) production, and continuous enhancement (Kaizen) [19]. Companies find and remove activities without added value to make their processes work better. Under JIT methods, plant owners obtain their materials exactly when they require them, which lowers stockpiling expenses and prevents materials from spoiling.

Agile Manufacturing allows biotech firms to quickly adjust production for goods that customers need right now since the market demands in this field change rapidly. The changing nature of biotechnology demands, like new illnesses, changing rules, and customized medicine, requires biotech companies to transform their production systems [20] rapidly.

5. Agile biotech companies implement

- Manufacturing centers that adjust production lines easily to produce different product orders
- Biotech tools that use single-use materials decrease cleaning requirements and lessen product contamination chances
- Teams of workers from different departments work together to make decisions rapidly
- Biotech companies quickly changed their production methods to make vaccines during the pandemic, telling us how well agile manufacturing works.

Biotech firms can gain superior performance results through the use of combined lean and agile practices. Lean helps companies eliminate unnecessary costs and waste while making sure they can switch directions easily [21]. Organizations use mixed lean and agile systems to deal with changing regulations, supply chain problems, and market trends, making their production efforts successful over time. Biotech companies will need to combine operational streamlining with flexibility to stay ahead in future saturation as new technology develops [22].

6. Technology and innovation in biotech supply chains

Today's biotech industry develops new innovative technology that helps companies run their supply chain better while also making it more dependable and visible. Biotech supply chain management performances improved through automation, artificial intelligence, blockchain, and digital twins, which cut costs, increased efficiency, and sped up market reaction [23].

- Technology systems based on automation and AI help processes run better and smarter by fixing errors while optimizing business decisions. Key applications include:

- The use of robot technology (RPA) lets businesses automate their daily tasks, including repeating job output management and creating mandatory files.

- AI systems predict market trends and stock changes while spotting problems in operations as they happen.

- Machine learning helps biotech manufacturers achieve better output results by examining production records and proposing production changes.

- AI supply chain control tower systems let organizations monitor their total supply chain operations to spot issues ahead of time and react quickly.

6.1 Edge computing in biotech manufacturing

The processing of data takes place at points nearest to its generation through edge computing instead of using centralized data centers. Real-time data control plays a vital role for industries using biotech when they need to process data at production sites, which supports optimal conditions for bioreactors, manufacturing equipment, and production lines.

6.1.1 Application in biotech

The implementation of edge computing technology in biotech manufacturing gives bioreactors the ability to monitor vital variables, including temperature, pH, and oxygen levels, instantly. Local edge devices handle the analysis of collected data at the site where it was gathered to enable on-the-spot modifications for production processes. The implementation of edge devices leads to higher batch production consistency and shorter production downtimes. The bioreactor systems of Lonza and GE Healthcare now use edge computing to let operators track preprogrammed setpoint drifts through immediate alert notifications, thus preventing batch failure.

6.2 5G in biotech manufacturing

The ultra-fast speeds, along with minimal response delays, make 5G technology superior to all previous cellular networks. The speed of 5G provides essential support to biotech operations, which demand large amounts of data processing.

6.2.1 Application in biotech

The introduction of 5G technology makes it possible to perform continuous real-time device monitoring and control of manufacturing systems. Through its capabilities, machines communicate more effectively with remote operators to track equipment conditions and guide production systems remotely. 5G technology enhances the monitoring and quick movement of materials between facilities through better inventory and logistics management. The network infrastructure of biotech facilities undergoes improvement through Pfizer's exploration of 5G technology for production stage connections and real-time factory monitoring systems data movement. 5G allows low-latency control over biotech equipment and sensors at every facility level.

6.3 Digital twins in biotech manufacturing

The physical system or process receives online replication through digital twins. Companies implement digital twins in biotech for biomanufacturing process simulation, which enables them to observe and predict operational outcomes, necessary maintenance tasks, and operational improvements that do not impact their real systems. The supply chain modeling technique known as digital twins makes duplicate copies of biotech business processes while allowing these companies to test various scenarios so they can detect and solve problems. These digital models enable businesses to achieve their generic objective by developing equipment failure prediction techniques that decrease downtime. Optimize logistics and distribution strategies [24]. The company should better comply through early risk assessment to prevent upcoming threats. The quality functions of factories remain excellent because they implement industrial IoT processes to meet production requirements. The promotion of such technological innovations helps biotech companies establish the essential supply chain structure needed for effective and sustainable progress in the sector's developing ecosystem [25].

6.3.1 Application in biotech

Digital twins enable analysts and operators to predict system failure modes by evaluating bioreactor responses in diverse operating parameters; therefore, they can modify system operations as needed. Digital twin technology operating at Novartis production centers allows the facility to create precise virtual models representing the complete production path of cell and gene therapies. Novartis uses a digital replica of its bioreactors that combines IoT sensor information with the system to forecast system failure areas and find ideal operational settings that lead to better yields and quality results.

6.4 Blockchain in biotech supply chains

The transaction data managed by blockchain systems exists as immutable and transparent decentralized records that benefit all participants. The biotechnology industry adopts blockchain as an essential tool to provide both security and traceability throughout its supply chain, especially for refrigeration-sensitive items such as vaccines and biologics.

6.4.1 Application in biotech

The use of blockchain technology establishes an unalterable transaction record that monitors biotech products across their entire supply chain from their raw resources until the final product reaches the customers. Blockchain delivers exceptional value for temperature-controlled biologic monitoring by helping companies maintain strict compliance with cold chain requirements in both storage and transportation. The major biotech manufacturers Pfizer applied blockchain technology to monitor vaccine storage conditions throughout the COVID-19 pandemic. The proper vaccine temperature maintenance throughout the supply chain was guaranteed through these systems because correct temperatures play a crucial role in preserving vaccine effectiveness.

6.5 Real-time visibility

Having a clear view of the current positions of raw and packing materials, semi-finished and finished products [26].

6.6 Control over original documents

Effective storage of such records as approvals, batches, and quality certificates [27].

6.7 Better collaboration

A record that cannot be changed will ensure better cooperation between suppliers, manufacturers, and regulatory bodies. Top drug-makers have also embraced a blockchain in monitoring the delivery of vaccines in an effort to contain the products' spoiling due to non-adherence to cold storage conditions [28].

6.8 Risk management and resilience building

Lack of risk management and resilience is costly to companies involved in the manufacturing of biotech products, especially in a province that requires continued production and delivery of high-quality results to save lives. Since the biotech products supply chain entails component/source sourcing from different regions, involves highly sensitive products that require temperature control during the shipping process and are affected by regulatory protocols, firms/agencies have to go for more active risk management and improve on the supply processes resilience to shocks [29]. The following are some of the reasons that make Biotech supply chains vulnerable to disruption: Supply chain disruptions can be attributed to geopolitical events, disease outbreaks, raw material shortages, and transportation issues. To overcome all these risks, companies are developing the following measures: Supplier diversification also aims to diversify available supply sources by developing other supply chain alternatives from other suppliers [30].

6.9 Nearshoring and restoring

Pulling production nearer the key markets of demand in order to reduce risks that are occasioned by globalization and to have better control over the supply chain system [31].

6.10 Inventory management

It is the process of stocking up some inventory levels of raw materials ahead of time so that supply shocks do not interrupt production processes [32]. For instance, the recent public health crisis in the form of COVID-19 made biotech firms focus on weaknesses in the supply chain, supplier diversification, and inventory management as concerns supplier dependencies and increased inventory reservist intensity, particularly for reagents and active pharmaceutical ingredients (APIs) [33]. Disaster and continuity management are crucial in the manufacturing industry mainly because of business continuity planning. Some of the possible components of a sound BCP are as follows:

6.11 Housing plan

Lara should consider dealing with such issues as regulatory shutdowns and potential cyber-attacks or any other calamities through scenario planning. Facilities duplication: the use of many factories as a way of avoiding the effects of loss of productivity in case of a disaster in a specific region [34].

6.12 Digital supply chain monitoring

Applying AI and IoT-based identification of weak signals to react proactively in case of disturbances. It has also been observed that most biotech organizations are incorporating automation and robotics in their manufacturing to cut their reliance on human capital, and this insulates them from such incidences [35].

6.13 Cyber security and data protection

With the growth of more technologically advanced platforms in the industry, different biotech companies are at risk of cyber risks associated with cloud systems and artificial intelligence applications. A cyber-attack might affect a patient, IP, or manufacturing equipment that contains and processes data, resulting in regulatory issues and financial problems [36]. Thus, there is a need to come up with the following factors that would allow firms to minimize cybersecurity risks:

- Strong measures that have to be incorporated include Advanced security measures, frequent security checks, and scans.

- The above viewpoints suggest the use of blockchain technology for enhanced secure data sharing.

- Some steps that may be taken include the following: Increase employees' awareness of good cyber hygiene and how to avoid phishing attacks.

Through the implementation of these risk management strategies, biotech companies are able to establish a defensive and sustainable supply chain that will be capable of delivering important medicines and therapies always [37].

6.14 Sustainability and green manufacturing in biotech

The following challenges relate to sustainability as a crucial factor that influences the efficiency and legal compliance of biotech businesses nowadays. As the governing systems demand environmental compliance measures from manufacturing industries, other pressure from clients, and call for climate-friendly ways of production, biotechnology industries are embracing environment-friendly manufacturing techniques, green supply chain management, and circular economy strategies to mitigate their consumption of resources and emission of greenhouse gases [38].

The biotech industry is perceived to have a major impact on the environmental effects of the manufacturing process. The concerns are high energy input, water consumption, and production of hazardous waste during the biotech production processes. Companies are now prioritizing:

- Modern construction and usage of proper technologies to conserve energy through the use of renewable energy, such as solar energy, efficient lighting, and central heating and ventilation systems in manufacturing plants.

- There are several other ways through which effective conservation measures were applied, for instance, in the recycling process of water and the development of closed-loop water systems.

- The implementation of green chemistry principles with the intention of substituting hazardous solvents and chemicals with others that are environmentally friendly.

For instance, the use of single-use bioprocessing systems; companies such as Applied Biosystems are adopting the use of bioreactors, which have a lower consumption of water and energy than stainless steel bioreactors, which normally require washing and sterilization [39].

6.15 Sustainable sourcing and supply chain optimization

Being environmentally sensitive is an important factor in a supply chain that biotech firms need to pay attention to as a way of sourcing raw materials. Strategies include:

- That is, sourcing products from environmentally friendly suppliers who maintain policies on the environment and social responsibility as well.

- The first and rather obvious method to minimize relative carbon emission, thus Greenland's Global warming impact, is to source locally, whereby transportation is a major consideration as it will require shipment from other countries.

- Reducing the packaging material by the use of biodegradable /recyclable substances in the storage and transportation of the products.
- The biotech sectors are also using blockchain transparency to enhance the supply chain, which can only be obtained from ethical, more sustainable sources.

6.16 Circular economy approaches in biotech

A change in the trend is observed where the biotech industry is moving towards a circular economy, which majors on redesigning systems for more efficiency in resource utilization, recycling, and reuse [40]. Key initiatives include:

- Using the product of one process in another process where a totally different output may be produced.
- Pipette tips, any plastic containers, such as tips of pipettes, tips of culture flasks, Petri dishes, and the like.
- Purchasing carbon credits for emission offset to make up for the pollution from the manufacturing process and transportation.

These sustainability practices help biotech companies restore their environmental impact and build better efficiency and legal compliance. With changing global ecological standards within the operations of manufacturing companies, the ones that adapt to GREEN strategies should be assumed to be significant market players in the future [41].

7. Future trends in biotech manufacturing and supply chain

The biotechnology industry is an emerging field consisting of many segments that are constantly evolving due to changing technology, automated processes, sustainability, and the medicine industry. Some of the things that are forthcoming in the making of the biotech manufacturing and supply chain are as follows (**Figure 3**).

7.1 Industry 4.0

Biotech manufacturing is experiencing a huge shift following the integration of smart technologies in industries. Smart factories enable the use of AI, ML, robotics, and ICT in the manufacturing system to enhance production procedures. These technologies allow the Use of microprocessors to monitor certain attached equipment to detect when they are likely to break down, thus serving as preventive measures for some equipment [42]. High-speed production lines whose goal is to minimize contact with human beings to limit problems caused by human interference.

SCM solutions forecast the many unexpected occurrences that are likely to affect the supply chain so as to minimize the flow of inventory. Biotech companies are now using digital twins, which create a duplicate of manufacturing processes for analyzing and tweaking production plans. Personalized Medications and Modifying the Model of Manufacturing As clinical and gene target applications grew larger, biotech

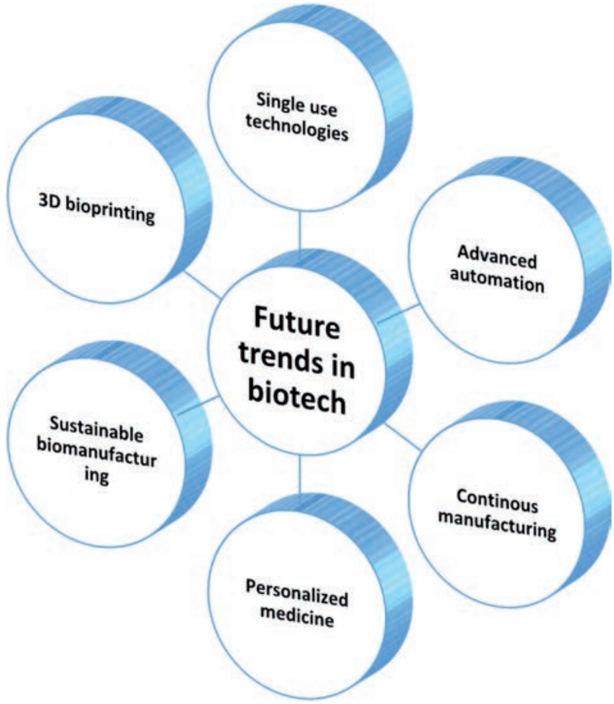

Figure 3.
Shows future trends in biotech.

companies started shifting from a mass production model to regional factories [43]. This shift enables:

- Faster delivery of customized therapies to patients.
- Reduced reliance on long, complex supply chains.
- Thus, the creation of localized regulated productions serves as an enhancement to regulation.

This bio-manufacturing concept, backed up by modular production units, means that the production facility can be pulled together to provide local coverage that is more effective and responsive to the needs of the market [44]. The biotech industry is embracing sustainability and or green biotechnology innovations:

- There would be decreased use of petrochemicals with more auxiliaries, intermediates, and products based on feedstocks.
- Carbon-neural manufacturing using REs for energy.
- Reuse and recycling, recycling, contouring, and reduction in the usage of resources.
- Thus, enzymatic production and new-generation synbio tools for chemical production are considered promising substitutes to conventional, resource-greedy techniques.

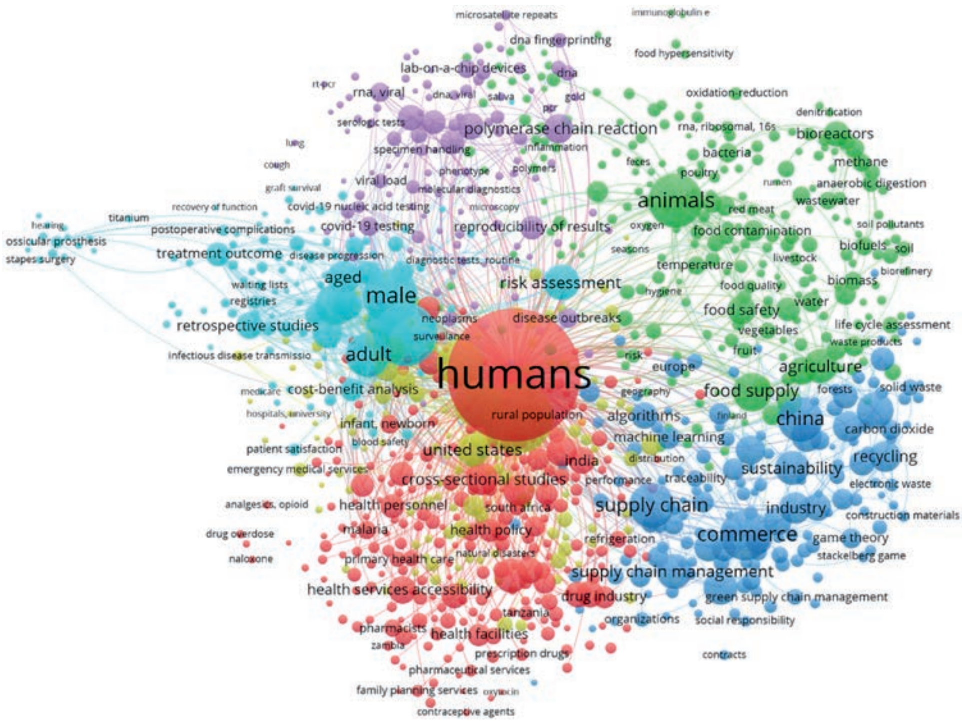

Figure 4.
Researches done on supply chain strategies for past 10 years.

Increased transparency/ security for the supply chain in recent years, blockchain technology, has been adopted within the Biotech industry to bring the following benefits to the chain supply:

- Tamper-proof records for regulatory compliance.
- This helps to achieve end-to-end -traceability of raw materials and finished products that are involved in the manufacturing process.
- Improved counterfeit prevention through secure digital verification.

That is why such trends are important and why all biotech companies need to begin innovating and streamlining in the current evolving industry. The fourth and fifth requirements are defined by the ability to apply new technologies to make processes and supply chains more efficient and sustainable in the biotech manufacturing environment [45]. Several studies have been conducted over the last 10 years to evaluate the worth of supply chain strategies, as shown in **Figure 4**, which is evidence of the importance of supply chains in different companies.

8. Conclusion

The biotechnology industry is a very sensitive industry where many factors, social, political, environmental, and even technological, must be well addressed when coordinating manufacturing and supply chain processes for overall production efficiency. Issues like regulatory concerns, supply chain issues, and high production costs need to be addressed in order to cope with certain aspects. Coordination between manufacturing and supply chain management has sheer importance in terms of the effectiveness, flexibility, and robustness of manufacturing organizations. Companies in the biotechnology industry must employ lean and agile manufacturing to cut on costs and time through minimizing the flow of waste within the firm and adapting to the changes in the market respectively. Use of automation, artificial intelligence, block chain and digital twining has further amplified biotech operations by integrating real time decisive making, transparency and efficiency. Risk management is one more important feature in the formation of a reliable biotech supply chain. It is now compulsory for companies to look into its weaker links in the supply chain, threats from cyber criminals, and interruption of business operations. Moreover, there are increasing concerns regarding eco-friendly manufacturing practices across heed, and respective industries are punctuating sustainable production, as well as the use of resources and the practice of circular economy principles. The specific forces that will shape the future of biotechnology include Smart factories, where advanced planning and control systems are already starting to appear, decentralized manufacturing, personalized medicine, and the integration of blockchain applications in biotechnology. Those who adapt towards these changes in advanced technology and sustainability shall be advantaged in the eyes of growth and also be a lasting key to success in any competitive market.

In the long run, biotech companies will have to consider cost, quality, and adaptability as an organizational structure in order to develop robust and dynamic organizations. They are in a position to amplify their efficiency and performance, achieve compliance with legislation and other requirements, and provide international clients with high-quality treatment that can save lives.

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Chapter 5

Enhancing Supply Chain Resilience through Strategic Inventory Management and Technological Integration in Extreme Climate Contexts

Mharzi Rachid, Ben Kacem Abderrahmane, Mharzi Hassan and Elouadi Abdelmajid

Abstract

This chapter investigates the dynamics of supply chains (SCs) for vital products in Morocco, encountering climate disruptions. It showcases the use of digital twin technology and discrete-event simulation (DES) to enhance logistics chain resilience (LCRES) and operational performance. By integrating advanced simulation and optimization techniques with sensitivity analyses (SAs), the study provides actionable insights for managing extreme weather disruptions (EWDs), improving preparedness, and ensuring essential supplies remain accessible during crises. It emphasizes the transformative potential of digital twin technology in bridging theoretical frameworks with practical applications for useful resilience-centered emergency management (RCEM) and fast responses to disruptions. Advocating for a service-oriented approach, it adapts lean systems to sustain operations within the climate-related humanitarian supply chain (CRHSC). Digital twin-generated key performance indicators (KPIs) support SCs' capability to navigate disruptions while optimizing inventory availability. The proposed framework assesses vulnerabilities in critical facilities and promotes stakeholder collaboration. Ultimately, the study aims to equip RCEM professionals with innovative tools to enhance decision-making (DM) processes and operational strategies while also mitigating climate change's adverse effects on vulnerable communities and critical infrastructure.

Keywords: humanitarian supply chain, logistics resilience engineering, climate disruptions, discrete-event simulation, decision support systems

1. Introduction

Morocco has recently experienced significant climate changes, leading to extreme weather events such as summer flooding and heavy winter snowfall in the south, along with wildfires and inundations in the north. These severe conditions have clearly exposed vulnerabilities in at-risk communities and revealed significant gaps in emergency preparedness. The increasing frequency of natural disasters presents unique challenges for CRHSCs, leading to operational and financial disruptions from facility shutdowns and inaccessibility. In low-income countries, where vulnerabilities are pronounced, it is essential to focus on extreme weather RCEM and usually recommend prioritizing strategic preparedness and resilience enhancement measures over post-disaster management, especially adaptive strategies to mitigate the effects of climate change.

The Moroccan Organization of Emergency Response (ORSEC) Plan is pivotal in RCEM [1]. Nevertheless, in order to enhance its performance, there is an urgent need for the development of operational and dynamic systems to improve efficiency and recovery efforts. This requirement is consistent with Morocco's national risk management strategy [1], which underscores comprehensive risk assessment and proactive measures. Understanding climate disaster risks and investing in RCEM are crucial for building resilience, reducing economic losses, safeguarding critical infrastructure, and enhancing information dissemination, specifically related to RCEM. The focus is on logistics for climate-related damaging event preparedness and response [1, 2]. We aim to assist RCEM managers in successfully managing SCs amid EWDs.

A key challenge is that emergency response planners struggle with slow responses due to insufficient guidance. However, recent developments are reshaping SC managers' roles, prompting them to adopt strategic and proactive approaches to enhance organizational resilience and ensure long-term success [3]. Implementing robust RCEM strategies sustains operational performance during outages and strengthens vulnerable communities against climate-related hazards.

The goal is to use data analytics and modeling tools to simulate the effects of EWDs on CRHSC operations. Extreme weather RCEM logisticians can improve situational awareness and operational efficiency with Geographic Information Systems (GIS), which guarantee enhanced mapping [4] capabilities. Companies must optimize their processes and regularly assess risks and procedures within their CRHSCs to anticipate and mitigate the impacts of disruption, staying pertinent in an ever-evolving setting. Resilient SCs are crucial for integrated RCEM, emphasizing the need for preventive planning and data-driven stress tests to gauge the impacts of disruption. In particular, RCEM agencies can dismantle organizational barriers, attain full transparency, improve the sharing of timely information, and better coordinate their response efforts [5] by rapidly adjusting SCs and harnessing cutting-edge technologies. Equipped with innovative collaborative solutions, these operators navigate obstacles, adapt to emerging needs, and uphold their critical role in global emergency logistics.

Fortunately, simulation models can forecast goods flow during disruptions and suggest routing and inventory adjustments, facilitating adaptable response plans based on real-time data and evolving conditions. We can assess the outcomes of these efforts post-event through monitoring metrics and sensitivity evaluations to refine our strategies. KPIs track operational performance and profitability, with simulation-derived KPIs supporting DM [6, 7] for emergency response managers. The study underscores the value of digital twin [6] simulation tools in overcoming logistics obstacles within RCEM. Optimization and simulation modeling enhance LCRES by providing data-driven insights for optimized DM [8] and proposing guidelines for inventory availability enhancement. Our experiments focus on emergency preparedness and community responses to EWD scenarios. Using the AnyLogistix

(ALX) platform, we created a DES model [4] to analyze the impact of environmental instability on multi-stage supply chains (SCs), specifically modeling route closures between suppliers and distribution facilities (DFs), facility shutdowns, as well as demand fluctuations. Via simulation, this model assesses the risks, resilience, and financial performance [9] associated with EWDs, offering structured recommendations for stabilizing and recovering SCs.

Guided by the research gap elucidated in the literature review section below, we outline two major research questions (RQ) for our study as follows:

RQ1: How do digital twins enhance the understanding of climate-related disruptions on regular logistics operations, and what are the core factors of these impacts?

RQ2: What insights can our analyses of resilience, risk, and sensitivity offer to enhance proactive and responsive RCEM for maintaining supply chain stability during climate change crises?

This chapter applies resilience engineering principles to reduce vulnerability to climate-related events, advocating for proactive disaster preparedness in Morocco. It presents a data-driven digital twin framework to deepen understanding of risks and uncertainties [10]. A conceptual model for smarter RCEM and LCRES in CRHSCs, employing decision support tools to assess information flows and plan daily activities in the context of severe weather scenarios. Additionally, this cohesive approach ensures continuity of operations [6] in emergencies through real-time collaborative routing, improving responsiveness and minimizing waste while attending to the needs of affected communities. We underscore the need for variation computation experiments, alongside SC dynamics simulations and risk analysis, to tackle CRHSC challenges, especially during EWD emergencies. Section 2 reviews simulation-driven DM support and resilience tools, estimating variation simulations and the managerial insights gained from SAs. This review highlights the research gap that this study addresses. Next, in Section 3, we outline the problem, its context, and describe the materials and methods used. After presenting our solution approach and DES experiments exploring various scenarios of EWDs, we detail the case study. Our methodology includes optimization, simulation, variation, SA, and statistical comparison. Subsequently, Section 4 is dedicated to the simulation results. We then present the findings of SAs, including variation replications and the time to recover (TTR) analysis, to extract insights for climate-related RCEM. In addition, we offer actionable suggestions to enhance LCRES for the future. Finally, we conclude the research in Section 6.

2. Literature review

SC disruption denotes unexpected events interrupting the regular flow of goods, services, information, or resources within SCs [3]. In the era of growing interconnectedness and frequent disruptions, SCs face increased vulnerability to disruptions due to their complex and interdependent nature [11–14]. Even minor disturbances in one part can cause significant ripple effects, leading to broader disruptions. Hence, SC risk management is evolving from traditional methodologies focused on a singular organizational framework to approaches that consider the entire interconnected system [15]. However, research often emphasizes immediate impacts rather than proactive RCEM approaches aimed at maintaining service levels via alternative logistics solutions.

The ability of the system to adapt to disruptions hinges on scenario planning that formulates actionable responses, identifies resource gaps, and enhances LCRES.

It prioritizes adaptability rather than merely pinpointing risks, involving proactive resilience-building strategies utilizing simulation models to bolster CRHSCs against unanticipated disruptions [16]. Moreover, SCs exhibiting higher vulnerability benefit more from proactive adaptations before a damaging event. Preemptive measures taken prior to a disruption yield better outcomes than reactive adjustments made during the event, advocating for sequential rather than simultaneous changes in network design and operational policies to maintain stability [17]. The model emphasizes early detection of risks [12, 18] and continuous monitoring of publicly available data for timely disruption indicators. Besides, regular updates to the plan promote flexibility, ensuring reliable operations amidst evolving challenges, and proposing a robust action plan to tackle disruptions [19] in CRHSCs.

A critical research gap identified in the study by Er Kara et al. [15] is the absence of comprehensive models to quantify climate change's effects on SC performance, emphasizing simulation, modeling, improved information sharing, and stakeholder collaboration. Clearly, the practical application of emerging technological tools for managing disruptions is scarce [20, 21], and simulation-based studies on large-scale SC disruptions management often overlook high-demand essential products [21]. Then, analytical tools traditionally fail to capture uncertainty and the dynamic nature of disruptions, emphasizing the value of computer simulation [22].

However, Bag et al. [23] have highlighted that big data improves SC visibility and resource utilization, enabling strategic adjustments in response to adverse weather. Liu et al. [24] have also offered guidance on leveraging big data to boost uncertainty management in global SCs. The implementation of both big data-assisted human processes and big data-driven automation in DM processes enhances LCRES, particularly in low-dynamic environments. For their part, Modgil et al. [25] have employed AI to assist SC managers in sensing risks, analyzing scenarios, reconfiguring operations, and activating response strategies during interruptions.

Digitalization increases visibility [26] and control in SCs, indeed improving inventory management via real-time monitoring of SC activities, transparency, predictive analytics, analysis of historical disruption data, and collaborative platforms. These key elements facilitate informed DM and preventive action. Simulation-based DM support systems aim to reduce harm, enhance efficiency, manage demand, and improve disaster evacuation tactics [27]. In a contrasting manner, Pavlov et al. [28] have highlighted the need for systematically identifying realistic SC disruption scenarios with varying degrees of risk aversion. Simulating real-world SCs serves to extract operational implications for LCRES [29], as hybrid simulation-optimized models refine DM processes and competently manage complex SC risks [30] in a flexible manner. Timperio et al. [31] previously combined practitioners' real-world experience with analytical and dynamic simulation methods to improve inventory. Additionally, Liu et al. [12] have tackled the computational challenges of performing thorough SAs for various failure scenarios, which normally require numerous simulations. They employed artificial neural networks and ensemble-based methods to reduce simulation requirements without compromising result quality. Meanwhile, Wu et al. [32] have quantified system resilience by incorporating infrastructure vulnerability, emergency operations impact, and the time-sensitivity of the emergency response.

Subsequently, we focus on SA, which evaluates how changes in input parameters affect model outcomes. This helps decision-makers prioritize critical factors for risk mitigation and optimization. SAs measure the model's responsiveness, quantifying the LCRES to disruptions and enhancing strategic planning and resource distribution during crisis scenarios [33]. A transshipment model by Marmolejo-Saucedo et al. [34] have found efficient routes for product transportation and assessed the impact of varying demand levels on SC performance. The SA by Yılmaz et al. [5] has demonstrated that a centralized distribution model enhances medical LCRES compared to a decentralized model, offering cost efficiency and adaptability to demand uncertainty caused by disruptions. Single hub systems streamline inventory management, improving coordination to reduce inconveniences during demand spikes. Specifically, Aldrighetti et al. [35] have analyzed a centralized healthcare supply network using ALX, focusing on disruption impacts and mitigation strategies to maintain service levels and minimize costs, demonstrating that the optimal recovery strategy depends on the characteristics of the disruption.

Piqueiro et al. [10] have also explored demand variability in a biomass SC using simulations and SAs. Their model examined increased biomass availability and simulated unexpected demand surges. For strategic decisions on facility locations, capacities, and distribution, the following framework by Fattahi et al. [36] has designed SC networks that accommodate uncertain demand and account for recovery times from disruptions. Accordingly, Rahman et al.'s study [14] addresses the effects of increased demand for alternative products during disruption events and the use of multiple KPIs to quantify impacts.

Some studies utilized the Monte Carlo Simulation. Firstly, Braik et al. [11] have examined restoration strategies, highlighting the benefits of prioritizing critical facilities through SA of fluctuating inputs (e.g., supply levels, lead times, demand variability). Then, Palomino Romani et al. [7] have studied how stochastic parameters affect surge capacity and functionality loss in post-earthquake scenarios, particularly regarding increased patient volumes. Their simulations optimized the modeling of casualties and the evaluation of building damage, enhancing the accuracy of their DES model for patient flows and yielding better estimates of KPIs like wait times and length of stay. Previously, via resilience and satisfaction rate indices, Ni et al. [37] have quantitatively assessed LCRES, identifying failure and repair rates as key factors in their SA, which informs inventory strategies to minimize the effects of extreme weather and disruptions.

Numerous pertinent studies have performed SAs on significant parameters to configure the optimal networks and suggest useful decision aids. Ghasemi [38] has developed a simulation-optimization-based model considering simultaneous resiliency and efficiency in vital SCs during COVID-19, handling uncertain parameters. Then, Martinez-Pastor et al. [18] have combined local and global methods to pinpoint key factors influencing transport network performance in the face of damaging events, thereby enhancing LCRES for DM through scenario mapping. Previously, Hosseini et al. [39] have investigated resilient supplier selection and optimal order reallocation amid disruption risks to enhance performance. Besides uncertainty in demand, the study has analyzed the impact of varying resilience cost thresholds on DM, noting that higher demand increases supplier selection and restoration costs.

Furthermore, we found more affinities with other studies, which employed variation experiments to determine how changes in specific parameters influenced the model's outcomes [8], thereby demonstrating the sensitivity of KPIs to various SC factors [3, 40]. By varying inputs like order quantities and lead times, researchers identify optimal settings for improved performance while controlling experimental conditions. In SAs, the use of VAR is to isolate the effects of specific variables, optimizing them, while Time-To-Recover analysis (TTRA) considers the overall system behavior. Statistical feedback from prior experiments highlights critical factors [40], simplifying the analysis process and enabling informed decisions in fast-paced environments. SA supports proactive RCEM by examining specific parameters, helping policymakers determine appropriate resilience practices. In addition, employing VAR refines key SC parameters and bolsters DM processes through empirical data-driven insights. The approach aims to improve the quality of available information for DM and to validate our model by analyzing result sensitivity to changing parameters. It will enable us to find the optimal solution that minimizes functionality losses [7] while ensuring the required service quality is reached.

In many studies [1, 26, 41], variation experiments with inputs like reorder points and demand confirmed the model's sensitivity, but these individual parameter analyses did not yield insights or actionable RCEM strategies. Nonetheless, Moosavi et al. [8] have employed ALX's "Variation Experiment" feature [4] to conduct an SA, specifically adjusting inventory levels and observing the resulting changes in financial performance to determine the optimal inventory level. In a similar vein, Ivanov's variation experiments [42] validated the model by varying demand, safety stock, and production capacity, despite some financial destabilization in disrupted modes with and without recovery policies. More recently, Mühlhofer et al. [13] have modeled a disaster RCEM framework to assess how varying hazard intensities affect basic service disruptions and structural damage. Key model assumptions include variations in path thresholds, infrastructure vulnerabilities, and functionality levels, stressing the significance of careful parameter selection for reliable risk assessments and emergency response strategies. In addition, it is worth mentioning that time delays emerged as a notably prevalent form of SC disruption, based on this comprehensive literature review.

The present study distinguishes itself by introducing a simulation-validated model for optimizing the location of resilient DFs in climate-related humanitarian supply chains (CRHSC). Unlike previous research, it incorporates SAs through variation simulations to enhance inventory management. Our innovative model extends LCRES frameworks, focusing on the challenges crisis logisticians face during EWDs. It aims to optimize inventory availability while maintaining functionality [18] and profitability. Our research utilizes a digital twin-based DES to assess EWDs and backup strategies using real-time data (e.g., demand fluctuations, transportation disruptions) for informed DM and operational forecasting. This study uniquely evaluates risks and resilience in climate-related RCEM in Morocco. We utilized the ALX platform to simulate [19] the proposed DES model for capturing how extreme weather events, such as floods and wildfires, disrupt multi-stage CRHSCs. The model accounts for supplier-to-DFs route closures and the resulting demand spikes. Designed to enhance the capability of CRHSCs in navigating these issues, we considered two alternative distribution facilities (ADFs) accessible during the shutdown periods, Halt-Period1 and Halt-Period2. Our results show the model effectively preempts disruptions, enhances service accessibility, and minimizes negative impacts. The SA assesses key parameters affecting the model's performance [26] in delivering relief products. However, further research with variation simulations is necessary to optimize proactive risk reduction initiatives and relief efforts before and during damaging events.

3. Materials and methods

This research addresses the growing issue of SC vulnerability, a problem recently discussed in the Harvard Business Review (September 2023) [43] with specific reference to inventory challenges. To improve LCRES in extreme climate contexts, the study utilizes DES. Optimizing inventory reduces excess stock and shortages during demand fluctuations caused by disruptions [32]. In Morocco, recent disasters highlight the need for digital twins to map supply networks and ensure visibility for effective RCEM [1]. Indeed, we explore the use of digital twin technology to model EWDs via DES in ALX. During emergencies, ALX captures randomness in the modeling chain behavior, enabling risk assessment and identifying cause-effect dependencies. This valuable tool understands SC vulnerabilities and tests risk mitigation strategies in a controlled environment. While prioritizing sustainability, this study promotes a service-oriented approach that adapts lean systems to accommodate evolving circumstances, as the traditional event-centered risk management approach is economically unfeasible [31]. It underscores the trade-off between reducing costs and enhancing LCRES, advocating for preventive planning through data-driven stress tests. As the CRHSC is intricate and vital due to its impact on human lives, it is crucial to transition from an efficiency-driven perspective to an RCEM, particularly in addressing EWDs' challenges. Furthermore, given the significant effects of transportation disruptions, it is essential to prioritize logistics and transportation resilience when planning for climate-related emergency situations.

The plan is to develop cost-effective, user-friendly, and high-quality solutions with RCEM stakeholders, enhancing operational proactive strategies to configure resilient SCs [44] in the face of EWDs. Under different scenarios, encompassing disrupted and non-disrupted conditions, the framework provides insights into mitigation and stabilization strategies. Therefore, to anticipate the worst-case scenarios arising from outages, we utilize quantitative methods and conceptual frameworks to simulate the CRHSC. By incorporating greenfield analysis, network optimization [4], SC operations simulations (SIM), variation experiments (VAR), Time-To-Recover analysis (TTRA), and risk scenario evaluation, this robust hybrid model allows obtaining viable solutions.

We created a scenario planning tool to capture how the CRHSCs respond to unpredictable EWDs. The parameters employed include the selection of emergency supplies needed by the affected communities. Our analysis focuses on five essential products and 28 at-risk-of-EWDs Moroccan departments. Demand consists of established daily requests for food, medical, and hygiene supplies, as well as historical weekly requirements for blankets and mattresses [1]. Moreover, the scheduling of these periodic demands is executed randomly to mirror real-world complexities and enhance SC dynamics.

We account for one customer for each location, with demand determined by population density, estimating an average of four individuals per household. By minimizing the total traveled distance to fulfill all demands, the greenfield analysis identified seven attractive locations for regional DFs, including five main SC sites labeled DF1, DF2, DF3, DF4, and DF5, along with two alternative sites, namely ADF1 and ADF2. In our network optimization experiment, based on efficient network utilization, we derive the optimized profitability structure of our CRHSC. As illustrated in **Figure 1**, the DFs are strategically positioned in various locations to avoid the risk of concentration.

Thus, our network comprises 28 customers, 12 in the south and 16 in the north, seven operational warehouses, and one supplier referred to as MainSupplier. Vehicles can transport unlimited quantities using Less-Than-Load (LTL) freight. Transportation costs depend on item weight and distance traveled. It should be noted that pricing is based on standard online comparisons and does not influence our

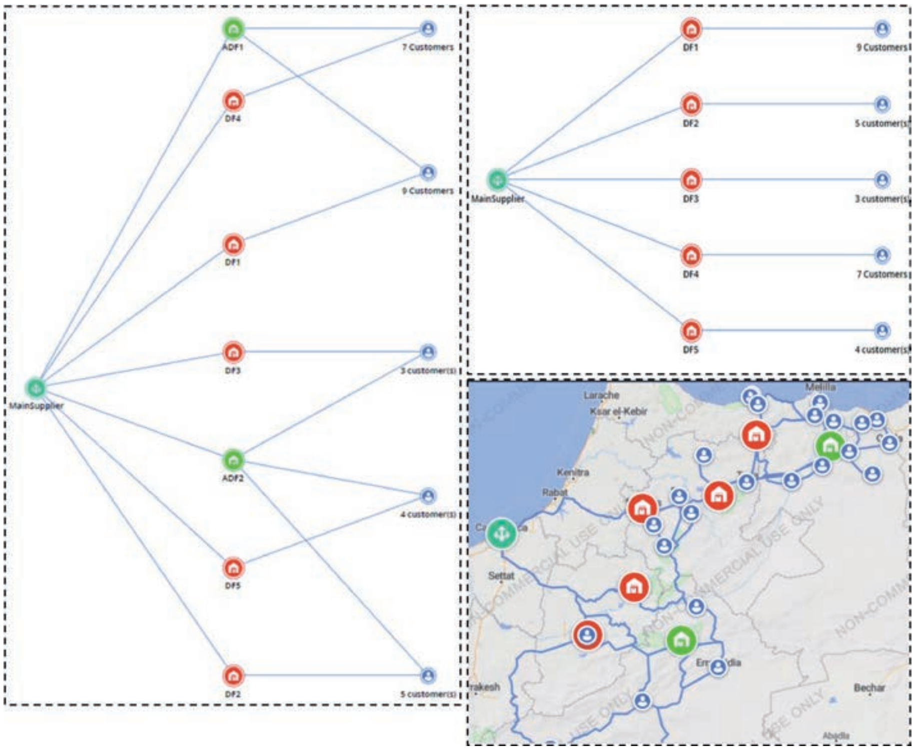

Figure 1.
The design logic of our two CRHSC networks along with the corresponding GIS map.

research outcomes. We used ALX to develop an appropriate three-echelon design logic for our distribution network with the five main sites. This involved considering two alternative distribution sites to determine the optimal set of flows and facilities. Our analysis resulted in a model with seven warehouses. In our first two simulation scenarios, we modeled the actual product delivery using the main facilities. For the remaining three tests, we used a model with seven facilities. These setups were visualized on a GIS map, providing detailed real-time statistics. Specifically, in the experiments carried out, we employ dynamic sources that have the most inventory from the suppliers to DFs, along with the fastest dynamic sources from those hubs directly to the 28 vulnerable departments. The simulation of the proposed issue was conducted over the course of an entire year, starting from January 1, 2025, and ending on December 31, 2025, by varying scenarios.

In order to reduce the number of possible "what-if" configurations [9, 40], five distinct scenarios were created in this simulation to illustrate the effects of EWDs on CRHSC networks as detailed below:

S-I: Scenario of the CRHSC during normal operations.

S-II: Scenario involving the CRHSC network facing EWDs, lacking a backup system.

S-III: Scenario S-II, including a backup system to achieve the required service level.

S-IV: Scenario S-II, incorporating VAR to isolate the effects of inventory parameters on the backlog statistics.

S-V: Scenario S-II, integrating VAR to quantify the impact of inventory parameters on the statistics of late orders.

These developed scenarios are characterized by various events and other features within the simulation model, as shown in **Table 1**.

It is important to note that the duration of treatment in our experiments is segmented into five periods: Timeperiod1 (Jan 01–July 09), Halt_Period1, Timeperiod2 (Aug 03–Aug 12), Halt_Period2, and Timeperiod3 (Sep 06–Dec 31) (refer to **Table 1**). Wildfires' EWDs impact northern regions, while floods disrupt southern localities (**Table 1**). During shutdowns, main DFs are inactive. Alternative site ADF1 operates only during Halt_Period1, and ADF2 is active only during Halt_Period2. Stress testing is indeed employed for a thorough analysis and solution refinement [44].

To evaluate the feasibility of solutions and ensure they reach the required service quality, we develop computational simulations (e.g., SIM, VAR, TTRA). In our experiments, we assume that warehouses operate without any capacity limitations. We establish various operational parameters, including the acceptance of backorders for demand and an expected lead time (ELT) of 1 day for all orders. We utilize continuous, rather than periodic, inventory reviews to provide real-time tracking [8] and enable prompt, informed, and actionable decisions. To validate the simulation, we utilized several approaches: comparing it against a standard supply flow scenario and performing SAs to evaluate its responsiveness to different operational factors.

Therefore, the models are implemented to assess their impact on processes. We developed and validated a simulation model that considers demand, lead time, an (s, S) inventory control policy, production management, and logistics optimization [1, 26]. The reorder point (s) is established at 50% of the target level (S), and shipments are handled using a FIFO priority. By integrating various elements into the digital SC twin, efficient transportation routes are determined, customized to fit the specific features and operational standards of the CRHSC. Additionally, conducting several tests with various setups resulted in no stockouts. By examining operational and financial KPIs, we have pinpointed the more resilient model with five DFs, illustrated in **Figure 1**, that manages the flow of our supply operations. This S-I configuration is adopted as our disruption-free scenario for further assessment. The CRHSC is designed to be adaptable and resilient, which is crucial for providing care to vulnerable communities, especially during EWDs. In **Figure 1**, the second CRHSC structure for scenario III is also illustrated, which shows seven DFs. Simulation investigates how disruptions propagate in dynamic environments and assesses mitigation strategies [40], thereby deepening the understanding of SCs. This preemptive method enhances operational efficiency, maintains consistency, reduces irregularities, optimizes performance, and develops a DM support model. The study examined four EWDs belonging to two categories (see **Table 1**). This involved setting eight interruptions and restorations for supply and capacity, as well as abrupt increases in demand. Every one of the eight events triggers modifications within the system, which in turn affect the scenario data dynamically during runtime [26]. The planned interruptions were designed to reflect EWDs throughout the 28 Moroccan provinces. In the southern region, 12 administrative divisions face flooding EWDs during August and September, whereas 16 departments in the northern region suffer from intense wildfires in July and August.

Therefore, in S-I, we replicate EWDs-free usual CRHSCs operations. In S-II, we implement the EWDs. Subsequently, in S-III, LCRES assessments were validated through a corrective policy involving the establishment of ADFs (see **Table 1**) to mitigate the evidenced logistical weaknesses. Ultimately, we assign a probability of 1 for all events at specified times of disruptions and recoveries. Therefore, we assessed the simulation results and the success of redundancy strategies in stabilizing SC during crises.

Configuration feature	Period of occurrence	Scenarios				
		S-I	S-II	S-III	S-IV	S-V
Path from MainSupplier to northern DFs temporarily closed	Halt_period1 from 10/07/2025 to 02/08/2025		✓	✓	✓	✓
Path from MainSupplier to southern DFs temporarily closed	Halt_period2 from 13/08/2025 to 05/09/2025		✓	✓	✓	✓
Demand coefficient from northern localities is 1	From 01/01/2025 to 14/07/2025	✓	✓	✓	✓	✓
Demand coefficient from northern localities is 1.75	From 15/07/2025 to 22/10/2025		✓	✓	✓	✓
Demand coefficient from northern localities is 1	From 23/10/2025 to 31/12/2025	✓	✓	✓	✓	✓
Demand coefficient from southern localities is 1	From 01/01/2025 to 14/08/2025	✓	✓	✓	✓	✓
Demand coefficient from southern localities is 2.25	From 15/08/2025 to 02/11/2025		✓	✓	✓	✓
Demand coefficient from southern localities is 1	From 03/11/2025 to 31/12/2025	✓	✓	✓	✓	✓
Accessibility from MainSupplier to ADF1 serving northern departments	During Halt_period1			✓		
Accessibility from MainSupplier to ADF2 serving southern departments	During Halt_period2			✓		
VAR tests on backlog statistics					✓	
VAR tests on delayed orders statistics						✓

Table 1.
Set of the various scenarios S-I, S-II, S-III, S-IV, and S-V related configuration features.

Our analysis considered KPIs such as financial performance, on-time service levels, average daily product availability, fulfillment time, quantity of backlogged items, and fulfillment rates for delayed orders.

On the other hand, the study underscores the importance of identifying vulnerable products with lengthy recovery times and applying targeted LCRES measures. To that end, we computed the total TTR, defined as the duration needed to restore a particular node in the logistics network to its requested operability after a failure [45]. The required TTR is influenced by the established service level thresholds for breakdown and recovery [26]. As a target service level, we designated a product-based service level within the specified ELT, setting failure and recovery service levels at 0.96 and 0.99, respectively. Replication is crucial for ensuring consistency in results and detecting variability or irregularities in the data. Furthermore, our SAs involve variations of a single scenario by varying one or more parameters [4, 40], focusing on one of the more vulnerable CRHSC configurations to yield demonstrative results and anticipate interesting managerial insights. These VAR experiments showed that adjusting the replacement thresholds in a Min-max Policy (s, S) could significantly alleviate backlogs (see S-IV), thereby enhancing SC stability, although it did not reduce delays (see S-V).

4. Simulation results and sensitivity analyses

The higher impact on the CRHSC distribution system operations was observed for two disruptive events, namely the partial closure of transportation routes between suppliers and DFs and the resulting spikes in demand in severely impacted regions. These disruptions led to operational issues like delays and backlogs, worsening performance challenges. We thoroughly examined how it affects the logistics of CRHSC flows in EWD-affected areas of Morocco. KPIs revealed significant operational issues during climate-related damaging events. While profit was minimally affected, there was a marked rise in incomplete and late orders, despite a manageable backlog. Service levels declined, and demand coverage was insufficient due to EWDs (refer to S-II **Table 2** and **Figures 2** and **3**).

We evaluated in S-III the impact of corrective strategies on financial and customer performance in the CRHSC, simulating proactive mitigation of disrupted scenarios. The implementation of a sustainability policy proved successful, as illustrated in the S-III outcomes (see **Table 2**). The findings offer guidance for addressing critical SC issues in RCEM, highlighting the unique challenges of EWDs and providing insights to improve resilience and operational efficiency during crises. The study emphasizes the importance of demand fulfillment as a key measure of resilience, showing that RCEM agencies employing proactive recovery strategies can better satisfy customer needs during disruptions. Overall, the research confirms the value of redundancy strategies in alleviating the negative impacts of SC outages [46], stressing the need for recovery strategies and strong resilience measures for RCEM policymakers and practitioners, along with actionable recommendations to mitigate logistics disruption risks.

The simulations depicted in **Table 2** above demonstrate the movement of materials within the CRHSC. Important KPIs have been identified, as they are anticipated to play a vital role in assessing and enhancing SC performance. The consistently high cost-to-revenue ratio of approximately 89% indicates that different configurations do not affect financial performance in significantly contrasted ways. In the disrupted scenario S-II, the ratio of late orders increases to 3.39%, while the proportion of products delivered on time relative to the total outgoing items decreases to 96%.

Statistics name	S-I	S-II and S-V	S-III	S-IV
Average daily available inventory (in pcs)	252129.54	188121.56	228073.7064	188094.6
Backlogged products (in pcs)	Insignificant	6757	Insignificant	3179
Total number of orders placed by the customers (in pcs)	63720598.8	89930592.5	89930592.52	89930592.5
Ratio of backlogged products	0.000%	0.0075%	0.000%	0.0035%
Orders placed by customer (in orders)	33,572	33,572	33,572	33,572
Late orders	0	1138	0	1138
% ratio of late orders	0.000%	3.39%	0.000%	3.39%
Profit (in EUR)	205028747.6	305498706.5	275050858.7	307339633.8
ELT service level by products (ratio)	1	0.962184785	1	0.962583162
Time interval (in days) to reach 100% in deliveries	0.64	25.6	0.8	25.6
Mean lead time (in days)	0.14176776	0.5602106	0.147400084	0.560616847
Cost-to-revenue ratio	0.89564681	0.889839288	0.891206885	0.889178315
Revenue (in EUR)	1,964,757,903	2,773,209,264	2,528,200,974	2,773,280,632
Total cost (in EUR)	1,759,729,155	2,467,710,558	2,253,150,115	2,465,940,998
Transportation cost (in EUR)	213289553.3	321929879.2	284662962.9	321253112.8
Traveled distance (in km)	6477433.08	7066932.682	6365835.905	6988583.742
Average number of vehicles used (in vehicle)	10.16432999	12.06231048	33.02729609	12.5915791
Total TTR (in days)	0	1190	248	1190

Table 2.
KPIs of the various configurations.

Additionally, the worsening of the average lead time is extremely significant as it increases by about 300%.

In the mitigated scenario S-III, the enhancements in the KPIs appear to be quite promising. Still, the financial performance is nearly identical, with approximately 89% of revenues being used for operating expenses.

In TTRA experiments, we were interested in the total amount of time the CRHSC was running below the specified failure service level. The corrective operational policy enhances the TTR by approximately 79%, while the VAR-optimized two configurations, S-IV and S-V, do not show any improvement.

Furthermore, we performed two VAR analyses to analyze KPIs sensitivity to the changes in inventory thresholds. By adjusting the replacement levels in a Min-max Policy (s, S), we derive two interesting configurations, S-IV, focusing on the backlog KPI statistics, and S-V, on delays' statistics. According to the simulation outcomes from S-II, the VAR simulations that resulted in S-IV focused on the food inventory parameters of DF3 and DF5, whereas those that configured S-V were based on the food inventory parameters of DF1 and DF4.

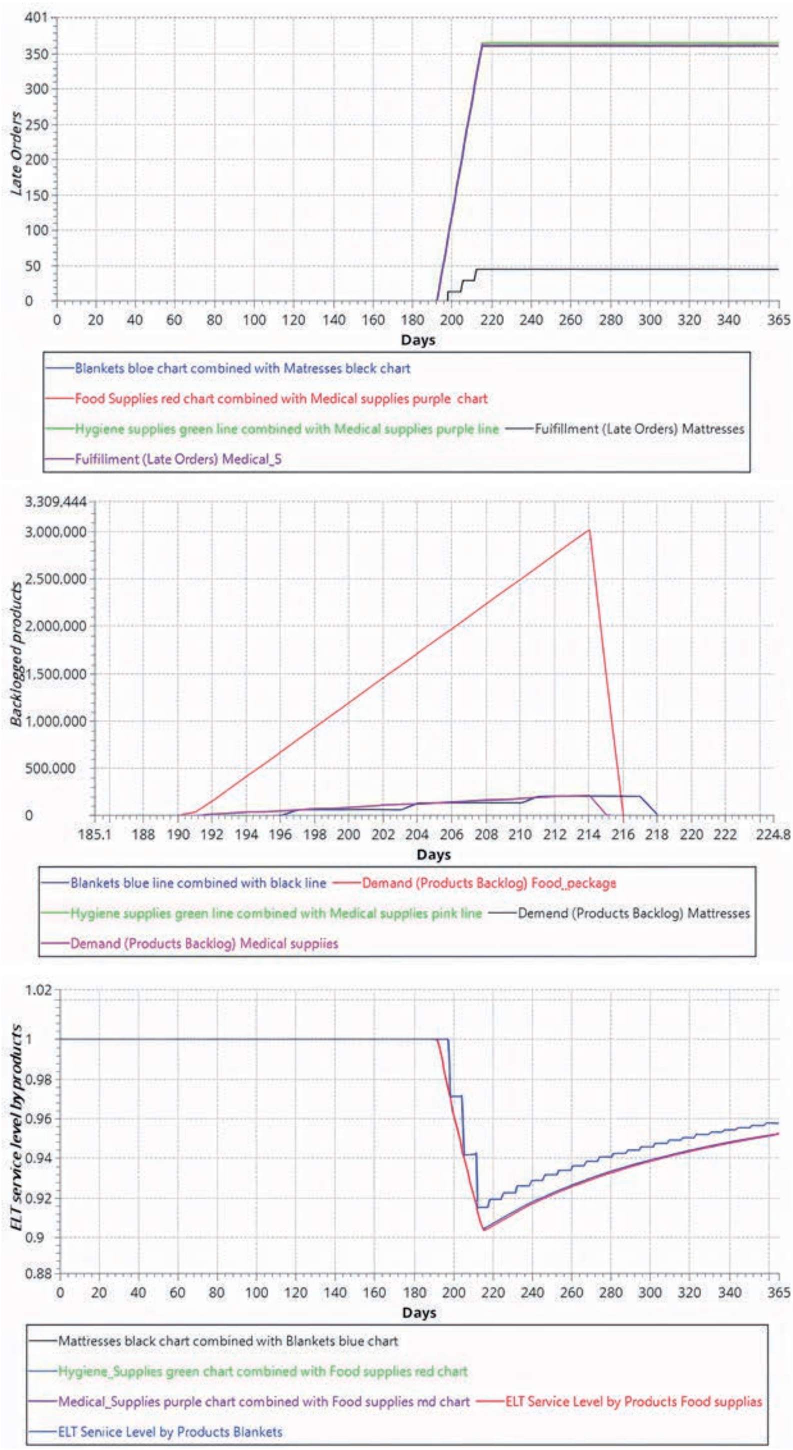

Figure 2.
The number of orders failed to arrive within an ELT of 1 day throughout the year/the number of backlogged products/and the proportion of product items delivered within the specified ELT in the disrupted scenario.

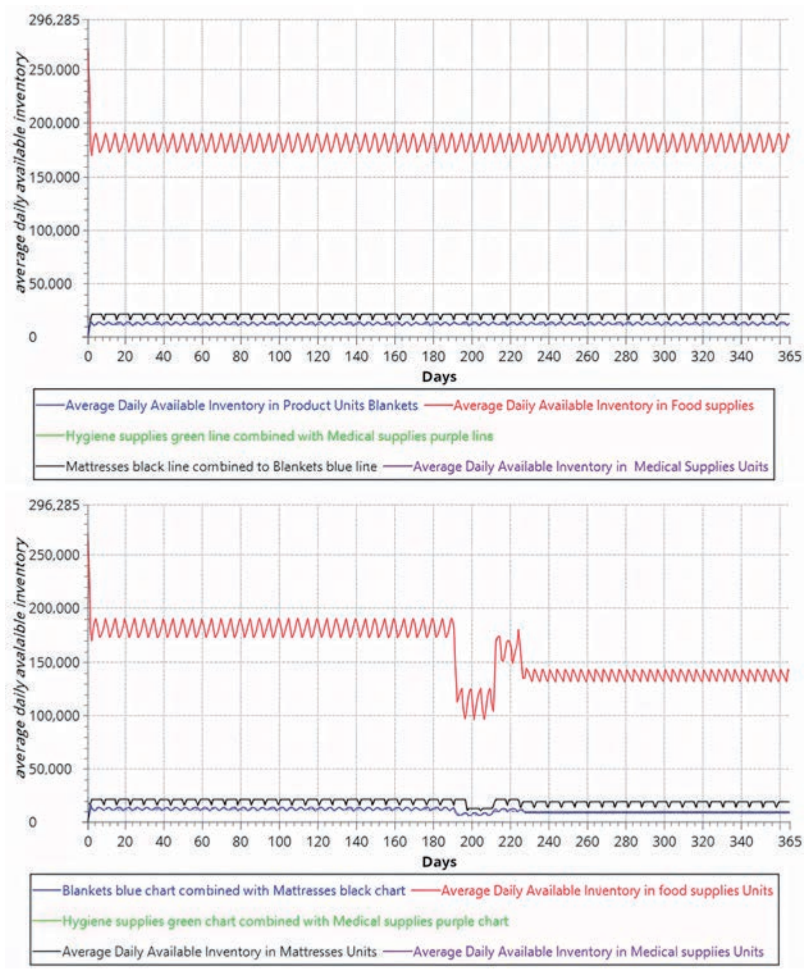

Figure 3.
The stock availability by products in the EWDs-free configuration S-I and in the disrupted scenario S-II.

In **Table 2**, the computational outcomes of delayed orders reveal that the VAR experiments did not enhance the ratio of delays, which remains unaffected at 3.39%. Comparatively, 3.39% appeared to be a notably persistent proportion, unlike the backlog ratio of 0.0075% too weak as it was improved through VAR replications to merely reach 0.0035%.

5. Discussion and implications

The paper promotes a proactive strategy for preparing for climate-related disasters in Morocco. It underscores the need for investments in buffer stocks, the use of advanced modeling technologies, and improved resource management and stakeholder coordination to enhance DM and LCRES. Managers should foresee challenges and create well-prepared recovery plans to sustain service levels and operational efficiency during emergencies, thus improving recovery times and disaster response readiness.

Our research emphasizes the importance of simulation-based DM support in assessing EWDs and the efficacy of RCEM's mitigation strategies for stabilizing logistics. Given the significant impact of transportation disruptions, prioritizing logistics and transportation resilience is essential for emergency planning. The proposed framework aids in understanding operational dynamics, identifying vulnerable products with longer recovery times, and implementing targeted resilience measures while ensuring end-to-end visibility in SC operations.

Quantitative resilience assessments enhance resource allocation and strategic planning. For sustainable post-disruption SCs, recommendations include establishing alternative warehouses to mitigate logistical vulnerabilities and ensuring robust inventory management and flexibility. Managers should simulate various scenarios to evaluate performance impacts, as streamlined coordination among RCEM's logistics actors relies on improved communication and data sharing. The model can be implemented using user-friendly ALX SC simulation software, with structured guidelines provided for easier adoption, despite potential training needs.

Emergency managers should evaluate trade-offs between strategies to optimize SC resilience and performance during disruptions. Our findings indicate that maintaining inventory availability can lead to favorable financial outcomes. Agencies must adopt a multifaceted RCEM approach, integrating tailored strategies and continuously assessing adaptation policies to enhance SC performance. Simulation results highlight the need for improved SC visibility and flexibility. Organizations with robust digital infrastructures and collaborative networks managed crises with improved coordination. Inventory optimization is essential to balance stockouts and excess inventory. Understanding TTR metrics helps identify vulnerable products and inform targeted resilience strategies. The set of variation experiments carried out confirmed the model's sensitivity. Continuous improvement in SC practices promotes a proactive approach to future disruptions.

The hazard revealed critical flaws in CRHSCs that must be addressed for better resilience. Increased demand and partial facility inaccessibility significantly impact SC operations, indicating that the traditional emergency logistics framework requires substantial improvement. The study's simulation model demonstrates that a redundancy strategy successfully mitigates risks.

Policymakers should invest in buffer stocks and alternative distribution methods to ensure high-demand supplies, enhance stakeholder coordination, and utilize technology for improved DM. This study addresses gaps in emergency supply chain management literature, laying the groundwork for future research and practical applications aimed at strengthening LCRES. Limitations include dependence on secondary data and the necessity for quantitative validation of suggested improvements in subsequent studies. Although digital twins facilitate real-time monitoring, their performance and scalability may be compromised by data inconsistencies, limited computational resources, and integration issues with legacy systems.

6. Conclusion

Research increasingly emphasizes supporting emergency managers in strengthening logistics resilience against significant risks, highlighting the importance of digital twins, inventory management, adaptability, collaboration, visibility, and analytical tools for performance modeling and assessment. This study developed a discrete-event simulation methodology to assess the impacts of disruptive events on critical supply chains, focusing on key operational and financial performance indicators to aid analysis and decision-making. Establishing backup distribution facilities enhances resilience to climate-related disruptions and boosts flexibility. Various plans were tested and compared to enable supply chains to swiftly identify risks, analyze scenarios, reconfigure operations, optimize network setups, and implement tailored response strategies during dynamic disruptions.

The findings outline a strategy for resilient supply chains during disruptions, emphasizing the need for better policies and recovery plans to maintain continuity. Key recommendations involve investing in digital technologies for enhanced visibility and creating a centralized platform for contingency planning to improve coordination and efficiency. The framework aids in quantitatively assessing supply chain resilience, facilitating the selection of recovery strategies and decision-making. The study also identifies challenges for disruption managers and suggests strategies like increasing inventory and diversifying supply sources to bolster resilience.

Future research should validate this methodology in various contexts, standardize recovery efforts through digital technologies, balance cost-efficiency with resilience, and explore the integration of blockchain and AI for logistics resilience. Because the variation analysis results have led to inconclusive management insights, more thorough research should be conducted to confirm our deductions and to deepen the understanding of the model sensitivity.

The present paper emphasizes key performance indicators, but there is potential for deeper investigation into the financial implications of various resilience strategies. This could contribute to more comprehensive frameworks that align performance with profitability, especially in regions facing increasing climate-related uncertainties like Morocco. Additionally, addressing carbon costs in supply chain operations and expanding analyses to include diverse factors and locations are recommended.

The study highlights the importance of efficiently coordinating aid distribution for timely delivery to those in need, particularly in the context of climate-related hazards, underscoring the vital role of supply chain resilience in emergency preparedness and response.

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Conflict of interest

The authors have no competing interests to declare that are relevant to the content of this article.

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Since the year 2000, the rapid development of educational technology and internet technology has brought significant attention to e-learning. Many studies have focused on understanding how to enhance learners' experiences and promote deeper engagement with learning content through e-learning to achieve better learning outcomes. Subsequently, from early 2020 over the span of the next three years, due to the impact of the COVID-19 pandemic, governments across many countries and regions implemented policies such as "Classes Suspended but Learning Continues," by conducting teaching and learning online. This has led to significant attention to e-learning by the academic and educational communities. Consequently, during these years, many studies on e-learning in the context of the pandemic have been published. However, as we enter the post-pandemic era, physical learning spaces are no longer restricted, and people have gained new insights into e-learning based on their experiences during the pandemic. Additionally, in the context of the ongoing digital transformation of education, it is also necessary to further explore e-learning topics in the era of Education 4. 0. In summary, this book compiles the latest research findings on e-learning, helping readers to understand the e-learning research outcomes of scholars from different countries and regions.

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