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Future Frontiers in Operations Management

Navigating the 21st Century

*Edited by Muddassar Sarfraz
and Muhammad Mohsin*



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IntechOpen Book Series

Industrial Engineering and Management

Volume 16

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.

Here are the key components of Production Engineering and Operational Excellence: Process Optimization; Operational Excellence; Manufacturing Systems Design; Quality Management; Supply Chain Optimization; Production Planning and Scheduling; Automation and Technology Integration; Health, Safety, and Environmental Management; Cost Management; Performance Measurement and Key Performance Indicators (KPIs); Continuous Improvement and Innovation. 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 (ISMSEM). 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 Editors



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Dr. Muhammad Mohsin is an Associate Professor at the Faculty of Business, Hunan University of Humanities, Science and Technology (HUHST). He holds a Doctorate in Management Sciences with a specialization in Finance. Dr. Mohsin is a dedicated academic and researcher whose impactful publications have made significant contributions to the fields of Business and Finance. His scholarly work includes numerous research articles, and he has actively participated in international conferences and seminars. His research has been widely read across the globe, with thousands of readers and hundreds of citations from fellow researchers. In recognition of his academic excellence, Dr. Mohsin received the prestigious *Outstanding Foreign Student Award* in 2018 from the China Scholarship Council (CSC). As a prominent young scholar, he has conducted numerous training sessions and seminars on Advanced Research Methods, Data Analysis Techniques, and Business Analytics & Efficiencies. Dr. Mohsin is affiliated with several research societies and serves on departmental boards of studies at leading universities in Pakistan. He has also worked extensively on various aspects of digitalization, serving as a lead and guest editor for special issues in renowned journals. Additionally, he has contributed as a reviewer for multiple high-impact journals and has been recognized with several certificates for his technical and theoretical expertise. His research and teaching interests span Green Finance, Sustainable Development, and Digital Finance, where he continues to explore emerging frontiers and drive scholarly innovation.

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Preface

From catastrophic natural disasters to escalating cyberattacks, the business landscape has become complex, requiring robust and innovative approaches to manage risk. In the 21st century, organizations are increasingly facing a myriad of risks that have significantly challenged the firms' operational resilience and strategic agility. Operations management drives the firm's efficiency and business processes, ensuring its success. As the business landscape has become more complex than ever, organizations have shifted their focus towards supply chain optimization.

Future Frontiers in Operations Management – Navigating the 21st Century delves into the multifaceted world of changes, offering an in-depth examination of contemporary challenges across various industries. This book is designed to serve the worldwide institutions striving to achieve operational resilience. It presents a nuanced understanding of new trends and patterns and builds a solid foundation of concepts that contribute to the existing literature. By bringing together the wealth of knowledge from leading experts, this book serves as a comprehensive guide for individuals seeking to enhance their operational capabilities. This book presents diverse viewpoints, principles, and theories on operations management. It provides individuals, governments, policymakers, professionals, and practitioners with an understanding of the evolution of operations management. It presents knowledge on the key concepts, opportunities, and challenges, offering practical insights and transformative strategies to worldwide stakeholders.

Key aspects covered in this book include:

- The Evolution of Operations Management.
- The Strategic Importance of Operations Management- Navigating Complexities of 21st Challenges and Opportunities.
- The Role of Individuals in Operations Management: Case Examples from Diverse Markets Solutions and Practices for Overcoming Challenges.

The current turbulent environment and diverse customer needs today demand that firms develop skills, knowledge, and competencies that ensure effective production and operations management. As it is difficult for managers to handle the evolving operational complexities, businesses are prioritizing strategies and operations to assess the internal and external threats. Businesses strive to improve productivity, efficiency, and effectiveness. In today's hypercompetitive environment, effective supply chain management emerges as the strategic pillar underlining organizational resilience. The landscape of global commerce, affected by intensifying globalization, technological innovation, and rising socio-political and environmental disruptions, compels firms to acquire adaptability, agility, and resilience. In the world of computer technology, operational efficiency is pivotal in decision-making. Operations

management requires a wide range of technologies and methodologies to resolve the problems. Artificial intelligence has emerged as a transformative force in optimizing core business processes. Artificial intelligence and other digital tools, such as predictive analytical algorithms, have inspired human capabilities, supporting the firm's data-driven decision-making, workflows, and operational efficiency. The rapid surge of AI has fueled the technological and strategic infrastructures. Information technology is essential for managing the supply chain network. The key challenge today is to implement organizational information-processing systems, supported by performance measurement systems, that enable business partners to share data with stakeholders. The new digital techniques ensure the strategic implementation of operations management.

As a result, industries worldwide are becoming more sustainable, prompting global industries to adopt digital technologies and sustainable practices. Sustainability is meeting the needs of today's societies. Organizations today are striving to achieve exceptional development without compromising the demands of future generations. Exploring digitalization, collaboration, and flexibility can serve as a guiding light for managers in developing a robust, sustainable supply chain. That can help firms navigate the 21st-century workforce shortage and labor regulations, and minimize costs and employee workload. Optimal matching or workforce scheduling helps companies manage irregular employee workloads through staff rostering and daily scheduling. This shows that optimization enhances efficiency and effectiveness in today's world.

The book chapters comprehensively address critical factors in operations management, offering a multifaceted exploration of how data and risks shape the firm's operations. The book emphasizes the importance of data-driven decision-making in identifying and mitigating risk by applying optimization techniques and tools, enhancing firms' efficiency and resilience. One chapter emphasizes the importance of supply chain resilience in withstanding the unfavorable effects of various threats. For example, it reinforces the use of blockchain systems for supply chain transparency and audits, thereby resolving businesses' deficiencies. One chapter describes how to identify key indicators and guides the organization's productivity and strategic improvement initiatives. By providing examples of GRI and the balanced scorecard under the performance prism, it encourages the design of a decision-making model for supply chain sustainability. By continuing to explore the implications of these threats and risks in managing operations, the book chapters underscore strategies that can help firms plan, identify, and analyze risks. It emphasizes maintaining stability and effective business management. It supports process excellence and lean production. The chapters outline the principles and practices that ensure the firm's efficiency and sustainability, and highlight clean methodologies that companies can adopt to streamline operations and enhance sustainability in today's evolving landscape. To become efficient and maintain operations management, it highlights the significance of workforce scheduling and human-centric approaches. It discusses the complexities of managing the labor shortage and developing workforce capabilities to meet the operational demands. For example, one book chapter offers practical insights into staff roasting and the integration of human factors into operations management to achieve goals. It also emphasizes the adoption of advanced digital technology in operations. By illustrating the example of artificial intelligence and digital technologies in operations, it explains how the practical applications of various technologies, such as artificial intelligence and predictive analytics, enhance the firm's operations,

efficiency, and decision-making. Overall, the book chapters provide a holistic view of operations management in the rapidly evolving business environment. By emphasizing the synergy among these elements, the book serves as a strategic roadmap, guiding stakeholders seeking to improve the firm's performance.

This book brings together the major components necessary for success in today's rapidly changing world. It explores best practices that effectively tackle the problem in the real world. Its chapters offer advanced, up-to-date knowledge of operations management and answer all questions by highlighting practical methodologies. This book is a must-read for anyone seeking to navigate the challenges of the 21st century. This is a helpful book that features new tactics and opportunities to foster operations management. Together, these book chapters present a nuanced understanding of operations management. All its chapters are unique and gain the attention of worldwide stakeholders. The editor would like to thank all the contributors for their valuable input, which has made this book a success for global readers.

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Section 1

Foundations of Data, Risk,
and Optimization in
Operations

Structured Contract Execution for Data Quality and Value Preservation in Supply Chains

Rob Christiaanse

Abstract

This chapter proposes a formal alternative to blockchain-based ledgers by reconstructing the logic of bilateral exchange relationships using projective geometry and categorical methods. We show that the normative identity of a financial contract can be faithfully embedded into a projective elliptic curve, yielding an algebraic structure isomorphic to double-entry bookkeeping. This geometric realization enables compositional transaction modeling through the elliptic group law and supports structured reasoning about contract compliance, reversibility, and balance. In contrast to distributed ledger technologies, which often fail to preserve bilateral symmetry and internal control logic, our framework enforces normative integrity by construction. We analyze the limitations of blockchain systems in supply chain transparency and auditing and present a category-theoretic model that resolves these deficiencies through local contract verification and structured composition. The resulting framework extends naturally to multi-agent reasoning, tiered supply chains, and digital audit systems, offering a mathematically rigorous foundation for trustworthy and scalable accountability infrastructures.

Keywords: contract theory, projective geometry, double-entry bookkeeping, elliptic curves, category theory, internal control, blockchain critique, supply chain transparency, normative logic, compositional audit systems

1. Introduction

Following Sarkis [1], information is needed to manage supply chains enabling supply chain partners to evaluate the performance of the supply chain partners involved. The key challenge that senior management of an organization faces is how to accomplish organizational information processing systems, supported by performance measurement systems, that enable supply chain partners in the provisioning of products, services and data that add value for customers, and the stakeholders with the value chain [2, 3]. It is widely acknowledged that the absence of proper metrics leads to failure in meeting the business objectives of supply chain partners [4]. Several factors underscore the need for adequate metrics in managing supply chains; for example, the lack of metrics that capture performance across the supply chain, the need to determine the contribution of an individual organization in respect to the

overall supply chain performance; and foremost the need to manage the complexity of supply chain management. In short, supply chain management (SCM) can be characterized as follows.

First, SCM applies a cross-organizational perspective that ranges from the source of supply to the final end-customer i.e., from cradle to cradle. SCM goals apply to individual supply chain partners as well as to the entire supply chain network. Secondly, SCM integrates information flows and financial flows into its perspective since these are important sources of supply chain value. Thirdly, SCM can no longer apply purely financial measures of success only, but must be viewed as a multidimensional construct [5–7].

1.1 Information complexity: Traceability, compliance, trust and the limits of human judgment

Despite the growing precision and automation in digital systems, there are three important concepts we need to be aware of in evaluating the performance of supply chain partners. There is the problem of adverse selection. Adverse selection arises when parties possess asymmetric information *ex ante*—leading to hidden quality, mispricing, or strategic misrepresentation. *Ex-post*, we encounter moral hazard problems. Moral hazard emerges *ex post*, when unobservable actions affect outcomes—especially in delegation, automation, or subcontracting. Last but not least there is the issue of non-verifiability. Non-verifiability concerns cases where outcomes, quality, or effort cannot be directly observed or proven—a key obstacle in legal enforcement and auditing continue to undermine trust and efficiency in contractual settings—now at scale and velocity that overwhelm human oversight. These issues all *increase entropy*—the uncertainty in distinguishing compliant from non-compliant behavior contractually viewed. As entropy grows, so too does the cost of contracting, controlling, and auditing. In economics, such costs are known as *transaction costs*, and they are not merely frictions—they are structural barriers to efficient exchange. We know that governance structures (markets, hierarchies, hybrids) arise precisely to mitigate these costs [7–10], but traditional governance is slow, manual, and brittle in the face of modern complexity.

Blockchain systems have been proposed as solutions to opacity in global value chains. It is essential to critically assess the promises and limitations of blockchain technologies—particularly in supply chain contexts, where *traceability*, *compliance*, and *trust* are central concerns. Recent scholarly work reveals that many of these promises are either overstated or structurally fragile.

We have identified five major concerns. The first concern we have coined as epistemic fragility of consensus in Supply Chains relates to the adequacy of consensus mechanisms. Researchers [11–13] emphasize that consensus mechanisms in blockchain *do not equate to semantic correctness*. In supply chains, where actors must reason over certifications, quality declarations, and origin claims, agreement is not enough: what matters is *whether a contract structurally complies* with legal, ethical, or regulatory norms. As we will see projective ledger logic addresses this by embedding verification into *algebraic form*—ensuring that contract points satisfy definable geometric constraints rather than merely existing on a replicated ledger. Next, we have the issue of corrigibility and legal compliance. Walch [14] and Raskin [15] highlight the normative rigidity of blockchain’s immutability. In supply chains, *contracts often require amendments*—due to delivery delays, quality disputes, or changes in regulatory status. The inability to “correct” an entry without re-writing the entire history renders blockchain unsuitable for real-time

resolution. Our symbolic model handles such corrections as *structured deviations* (ϵ), allowing for *traceable, local adjustments* without a loss of systemic integrity. Then, we have the problem of performance and scalability constraints. Treiblmeier [16] documents persistent *performance bottlenecks* in blockchain systems. This is especially problematic in high-volume supply networks (e.g., perishable goods, fast fashion, or parts manufacturing), where timeliness is key. Our approach removes the burden of consensus verification by making *compliance computable at the contract level*, allowing for rapid and local validation of transaction integrity. The fourth concern relates to governance and trust displacement. In global supply chains, trust is often distributed among intermediaries, certifiers, and auditors. Zyskind et al. [17] and De Filippi [18] argue that blockchain's decentralization merely *reallocates trust to code maintainers and node operators*, without institutional accountability. The projective ledger logic reframes trust not as an emergent property of replication, but as *structural symmetry under role inversion* (e.g., buyer–seller duality), offering a *normative and auditable representation* of value exchange. Next, we have privacy vs. transparency in compliance concerns. There is a growing tension between transparency and privacy. In supply chains, firms must often *protect supplier identities, cost structures, or sensitive compliance documents*. Fully transparent ledgers create exposure risk, especially for small actors. Our model allows for *symbolic verification without full disclosure*—only the compliance outcome (curve membership) needs to be shared, preserving both traceability and confidentiality [19–22]. Finally, we have identified environmental and ethical sustainability issues we need to address. Scholars critique the energy footprint of PoW systems. In sustainability-focused supply chains—such as organic food, timber, or ethical textiles—using an energy-intensive verification mechanism undermines the very values the chain is meant to promote. By design, the projective ledger *requires no replication, mining, or irreversible broadcast*. Verification is symbolic and *zero-carbon*, aligning with sustainability goals both in process and purpose [23–26].

We have summarized the blockchain critiques and supply chain relevance in **Table 1**. To address these concerns, we introduce a symbolic ledger framework rooted in algebraic geometry and projective logic, enabling norm-compliant contract verification.

Theme	Blockchain critique (Literature)	Supply chain relevance and symbolic ledger response
Epistemic Fragility	Consensus lacks deductive truth	Structural compliance is necessary for certifications and traceability; symbolic verification ensures algebraic correctness.
Corrigibility	Immutability prevents correction	Supply contracts require legal flexibility; deviation ϵ and correction term d allow localized repair.
Scalability	Blockchain introduces latency and resource load	High-volume chains need fast compliance checks; symbolic validation is local and instantaneous.
Governance	Trust is displaced to technical actors	Projective ledger offers role-based structural accountability via symmetric transformations.
Privacy vs. Transparency	Full transparency undermines confidentiality	Firms need compliance verification without exposing trade secrets; symbolic outcome suffices.
Energy Use	PoW is environmentally unsustainable	Symbolic verification avoids mining and replication, aligning with eco-certification values.

Table 1.
Blockchain Critiques and Supply Chain Relevance.

1.2 Main research question

Modern digital economies rely increasingly on automated exchanges, distributed systems, and algorithmic agents. Blockchain systems as solutions to opacity in global value chains are structural limited in information traceability and correctness. We observe that non-verifiability concerns, i.e., cases where outcomes, quality, or effort cannot be directly observed or proven, lie at the heart of the problems addressed when using block chain technology to solve opacity problems in supply chains. This motivates the need for a formal, algebraic approach that is both principled and computationally decidable. Our central research question is:

How can algebraic theory be applied to guarantee verifiability in digital exchange relationships, thereby addressing opacity in global value chains?

We seek to develop a formally grounded, computable framework that treats deviations as algebraic-geometric displacements, ensuring verifiability, auditability, and composability of contractual information across agents and time.

1.3 Research approach

Following Lewis, good representations of meaning are only possible when they are accompanied by a specification of how those representations are used—for example, in communication or inference. Structure, defined as an assembly of components, should always be studied in tandem with an associated process—regardless of the nature of that process [27, 28].

This research follows the paradigm of *Design Science Research* (DSR) [29] and is best characterized as *Design Theory*. Specifically, it adopts the perspective of *Design-Relevant Explanatory/Predictive Theory* (DREPT), which augments the “How” question of design with explanatory information about “Why” the proposed design can be expected to work.

This explanatory information is derived from established *kernel theories*—including those from the domains of social sciences, economics, mathematics, computer science, and logic. Our goal is to contribute to theory-building in the design of effective and efficient governance and control systems. In this respect, the research can be seen as an instance of experimental scientific inquiry within a design-theoretic framework.

1.4 Overview

In this chapter, we propose a mathematically grounded alternative to blockchain for achieving supply chain transparency and auditable integrity. Building from the foundational principles of double-entry bookkeeping, we formalize economic transactions as points on a projective elliptic curve, establishing a structural isomorphism that preserves value symmetry, reversibility, and composability. We then analyze, from a logical perspective, why distributed ledger technologies like blockchain fail to satisfy the internal consistency and dual-account enforcement guaranteed by double-entry systems. Using this insight, we introduce a projective contract model with a built-in group law, enabling tiered supply chain transactions to be composed and verified categorically. The chapter culminates in a comparative analysis, a formal proposition diagnosing blockchain limitations, and a corollary with practical implications for internal audit, risk control, and the design of digital assurance infrastructures in complex supply networks.

1.4.1 Foundation

The theoretical foundation of this work draws on a confluence of number theory, algebraic geometry, and geometric reasoning. The treatment of elliptic curves follows the arithmetic and geometric principles developed in Silverman's *The Arithmetic of Elliptic Curves* [30], which served as the original inspiration for modeling bilateral exchange relationships using algebraic curves. The pedagogical clarity of Ireland and Rosen's *A Classical Introduction to Modern Number Theory* [31]—particularly their exposition of rational points and torsion structures—shaped the way semantic compliance is encoded in rational solutions. Computational and modular aspects were further refined through the MIT course *18.783: Elliptic Curves*, developed by Andrew Sutherland [32], which emphasized projective embeddings and cryptographic applicability—directly informing the projective ledger structure introduced here. While this model remains within the domain of elliptic curves (genus one), it respects the categorical compositionality and algebraic integrity that would, in more general settings, extend naturally to abelian varieties. As such, the proposed framework aligns classical foundations with a contemporary need for interpretable, accountable, and geometrically coherent models of contractual exchange.

The categorical architecture of the framework is inspired by Lawvere's pioneering work on functorial semantics and conceptual mathematics [33], where logical structure is treated as an object of study in itself. This perspective is carried forward in Adámek, Herrlich, and Strecker's *Abstract and Concrete Categories* [34], whose algebraic rigor supports the treatment of contracts as objects and evaluations as morphisms in a fibered and composable setting. Together, these foundations align classical mathematics with a contemporary need for interpretable, accountable, and geometrically coherent models of contractual exchange.

This chapter builds on the algebraic foundations of categorical theories as presented by Adámek et al. [35], whose generalization of Lawvere's algebraic theories provides a structural backbone for modeling contractual operations, norm constraints, and evaluation semantics within a fibered projective logic.

2. Research strategy

We seek to develop a formal framework for bilateral exchange based on the principle of value-preserving symmetry. Our strategy is anchored in the belief that effective governance in digital systems must not begin with heuristics, but with algebraic invariants that model economic reciprocity precisely. The result is not only a unified and interpretable theory of value exchange but also a system in which verifiability is a structural consequence. In particular:

Theorem 1.1 (The Verifiability Theorem): Let E be a digital exchange system consisting of a set of agents A , transactions T , and informational representations I . Suppose that:

1. Transactions T are only partially observable to agents A ,
2. The mapping $\phi : T \rightarrow I$ from transactions to information is not injective nor verifiable by external observers,
3. Agents operate under asymmetric information and bounded rationality.

Then the system E exhibits intrinsic *non-verifiability*, which induces:

- Moral hazard: actions unobservable or unverifiable post-contract,
- Adverse selection: hidden characteristics unobservable pre-contract,
- Breakdown in traceability: failure to validate the truthfulness of $\phi(T)$.

Sketch of Solution: Let $\mathbb{K}$ be a field suitable for digital representation (e.g., $\mathbb{Q}$, $\mathbb{Q}_p$, or a finite field $\mathbb{F}_q$). We propose that if ϕ can be lifted to a morphism $\Phi : T \rightarrow C \subseteq \mathbb{P}^2(\mathbb{K})$, where C is a projective algebraic curve (e.g., an elliptic curve), then deviations become geometrically tractable. Furthermore, if the structure of C supports a group law and functorial audit mappings, then:

1. Non-verifiability reduces to geometric eccentricity,
2. Traceability becomes a categorical invariant,
3. The system becomes computationally decidable for verification tasks.

Hence, algebraic theory offers a provably sufficient formal structure to overcome information-theoretic problems in digital exchanges.

Corollary 1 (Computational Decidability of Verifiability): If transactional mappings $\phi : T \rightarrow I$ are algebraically embedded into a projective curve $C \subseteq \mathbb{P}^2(\mathbb{K})$ with a well-defined group law and categorical structure, then:

- Verification of compliance becomes algorithmically decidable,
- Deviations from contract norms can be systematically classified,
- Human interpretability is preserved via symbolic audit traces.

This enables systems to scale beyond human comprehension while maintaining formal correctness and traceability.

In sum, we need a formal decidable theory combining value theory, algebraic geometry, and categorical logic into a model that is both mathematically rigorous and computationally operational, important for next-generation audit systems, trustworthy AI agents, and verifiable digital governance. The underlying belief is that traceability acts as a bridge in giving an answer on the question: “How to retain sight on the effectiveness of governance in a digitized ecosystems where human and algorithmic agents co-manage complex supply chains through algebraically verifiable interactions embedded in symbolic, value-preserving protocols”.

Conjecture 1 (Scalable Human-AI Co-Governance via Algebraic Traceability): If contractual and transactional logic is formulated in algebraic structures that admit symbolic traceability and compositional morphisms, then scalable human-AI co-governance becomes feasible— where:

- Human oversight focuses on norm-setting, interpretation, and exception handling,
- AI agents perform routine verification, consistency checks, and trace reconstruction,

- Misalignment is detectable through off-curve behavior or morphism failure, enabling transparent escalation and correction.

This conjecture posits that algebraically grounded traceability is not merely a feature of good system design, but a necessary precondition for trustworthy collaboration between human and artificial agents in complex value networks.

3. Foundations: Rational symmetry of exchange

First, we need to understand what an exchange relationship between seller and buyer exactly entails. More specifically, engaging in a trade is by definition a bilateral. We introduce the symmetric rational identity.

Context 1 (Symmetric Rational Identity — Axiom 0): Supply chain partners act in the marketplace both as buyers and sellers, but not simultaneously in the same trade they engage. But once a buyer has received, for example, the goods then the buyer becomes the seller of the goods, assuming that trading is the business function the supply chain partner in the value chain fulfills. So when a supply chain partner enters the marketplace then *a priori* the seller will evaluate goods over money. Likewise, the supply chain partners who enter the marketplace to buy goods, then *a priori* the buyer will evaluate money over goods, assuming that money is an accepted species for both the sellers and the buyers in the marketplace [8, 36].

Definition 1 (Symmetric Rational Identity — Axiom 0): Let χ denote a quantity of goods or services and μ a quantity of money, both expressed as positive rational numbers in $\mathbb{Q}^+$. A bilateral contract is said to satisfy the Symmetric Rational Identity (SRI) if the exchange rates from both perspectives—seller and buyer—are mutual inverses and preserve the value identity.

$$\boxed{\frac{\chi}{\mu} \cdot \mu = \chi \quad \text{and} \quad \frac{\mu}{\chi} \cdot \chi = \mu} \Rightarrow \boxed{\frac{\chi}{\mu} \cdot \frac{\mu}{\chi} = 1}$$

The logic is straightforward. Let $a \in \mathbb{Q}$ represent the amount of money paid, and $b \in \mathbb{Q} \setminus \{0\}$ the quantity of goods received. Define the buyer's exchange ratio as:

$$R = \frac{a}{b} \quad (\text{value per unit})$$

Then the seller's perspective on the same transaction is:

$$R^{-1} = \left(\frac{a}{b}\right)^{-1} = \frac{b}{a} \quad (\text{units per value})$$

The ratio pair $\left(\frac{a}{b}, \frac{b}{a}\right)$ is related by an involutive symmetry:

$$\frac{a}{b} = \left(\frac{b}{a}\right)^{-1} \quad \text{and} \quad \frac{b}{a} = \left(\frac{a}{b}\right)^{-1}$$

Thus, the exchange relation is structurally self-inverse under role reversal.

The SRI expresses the symmetry of value: each side gives and receives under a consistent rational valuation [4, 8].

Remark 1: This axiom encodes the foundational logic of reciprocity in bilateral exchange. As we will see, it is the algebraic analogue of double-entry accounting, where the identity between what is given and what is received must be preserved from both perspectives.

If a transaction violates this axiom—for instance, by applying inconsistent pricing, time distortion, or non-reciprocal obligations—the identity fails, and the exchange is no longer normatively symmetric. In such cases, deviation is introduced, which we later model geometrically as *contractual eccentricity* on a projective elliptic surface.

Definition 2 (Contract as Symmetric Rational Identity): A bilateral exchange is said to satisfy the Symmetric Rational Identity if the give and get components of the contract, denoted a and b , respectively, satisfy:

$$\frac{a}{b} = \frac{b}{a} \Leftrightarrow ab = ba \Leftrightarrow a^2 = b^2$$

This sharpens to the symmetric normative condition:

$$\boxed{a = \pm b}$$

which expresses that the exchange is normatively balanced under perfect reciprocity—a mutual mirroring of obligation and value.

Remark 2: The identity $a = \pm b$ defines a symmetric normative pairing, and can be seen as the algebraic core of a structurally sound contract. It implies that what is given and what is received are of equal normative weight, possibly in inverse roles.

This structure is foundational in capturing contractual integrity. As we will see, it is a special case of the general identity $X^2Z = Y^3$ known as a *projective elliptic curve*, where the contract ratio Z is neutral ($Z = \pm 1$) and no curvature is introduced. Deviations from this strict symmetry give rise to normative eccentricity, and are geometrically absorbed into a deformed elliptic surface.

4. Contract identity: Fixed points as the normative stance

Context 2 (Contract Identity as a Fixed Point): As we stated supply chain partners act in the marketplace both as buyers and sellers but not simultaneously in the same trade they engage. But once a buyer has received, for example, the goods then the buyer becomes the seller of the goods, assuming that trading is the business function the supply chain partner in the value chain fulfills. We could state that the seller transforms in a buyer and the buyer transforms into a seller.

Proposition 1 (Contract Identity as a Fixed Point): Let $T : \mathbb{Q}^+ \rightarrow \mathbb{Q}^+$ be the transformation defined by:

$$T(a) := \frac{1}{a}$$

This map expresses the role inversion between buyer and seller perspectives in a bilateral exchange.

A contract satisfies the *Symmetric Normative Pairing* if and only if a is a fixed point of $T \circ T$:

$$T(T(a)) = a \Leftrightarrow T^2(a) = a$$

More strongly, a contract is *perfectly reciprocal* when:

$$a = T(a) \Leftrightarrow a = \frac{1}{a} \Leftrightarrow a^2 = 1 \Leftrightarrow a = \pm 1$$

That is, the contract ratio is invariant under role inversion. The exchange is then a *normative fixed point* of the bilateral value system.

Remark 3: The fixed point interpretation sharpens the meaning of the equation $a = \pm b$. It shows that under dual interpretation—switching from give to get and *vice versa*—the contract maintains its structure. This is the logical core of trust: a contract is sound if its normative value is fixed under inversion. In the projective model of contracts, each valid transaction is represented not by absolute values but by their proportions. These proportions live in projective space, where role reversal corresponds to taking the inverse.

Geometrically, these fixed points lie on the diagonal symmetry of the contract space. In the projective elliptic formulation, they correspond to points with zero eccentricity and no curve distortion—a pure realization of Axiom 0.

This ensures that the system is balanced regardless of which side of the exchange is observed. Just like double-entry bookkeeping ensures that every debit has a matching credit, our model ensures that every buyer's view has a structurally equivalent seller's view. In our model, we use the Weierstrass form of an elliptic curve to structure the logic of symbolic exchange:

$$X^2Z = Y^3 + dZ^3$$

The Weierstrass form is the canonical representation of elliptic curves. It is the simplest algebraic form that preserves the essential symmetries needed for our model: self-inverse behavior, closure under addition, and projective homogeneity. This makes it both analyzable and structurally expressive.

Proposition 2 (Algebraic Eccentricity and Elliptic Correction): Let a contract be defined by the rational exchange ratio $a = \frac{\chi}{\mu} \in \mathbb{Q}^+$, and let $T(a) = \frac{1}{a}$ denote the role-inversion transformation between buyer and seller.

Define the *algebraic eccentricity* of the contract as:

$$\varepsilon := T(a) - a = \frac{1}{a} - a$$

This measures the normative deviation from symmetric pairing $a = \pm 1$. In the perfect case, we have $\varepsilon = 0$ and a is a fixed point of T .

Now consider the projective elliptic curve:

$$X^2Z = Y^3 + dZ^3$$

with $X = \chi$, $Y = \mu$, and $Z = \frac{\chi}{\mu} = a$.

Then the curve passes through the point (X, Y, Z) if and only if:

$$d = \frac{X^2Z - Y^3}{Z^3} = \frac{a^2\mu^2 \cdot a - \mu^3}{a^3} = \mu^2 \left(\frac{a^3 - 1}{a} \right)$$

Conclusion: The correction term d is fully determined by the algebraic eccentricity $\varepsilon = \frac{1}{a} - a$, scaled by μ^2 . It encodes how far the contract lies from perfect reciprocity and governs the curvature of the normative elliptic surface needed to absorb the deviation (**Figure 1**).

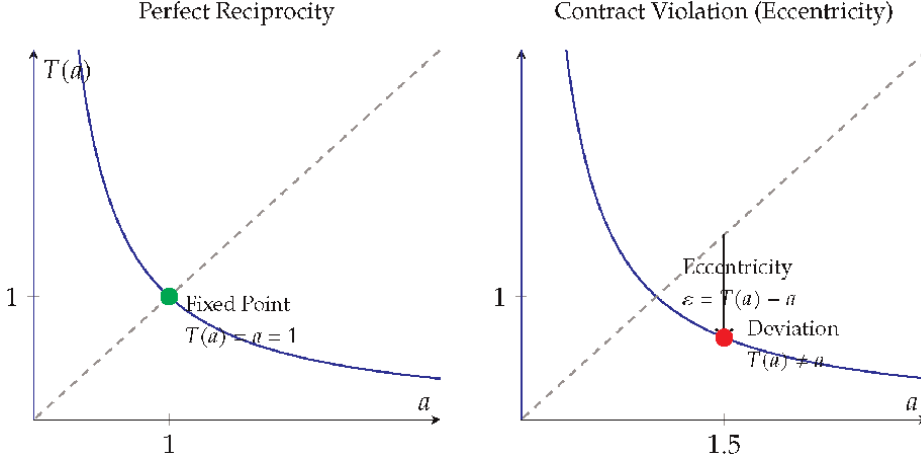


Figure 1.

Left: Perfect reciprocity as a fixed point $T(a) = a$. Right: Normative deviation $T(a) \neq a$, illustrated by vertical distance ε (contract eccentricity).

5. Symmetric contract section of the elliptic curve

Context 3 (Symmetric Contract Section: the case of normative space): The next step we have to take is to lift the affine symmetry constraint to projective space. First, we define the normative subcurve of E logically.

Definition 3 (Symmetric Contract Section of the Elliptic Curve): Let E be an elliptic curve defined over $\mathbb{Q}$ by the Weierstrass equation:

$$E : y^2 = x^3 + ax + b$$

Define the *symmetric diagonal* (the normative symmetry locus) as:

$$\Sigma := \{(x, y) \in \mathbb{Q}^2 | y = \pm x\}$$

Then we define the *symmetric normative subcurve* of E as:

$$E_\Sigma := E \cap \Sigma = \{(x, y) \in E | y = \pm x\}$$

This is the set of all points on the elliptic curve satisfying the Symmetric Rational Identity from Axiom 0 (**Figure 2**).

$$\begin{array}{ccc} E_\Sigma & \hookrightarrow & \Sigma \\ \downarrow & \lrcorner & \downarrow i_\Sigma \\ E & \xrightarrow{i_E} & \mathbb{A}^2(\mathbb{Q}) \end{array}$$

Figure 2.

Normative subcurve E_Σ as a pullback of the elliptic curve E and the symmetry constraint Σ in $\mathbb{A}^2(\mathbb{Q})$.

Remark 4: The pullback diagram above defines E_Σ categorically as the universal fiber product of E and Σ over the affine plane $\mathbb{A}^2(\mathbb{Q})$. This expresses the fact that E_Σ is the most precise refinement of E under the normative constraint imposed by Axiom 0—i.e., contract identity is preserved both algebraically and geometrically.

5.1 Projective interpretation of normative symmetry

To fully capture the structure of contract symmetry, we now lift the affine symmetry constraint to projective space. This allows us to include scaling behavior and points at infinity, and provides a canonical projective subspace of normative contracts.

Definition 4 (Projective Normative Subspace S_{norm}): Let $E \subset \mathbb{P}^2(\mathbb{Q})$ be the projective elliptic curve defined by:

$$Y^2Z = X^3 + aXZ^2 + bZ^3$$

We define the *projective symmetry line* as the union of two linear constraints:

$$\Sigma_{\mathbb{P}}^{\pm} := \{[X : Y : Z] \in \mathbb{P}^2(\mathbb{Q}) \mid X = Y \text{ or } X = -Y\}$$

Then the *projective normative subspace* is given by:

$$S_{\text{norm}} := E \cap \Sigma_{\mathbb{P}}^{\pm} = \{P \in E(\mathbb{Q}) \mid X = \pm Y\}$$

These are precisely the projective points on E that satisfy the Symmetric Rational Identity from Axiom 0 in homogeneous coordinates.

Remark 5: The projective interpretation captures all normatively symmetric contracts, including points at infinity, by expressing the condition $X = \pm Y$ in homogeneous form. This generalizes the affine symmetry condition $x = \pm y$ and allows the theory to be extended to rescaled or unnormalized contract values. The subset $S_{\text{norm}} \subset E(\mathbb{Q})$ defines a normatively pure stratum of the elliptic surface (**Figure 3**).

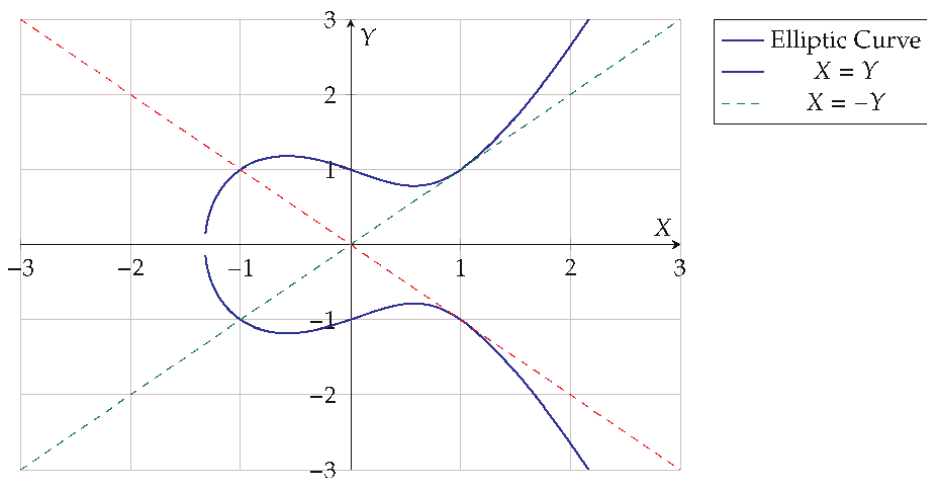


Figure 3. Intersection of the normative symmetry lines $X = \pm Y$ with the elliptic curve $Y^2 = X^3 - X + 1$ (projective form with $Z = 1$). Points of intersection define $S_{\text{norm}} \subset E(\mathbb{Q})$.

This projective refinement lays the groundwork for classifying compliant contracts in normalized form. In the next section, we explore how violations from this symmetry surface lead to measurable eccentricity and require curvature correction in the elliptic structure.

Proposition 3 (Normative Constraint on the Curve): A point (x, y) lies in E_Σ if and only if x satisfies the cubic constraint:

$$x^3 - x^2 + ax + b = 0$$

That is, by substituting $y = \pm x$ into the curve equation $y^2 = x^3 + ax + b$, we obtain:

$$x^2 = x^3 + ax + b \Leftrightarrow x^3 - x^2 + ax + b = 0$$

This defines the normative geometry of contract compliance: only those points on E which satisfy this cubic lie in the symmetry-preserving subcurve E_Σ .

Remark 6: The curve E_Σ contains precisely the set of bilateral exchanges that preserve value symmetry under role inversion (buyer $\leftrightarrow$ seller). Points on $E \setminus E_\Sigma$ correspond to contracts with norm deviations, measured algebraically via eccentricity and geometrically via curvature adjustment.

6. From algebraic symmetry to geometric realization

Context 4 (The role of Axiom 0): Axiom 0 ensures that value is preserved in rational form from both sides of the exchange, establishing a foundation of trust and fairness. To assess whether real-world contract data adheres to this principle, we need to lift the symmetric identity into a geometric domain.

This leads naturally to the construction of a *normative projective elliptic curve*, which serves as the geometric realization of the Symmetric Rational Identity. Points that satisfy the identity lie precisely on this curve, while violations manifest as deviations—quantified algebraically by an eccentricity term and geometrically by curve deformation. This formulation allows us to evaluate, compare, and audit contract outcomes in a mathematically principled way.

Theorem 1.2 (Normative Projective Elliptic Curve): Let $(X : Y : Z) \in \mathbb{P}^2(\mathbb{Q})$ represent a compliant bilateral contract transaction, where:

- $X \in \mathbb{Q}$ is the value received,
- $Y \in \mathbb{Q}$ is the value given,
- $Z = \frac{X}{Y}$ is the exchange rate or scaling factor,

then there exists a unique projective elliptic curve of the form:

$$X^2Z = Y^3 + cYZ^2 + dZ^3$$

with $c, d \in \mathbb{Q}$, such that $(X : Y : Z)$ lies on the curve.

If we set $c = 0$, then the unique value of d satisfying this identity is:

$$d = \frac{X^2Z - Y^3}{Z^3}$$

Step	Compliant transaction	Non-compliant transaction
Goods Delivered X	4300	4300
Price Paid Y	77,400	86,000
Exchange Ratio $Z = \frac{X}{Y}$	$\frac{1}{18}$	$\frac{1}{20}$
X^2Z	1,027,222.22	924,500
Y^3	4.64×10^{14}	6.36×10^{14}
Z^3	$\frac{1}{5,832}$	$\frac{1}{8,000}$
Correction Term d	$-4.64 \times 10^{14} \cdot 5,832$	$-6.36 \times 10^{14} \cdot 8,000$
Deviation Δd	-4.62×10^{15} , indicating structural contract deviation	

Table 2.
Comparison of Compliant and Non-Compliant Transactions.

This curve is called the *normative projective elliptic curve* associated with the contract identity.

Remark 7: This construction defines a normative structure within which contract compliance can be geometrically verified. Points not lying on this curve indicate distortion, penalty, or fraud.

Example 1 (Algebraic Test for Compliance): We compare two transactions involving the same delivery of $X = 4,300$ units (**Table 2**):

Stepwise Explanation.

1. *Same Quantity, Different Price*: Both transactions deliver $X = 4,300$ units. The compliant price is 77,400, while the non-compliant price is 86,000.
2. *Different Exchange Ratio*: The ratio $Z = \frac{X}{Y}$ drops from $\frac{1}{18}$ to $\frac{1}{20}$, indicating reduced efficiency for the buyer.
3. *Norm Test via Curve Equation*: Using the identity $X^2Z = Y^3 + dZ^3$, each transaction implies a correction term d . The compliant transaction satisfies the identity exactly. The non-compliant one does not.
4. *Deviation Quantifies Violation*: The difference,

$$\Delta d = d_{\text{non-compliant}} - d_{\text{compliant}} \approx -4.62 \times 10^{15},$$

reveals a structural deviation from the normative curve. This deviation serves as a formal compliance signal.

7. Categorical lifting of the contract identity

We now lift the structure of the normative contract identity into a categorical setting. This connects the algebraic contract identity with projective geometry and defines a morphism between abstract normative spaces and realized contractual outcomes.

Definition 5 (Identity Category $\mathcal{I}$): Let $\mathcal{I}$ be the category whose:

- Objects are triples $(X, Y, Z) \in \mathbb{Q}^3$ such that $X = ZY$ (i.e., compliant exchange triples).
- Morphisms are rational scalings $\lambda \in \mathbb{Q}$ acting as:

$$\phi : (X, Y, Z) \mapsto (\lambda X, \lambda Y, Z)$$

preserving the contract identity $X = ZY$.

Definition 6 (Contract Category $\mathcal{C}$): Let $\mathcal{C}$ be the category whose:

Objects are projective triples $(X, Y, Z) \in \mathbb{P}^2(\mathbb{Q})$,

- Each object satisfies a cubic constraint of the form:

$$X^2Z = Y^3 + cYZ^2 + dZ^3$$

for parameters $c, d \in \mathbb{Q}$.

- Morphisms are projective transformations preserving this relation.

Proposition 4 (Functor from Identity to Contract) There exists a covariant functor:

$$F : \mathcal{I} \rightarrow \mathcal{C}$$

such that:

- On objects:

$$F(X, Y, Z) := \mathcal{E}_{(X, Y, Z)} \quad \text{with} \quad \mathcal{E}_{(X, Y, Z)} : X^2Z = Y^3 + dZ^3$$

and

$$d = \frac{X^2Z - Y^3}{Z^3}$$

- On morphisms:

$$F(\phi) : \mathcal{E}_{(X_1, Y_1, Z)} \rightarrow \mathcal{E}_{(X_2, Y_2, Z)}$$

for ϕ scaling (X, Y) by λ , i.e.,

$$(X_2, Y_2) = (\lambda X_1, \lambda Y_1)$$

Remark 8: The functor F embeds the category of ideal identity-preserving transactions into the category of realized contractual structures. Points in $\mathcal{C}$ that lie outside the image of F represent norm violations and can be associated with contract eccentricity or penalty (**Figure 4**).

$$\begin{array}{ccc}
 (X_1, Y_1, Z) & \xrightarrow{\phi} & (X_2, Y_2, Z) \\
 \downarrow F & & \downarrow F \\
 \mathcal{E}_{(X_1, Y_1, Z)} & \xrightarrow{F(\phi)} & \mathcal{E}_{(X_2, Y_2, Z)}
 \end{array}$$

Figure 4.

Commutative diagram illustrating the functorial embedding $F: \mathcal{J} \rightarrow \mathcal{C}$ of identity-preserving contract triples into the category of projective elliptic contracts. The morphism ϕ maps the source contract (X_1, Y_1, Z) to a target contract (X_2, Y_2, Z) , preserving the exchange rate. Functor F maps these objects to corresponding elliptic curves $\mathcal{E}_{(X_1, Y_1, Z)}$ and $\mathcal{E}_{(X_2, Y_2, Z)}$, while ensuring that the morphism $F(\phi)$ satisfies curve consistency. The square commutes if $F(\phi) \circ F = F \circ \phi$, preserving contract semantics under transformation.

Proposition 5 (Contract Eccentricity Determines Curve Deformation): Let $(X, Y, Z) \in \mathbb{Q}^3$ be a contract exchange triple. Define the algebraic eccentricity ε of the contract identity as:

$$\varepsilon := X^2Z - Y^3$$

Then the projective elliptic curve:

$$X^2Z = Y^3 + dZ^3$$

passes through the point (X, Y, Z) if and only if:

$$d = \frac{\varepsilon}{Z^3} = \frac{X^2Z - Y^3}{Z^3}$$

That is, the curve must be *deformed* by an amount d proportional to the contract's eccentricity ε , normalized by the cube of the exchange ratio Z .

Remark 9 When $\varepsilon = 0$, we recover the ideal contract identity:

$$X = ZY \quad \Rightarrow \quad X^2Z = Y^3 \quad \Rightarrow \quad d = 0$$

This is the pure normative case, where the contract is geometrically embedded without distortion. When $\varepsilon \neq 0$, the elliptic curve is curved upward or downward to include the deviant point — d geometrically encodes this normative adjustment.

Example 2 (Functorial Mapping and Curve Deformation): Consider two contract transactions, both delivering $X = 4,300$ units of goods. We contrast a norm-compliant contract with a non-compliant one where the buyer overpays. We compute their algebraic eccentricities and the corresponding curve corrections via the functor $F: \mathcal{J} \rightarrow \mathcal{C}$ (**Table 3**).

Interpretation:

This mechanism allows the categorical model to encode trust, norm compliance, and financial fairness in algebraic-geometric terms.

Why Categorical Lifting? The contract identity $X = ZY$, while algebraically simple, becomes more powerful when placed in a categorical framework. This lifting allows us to move from isolated contract calculations to a structured space of transformations and relationships. It offers three major benefits:

Compliant contract (Normative)	Non-compliant contract (Deviant)
Buyer pays $Y = 77,400$	Buyer pays $Y = 86,000$
$Z = \frac{X}{Y} = \frac{4300}{77400} = \frac{1}{18}$	$Z = \frac{X}{Y} = \frac{4300}{86000} = \frac{43}{860}$
Algebraic eccentricity: $\varepsilon = X^2Z - Y^3 = 0$	$\varepsilon = X^2Z - Y^3 = 924,500 - 636,056,000,000,000$
Curve correction: $d = \frac{\varepsilon}{Z^3} = 0$	$d = \frac{\varepsilon}{Z^3} = -5.089 \times 10^{21}$
Maps to $\mathcal{E} : X^2Z = Y^3$ (ideal)	Maps to $\mathcal{E}' : X^2Z = Y^3 + dZ^3$ (deformed)

Table 3.

Comparison of compliant and non-compliant contracts based on elliptic curve invariants. The normative contract preserves the rational structure $X^2Z = Y^3$ with zero algebraic eccentricity and curve correction, mapping cleanly to the ideal curve $\mathcal{E}$. The deviant contract exhibits distortion in the payment ratio, resulting in non-zero eccentricity ε , a large correction term d , and a deformed mapping to a perturbed curve $\mathcal{E}' : X^2Z = Y^3 + dZ^3$. This illustrates diagnostic deviation in algebraic and geometric form.

- *Compositional reasoning:* Contracts are no longer just points but morphisms between exchange states—enabling comparison, correction, and generalization.
- *Semantic distinction:* Categorical lifting distinguishes ideal (normative) behavior from realized (possibly distorted) behavior through functorial embedding.
- *Interoperability:* This abstraction supports future integration with other logical systems (e.g., trust scoring, auditing logic, or risk diagnostics) through categorical composition and morphism mapping.

In this sense, category theory does not merely generalize—it preserves and structures the reasoning about contracts in a way that is traceable, composable, and formally robust.

8. Double-entry bookkeeping logic

Context 5 (Managing finance): Contractual relationships with suppliers and customers are managed and controlled by using accounting information systems measuring financial performance of an organization. Accounting information systems occur in many forms in practice. Think of ERP systems or company-wide information systems that form a combination of different functional systems and so on. All accounting information systems share one common feature and that is the accounting identity. The accounting identity is commonly known as the accounting law that states “the sum of debits equals the sum of credits” expressing the balance in our general ledger where we keep track of the financial position of an organization.

8.1 Double-entry bookkeeping as semantic trust infrastructure

The theory developed in this work draws its conceptual foundation from the logic of double-entry bookkeeping (DEB), a centuries-old system that ensures balance and accountability through dual registration: every transaction is recorded as a give and a get. This intrinsic symmetry aligns precisely with our categorical formulation of contract identities.

While blockchain technologies enforce consistency through consensus and cryptographic immutability, they do so at high computational and ecological costs. In contrast, DEB achieves trust through structural balance—each transaction must be internally consistent and externally reconcilable.

Double-entry bookkeeping	Projective elliptic logic
Ledger entry: Debit = Credit	Normative identity: $X^2Z = Y^3$
Valuation ratio implicit in amounts	Valuation encoded as $Z = \frac{X}{Y}$
Imbalance reveals error/fraud	Non-zero d reveals distortion/deviation
Reversing entries: debit $\leftrightarrow$ credit	Group inverse: $P \mapsto -P$
Audit trail through journal/ledger linkage	Algebraic trace via group law closure
Aggregate consistency over periods	Group associativity: $(P + Q) + R = P + (Q + R)$
Neutral entry (no effect)	Identity element O

Table 4.
Comparison: Double-Entry Bookkeeping vs. Projective Elliptic Logic.

Our categorical lifting of contract identities formalizes this principle: morphisms between identity-preserving objects enforce traceable mappings, and deviations (eccentricities) are explicitly captured as geometric deformations. In this sense, DEB is not merely an accounting convention—it becomes a lightweight, semantically rich alternative to blockchain’s distributed ledger.

This approach favors symbolic verification over brute-force consensus, making it more suitable for supply chains, financial auditing, and institutional governance, where correctness, accountability, and explainability matter more than irreversible replication.

8.2 Formal comparison: Double-entry bookkeeping vs. projective elliptic logic

To highlight the structural equivalence between traditional double-entry bookkeeping and the proposed elliptic curve framework, we provide a formal side-by-side comparison. This mapping illustrates how valuation, balance, and reversibility—foundational to accounting—are preserved and generalized in the algebraic model. Furthermore, this correspondence is not merely representational; it captures the semantics of financial consistency in a projective geometric setting (Table 4).

8.2.1 Connection to internal control framework (COSO 2013)

This comparison also clarifies how the proposed projective framework aligns with the objectives of internal control as articulated in COSO 2013. In particular, the double-entry logic, when lifted to a projective elliptic structure, reflects the core COSO principles of reliable financial reporting, control environment integrity, and transaction-level accountability. The group-theoretic structure ensures that all entries are normatively closed, traceable, and reversible—features essential for implementing control activities, ensuring accurate recording, and supporting auditability within a robust internal control system.

Proposition 6 (Isomorphism with Double-Entry Bookkeeping): Let $(X : Y : Z) \in \mathbb{P}^2(\mathbb{Q})$ represent a transaction under the normative contract identity, satisfying the projective elliptic equation:

$$X^2Z = Y^3 + cYZ^2 + dZ^3$$

Assume $c = 0$, and define the exchange rate as $Z = \frac{X}{Y}$. Then the equation becomes:

$$X^2Z = Y^3 + dZ^3$$

This equation is *isomorphic* to the logic of double-entry bookkeeping under the following interpretation:

- Y represents the *credit (given)* side of the transaction,
- X represents the *debit (received)* side,
- $Z = \frac{X}{Y}$ encodes the *valuation* or exchange ratio,
- The cubic correction term d encodes *non-conformity or distortion*, and vanishes under normative balance.

Proof: In double-entry bookkeeping, the fundamental identity is:

$$\text{Debit} = \text{Credit} \Leftrightarrow X = Y \Leftrightarrow Z = 1$$

Multiplying both sides by Y :

$$XY = Y^2 \Rightarrow X = \frac{Y^2}{Y} = Y$$

Now consider the projective elliptic identity with $c = 0$:

$$X^2Z = Y^3 + dZ^3$$

Substitute $Z = \frac{X}{Y}$ into both sides:

$$X^2 \cdot \frac{X}{Y} = Y^3 + d \cdot \left(\frac{X}{Y}\right)^3 \Rightarrow \frac{X^3}{Y} = Y^3 + d \cdot \frac{X^3}{Y^3}$$

Multiply both sides by Y^3 :

$$X^3Y^2 = Y^6 + dX^3 \Rightarrow X^3Y^2 - dX^3 = Y^6$$

Now factor X^3 from the left:

$$X^3(Y^2 - d) = Y^6$$

This shows that the correction term d encodes precisely the deviation of the debit valuation (in terms of X) from a conforming triple (X, Y, Z) where $X = ZY$ and $d = 0$.

Thus, the equality

$$X^2Z = Y^3$$

is satisfied if and only if the contract is perfectly reciprocal—exactly as in double-entry logic where:

$$\text{Debit Value} = \text{Credit Value}$$

Therefore, the elliptic identity under normative symmetry is algebraically and semantically isomorphic to the logic of double-entry bookkeeping.

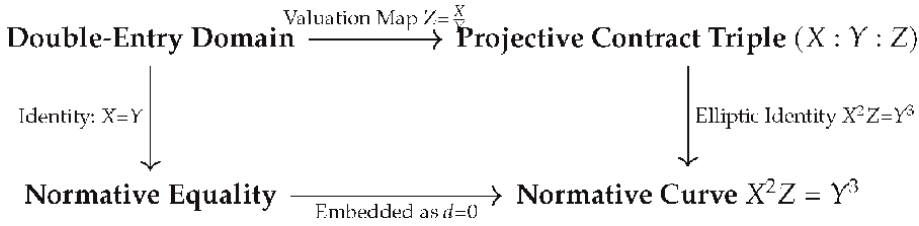


Figure 5.
 Commutative diagram linking double-entry logic to the projective elliptic contract identity.

Remark 10: This isomorphism reveals the deep connection between the algebraic geometry of contracts and the foundational logic of accounting. Just as double-entry bookkeeping ensures structural integrity in financial systems, the projective elliptic model ensures that every transaction is embedded in a consistent and auditable geometric surface (Figure 5).

8.3 Elliptic group law: The sum $P + Q = R$

Definition 7 (Normative Projective Elliptic Curve): Let E be the projective curve defined over $\mathbb{Q}$ by [30, 37]:

$$E : X^2Z = Y^3 + cYZ^2 + dZ^3$$

with $c, d \in \mathbb{Q}$, and $(X : Y : Z) \in \mathbb{P}^2(\mathbb{Q})$.

We define the set of *normative contract points* as:

$$E(\mathbb{Q}) := \{(X : Y : Z) \in \mathbb{P}^2(\mathbb{Q}) \mid (X, Y, Z) \text{ satisfies the curve equation}\}$$

Proposition 7 (Abelian Group Structure on $E(\mathbb{Q})$): The set $E(\mathbb{Q})$ of normative contract points on the projective elliptic curve admits the structure of an Abelian group under a binary operation $+$, defined geometrically by the classical chord-and-tangent method:

- The group identity element is the point at infinity $O = (0 : 1 : 0)$.
- For any $P \in E(\mathbb{Q})$, there exists an inverse $-P \in E(\mathbb{Q})$.
- The group operation $P + Q = R$ is defined by drawing the line through P and Q (or the tangent if $P = Q$), finding the third point of intersection with E , and reflecting across the symmetry line.

8.3.1 Sketch of proof

Sketch of Proof: It is a classical result that smooth cubic curves in projective space admit a natural Abelian group law. The curve

$$X^2Z = Y^3 + cYZ^2 + dZ^3$$

is a variant of the Weierstrass form and can be transformed into it under a rational change of coordinates (preserving isomorphism over $\mathbb{Q}$).

The chord-and-tangent construction defines a binary operation $+$: $E(\mathbb{Q}) \times E(\mathbb{Q}) \rightarrow E(\mathbb{Q})$ that is:

- *Associative*, via the cubic nature of E ,
- *Commutative*, due to the symmetric role of P and Q ,
- *Admits identity*, with $O = (0 : 1 : 0)$ as the neutral element,
- *Admits inverses*, where the inverse $-P$ of a point $P = (X : Y : Z)$ is its reflection under the elliptic symmetry (e.g., across $X = 0$ if transformed to Weierstrass coordinates).

In the context of contract logic, this means:

- *Combining contracts* corresponds to the group operation,
- *Reversing roles* (buyer/seller) corresponds to inversion,
- *The zero contract* (no value exchanged) corresponds to the identity point O ,
- *Norm-preserving combinations* lie on the curve and respect the group structure.

Thus, $E(\mathbb{Q})$ under $+$ forms an Abelian group isomorphic to classical elliptic curve groups, now endowed with normative interpretation.

Remark 11 (Connection to General Ledger Logic): The group structure defined on the projective elliptic curve $E(\mathbb{Q})$ models the logic of the general ledger in double-entry bookkeeping.

In this interpretation:

- A contract point $(X : Y : Z)$ represents a transaction: goods received (X), money paid (Y), and exchange rate (Z).
- The curve equation $X^2Z = Y^3 + dZ^3$ expresses the balance between debit and credit valuations.
- The point at infinity O plays the role of a zero-balance state—the netted closure of obligations.
- Reversing a transaction (crediting what was debited) corresponds to taking the group inverse $-P$.
- Adding two transactions corresponds to combining them in the ledger:
 $P + Q = R$.
- If $P + Q = O$, the transactions exactly offset: a balanced journal entry.

Thus, the elliptic group law is not just algebraically well-formed—it embodies the additive, reversible, and balanced nature of general ledger logic. This provides a deep geometric realization of financial consistency and opens the path toward categorical audit reasoning.

Proposition 8 (Group Law on the Normative Projective Curve): Let E be the projective elliptic curve over $\mathbb{Q}$ defined by:

$$E : X^2Z = Y^3 + cYZ^2 + dZ^3$$

with $c, d \in \mathbb{Q}$.

Then the set of $\mathbb{Q}$ -rational points $E(\mathbb{Q})$ forms an *Abelian group* under the elliptic curve addition law, with the point at infinity $O = (0 : 1 : 0)$ serving as the identity element.

Proof: We follow the classical construction of a group law on a smooth cubic curve in projective space. It is well-known from algebraic geometry that any non-singular cubic curve defined over a field K admits a natural group law with the following properties:

1. The curve E is defined as a homogeneous cubic in $\mathbb{P}^2$, i.e., total degree 3 in (X, Y, Z) .
2. The curve is *non-singular* (smooth), meaning it has no cusps or self-intersections. This can be verified by computing the partial derivatives of the defining equation and confirming that there is no common zero in projective space:

$$f(X, Y, Z) = X^2Z - Y^3 - cYZ^2 - dZ^3$$

$$\frac{\partial f}{\partial X} = 2XZ, \quad \frac{\partial f}{\partial Y} = -3Y^2 - cZ^2, \quad \frac{\partial f}{\partial Z} = X^2 - 2cYZ - 3dZ^2$$

The simultaneous vanishing of these three does not occur for any projective point satisfying the curve equation unless all coordinates are zero—which is excluded from $\mathbb{P}^2$. Thus, E is smooth.

3. The *group law* is defined geometrically:

- Given two points $P, Q \in E(\mathbb{Q})$, draw the line through P and Q (or tangent if $P = Q$).
- This line intersects E at a unique third point R' by Bézout's theorem (degree 3 implies three intersection points, counting multiplicities) [14].
- Define $P + Q$ as the reflection of R' through a fixed axis (e.g., reflection over the symmetry line if in affine form, or through a birational map).

4. This operation satisfies the axioms of a group:

Identity: The point at infinity $O = (0 : 1 : 0)$ acts as the neutral element.

Inverses: For any point $P = (X : Y : Z)$, the inverse $-P$ is the point obtained by reflecting P through the designated axis (usually $Y \mapsto -Y$ in Weierstrass form).

Associativity: The group law is associative; this is a non-trivial fact but follows from the properties of divisors and rational functions on elliptic curves ([12]).

Commutativity: The construction is symmetric in P and Q , hence commutative.

5. Since all operations are defined over $\mathbb{Q}$ and preserve rationality (the coefficients are rational and intersection points of rational lines with rational curves are rational), the group law is closed in $E(\mathbb{Q})$.

Therefore, $E(\mathbb{Q})$ forms an Abelian group under the elliptic addition law.

Remark 12: In the context of double-entry bookkeeping, this group law models the additive nature of transactional logic. Multiple contract obligations (debits and credits) compose into a balanced ledger if and only if their corresponding points on E sum to the identity O . Hence, the general ledger structure is a concrete realization of this elliptic Abelian group—not merely an analogy, but an isomorphic structure preserving value, symmetry, and reversibility.

8.4 Elliptic group law models double-entry composability

Theorem 1.3 (Elliptic Group Law Models Double-Entry Composability): Let E be an elliptic curve defined over $\mathbb{Q}$ by the Weierstrass equation:

$$E : y^2 = x^3 + ax + b$$

Let $P, Q \in E(\mathbb{Q})$ be two rational points representing debit and credit entries in a bilateral contract. Then their elliptic sum $R = P + Q$ defines a third point on the curve, representing the net result of the transaction.

This group law on E satisfies:

- *Closure*: $P + Q = R \in E(\mathbb{Q})$
- *Associativity*: $(P + Q) + R = P + (Q + R)$
- *Identity*: There exists a neutral point O (the point at infinity) such that $P + O = P$
- *Inverses*: For every $P \in E(\mathbb{Q})$, there exists $-P$ such that $P + (-P) = O$

Interpretation: The elliptic group law expresses the composability of contractual obligations under the double-entry principle. Just as accounting ensures every debit is matched by a credit, the curve ensures that composed transactions remain normatively closed. The sum $P + Q = R$ represents a ledger-balanced structure that is geometrically and algebraically preserved.

9. Categorical ledger logic

Definition 8 (Category of Normative Contracts): Let C be a category where:

- Objects are contract states $X \in E(\mathbb{Q})$, i.e., rational points on an elliptic curve representing normative values.
- Morphisms $f : X \rightarrow Y$ represent bilateral contract transformations, such as debits or credits, satisfying the elliptic relation.
- Composition of morphisms is given by the elliptic group law: if $f : X \rightarrow Y$ and $g : Y \rightarrow Z$, then $g \circ f := f + g : X \rightarrow Z$.

Definition 9 (Monoidal Structure on Contract Composition): The category C is equipped with a monoidal structure $(C, \otimes, O)$, where:

- The tensor product $\otimes$ is defined as pointwise elliptic addition of contract states: for $P, Q \in E(\mathbb{Q})$, $P \otimes Q := P + Q$.
- The unit object O is the point at infinity on the elliptic curve (the identity of the group law).
- The associativity and symmetry are inherited from the abelian group law on $E(\mathbb{Q})$.

Proposition 9 (Monoidal Category of Ledger Transactions): The category $(C, \otimes, O)$ forms a symmetric monoidal category of contract composition. Each morphism represents a normative transformation between contract states. Composability ensures:

$$\left(P \xrightarrow{f} Q \right) \otimes \left(Q \xrightarrow{g} R \right) = \left(P \xrightarrow{f+g} R \right)$$

under the condition that all points lie on the same elliptic curve $E(\mathbb{Q})$.

Remark 13: This categorical structure formalizes the logic of composable, auditable contract systems. It ensures:

1. Contract states are represented as rational points,
2. Transactions compose via group addition,
3. The entire structure respects associativity, symmetry, and identity,
4. Deviations from the curve indicate non-compliant or fraudulent behavior.

It generalizes double-entry bookkeeping as a monoidal category of value-preserving morphisms, making it suitable for automated control and verification via category-theoretic tooling (**Figure 6**).

Proposition 10 (Ledger Closure via Morphism Composition): Let C be the monoidal category of normative contracts, where:

$$\begin{array}{c} \begin{array}{ccccc} & & s \circ f & & \\ & \curvearrowright & & \curvearrowleft & \\ P & \xrightarrow{f} & Q & \xrightarrow{g} & R \end{array} \\ (P \xrightarrow{f} Q) \otimes (Q \xrightarrow{g} R) \longrightarrow (P \xrightarrow{s \circ f} R) \end{array}$$

Figure 6.

Monoidal composition of contract morphisms in the category of normative contracts. The top diagram shows sequential morphisms $f: P \rightarrow Q$ and $g: Q \rightarrow R$, composing to $s \circ f: P \rightarrow R$. The bottom expression represents the monoidal composition: $\left(P \xrightarrow{f} Q \right) \otimes \left(Q \xrightarrow{g} R \right) \rightarrow \left(P \xrightarrow{s \circ f} R \right)$. This models composable contract transformations under the elliptic group law, ensuring that composed obligations remain curve-consistent.

- Objects are contract states $P, Q, R \in E(\mathbb{Q})$,
- Morphisms are contractual obligations $f : P \rightarrow Q, g : Q \rightarrow R$ represented as elliptic additions,
- Composition is defined by $g \circ f := f + g : P \rightarrow R$ under the elliptic group law.

Then the morphism composition corresponds to ledger closure if and only if:

$$P + f + g = R \quad \text{and} \quad R \in E(\mathbb{Q})$$

That is, the composite contract state R lies on the elliptic curve E .

Equivalently:

$$(g \circ f)(P) = R \Leftrightarrow (P, Q, R) \text{ is a valid ledger path}$$

Proof Sketch: The morphisms f and g represent contract steps encoded as displacements on the elliptic curve. By the group law of $E(\mathbb{Q})$, the composition $g \circ f := f + g$ yields a new point $R = P + f + g$.

For R to be valid (ledger-balanced), it must lie on the curve E , i.e., satisfy the curve equation:

$$R = (x, y) \in \mathbb{Q}^2 \quad \text{and} \quad y^2 = x^3 + ax + b$$

This ensures the composability of obligations and closes the ledger flow under normative conditions. If $R \notin E(\mathbb{Q})$, then the composition violates the structural integrity of the ledger—i.e., a contract violation or inconsistency has occurred.

Theorem 1.4 (Morphism Composition and Ledger Closure): Let $P, Q, R \in E(\mathbb{Q})$ be rational points on an elliptic curve defined over $\mathbb{Q}$:

$$E : y^2 = x^3 + ax + b$$

Let $f : P \rightarrow Q, g : Q \rightarrow R$ be morphisms modeled by elliptic displacements, such that:

$$f = Q - P, \quad g = R - Q$$

Then:

$$g \circ f := f + g = (Q - P) + (R - Q) = R - P$$

Moreover, the morphism composition corresponds to a valid ledger closure if and only if:

$$R = P + f + g \in E(\mathbb{Q}) \Leftrightarrow R \in E(\mathbb{Q})$$

Proof: Let $E(\mathbb{Q})$ be the set of rational points on the elliptic curve E , equipped with the group law $+$. This law defines a commutative group with identity O (point at infinity), and inversion $-P$ corresponding to reflecting $P = (x, y)$ over the x -axis to $(x, -y)$.

Given:

$$f = Q - P \quad \text{and} \quad g = R - Q$$

Then the composite morphism is:

$$g \circ f := f + g = (Q - P) + (R - Q)$$

Using associativity and group identities:

$$(Q - P) + (R - Q) = (Q + (-P)) + (R + (-Q)) = Q + R - P - Q = R - P$$

So:

$$g \circ f = R - P$$

Now, this morphism corresponds to a path $P \rightarrow R$ if and only if $R \in E(\mathbb{Q})$, because otherwise the result is not a point in the category $\mathcal{C}$. That is:

$$g \circ f \in \text{Hom}_{\mathcal{C}}(P, R) \Leftrightarrow R \in E(\mathbb{Q})$$

In terms of coordinates: let $P = (x_1, y_1)$, $Q = (x_2, y_2)$, $R = (x_3, y_3) \in \mathbb{Q}^2$, and assume $P \neq Q$. The elliptic group law gives:

- Slope:

$$\lambda = \frac{y_2 - y_1}{x_2 - x_1}$$

- Then:

$$x_3 = \lambda^2 - x_1 - x_2, \quad y_3 = \lambda(x_1 - x_3) - y_1$$

If the result $R = (x_3, y_3) \in \mathbb{Q}^2$ satisfies $y_3^2 = x_3^3 + ax_3 + b$, then $R \in E(\mathbb{Q})$, and the composite morphism is defined.

Therefore, ledger closure is equivalent to curve membership of the result.

Remark 14 (Ledger Validity as Curve Membership): This result shows that in the context of the buyer:

- If the buyer executes a debit (morphism f) followed by a credit (morphism g), the resulting contract state R must lie on the elliptic curve $E(\mathbb{Q})$ for the ledger to be normatively valid.
- That is, the composite morphism $g \circ f = R - P$ corresponds to a valid ledger closure if and only if $R \in E(\mathbb{Q})$.
- If $R \notin E(\mathbb{Q})$, the contract sum lies off-curve, indicating a structural violation of the normative accounting identity—a misstatement or inconsistency in the transaction logic.

Geometrically, this means that morphism composition must land on the curve for trust to be preserved: only curve-consistent compositions are ledger-compliant.

Remark 15 (Validity Condition for Composed Contracts): The expression

$$g \circ f \in \text{Hom}_C(P, R) \Leftrightarrow R \in E(\mathbb{Q})$$

encodes the formal criterion for contract validity in the category C of normative transactions.

That is, a composed morphism $g \circ f$ (e.g., a debit followed by a credit) represents a legitimate ledger transformation from state P to state R if and only if the resulting contract state R lies on the elliptic curve $E(\mathbb{Q})$.

This reflects the composability condition of the ledger system: only those morphisms whose outcomes lie on the curve preserve contractual integrity. Points $R \notin E(\mathbb{Q})$ indicate inconsistencies, distortions, or violations of the double-entry principle.

Remark 16 (Applying the Logic to Real Contracts): We now operationalize the categorical and algebraic framework by imputing concrete transaction data from earlier examples into our morphism composition and elliptic curve equations.

Given:

- Initial contract state $P = (\chi_1, \mu_1, Z_1)$, e.g., $X = 4300$, $Y = 77400$, $Z = \frac{X}{Y} = \frac{1}{18}$.
- A subsequent morphism g with new payment $Y' = 86000$ for the same $X = 4300$, yielding $Z' = \frac{1}{20}$.
- Then $f = Q - P$, $g = R - Q$, and $g \circ f = R - P$.
- We compute whether $R \in E(\mathbb{Q})$ using the normative elliptic equation:

$$X^2Z = Y^3 + dZ^3 \quad \text{where} \quad d = \frac{X^2Z - Y^3}{Z^3}$$

By checking whether this identity holds for the new values, we determine:

- Whether the composed morphism $g \circ f$ is valid,
- Whether R lies on the normative elliptic curve,
- Whether ledger closure and structural integrity are preserved.

This demonstrates how the formal framework naturally leads to practical tests for contract compliance and allows digital audit systems to evaluate whether obligations remain within the valid categorical image of the identity-preserving functor.

Remark 17 (General Ledger Logic Equivalent): The categorical and geometric model developed above has a direct analogue in double-entry bookkeeping logic.

- Let $f : P \rightarrow Q$ represent a *debit entry* in which buyer paid \$86,000 for an order of 4300 jeans. The agreed price was \$77,400, so f represents a surplus payment of \$8600. This morphism reflects an obligation recorded in excess of the normative contract identity—i.e., a deviation from balanced double-entry.
- Let $g : Q \rightarrow R$ represent a *credit entry*, such as a factory refund, a delivery correction, or a compensating asset transfer to reconcile the surplus. If g precisely offsets f and the resulting contract state R lies on the elliptic curve, then the composite $g \circ f$ restores balance and satisfies the contract identity.

The elliptic curve condition $R \in E(\mathbb{Q})$ is equivalent to:

$$\text{Debits} = \text{Credits} \quad (\text{i.e., the ledger is closed})$$

In this sense, the elliptic curve acts as the *geometric general ledger surface*: any point R not lying on E reflects a breakdown in balance—a mismatch in the recorded obligations and entitlements.

The algebraic eccentricity $\varepsilon := X^2Z - Y^3$ serves as the contract's *ledger residual*: it quantifies how far the books are out of balance and provides a rigorous foundation for audit, trust scoring, or automatic correction.

Remark 18 (Ledger Eccentricity as Monetary Residual): In the buyer example, the algebraic eccentricity

$$\varepsilon := X^2Z - Y^3$$

abstractly measures the deviation from the normative contract identity. However, when evaluating the imbalance in the general ledger, a linearized interpretation is more intuitive.

We define the *ledger residual* as:

$$\varepsilon_{\text{ledger}} := Y_{\text{actual}} - Y_{\text{norm}} = 86,000 - 77,400 = \boxed{8,600 \text{ USD}}$$

This residual directly reflects how far the recorded transaction diverges from the symmetric contract identity. It provides a basis for financial audit, automatic exception handling, and trust scoring in digital accounting systems.

Remark 19 (Algebraic and Normalized Ledger Eccentricity): The algebraic eccentricity

$$\varepsilon := X^2Z - Y^3$$

is measured in units of currency cubed, and captures the numerical deviation between the value implied by the exchange ratio Z and the actual payment Y . It quantifies how far a transaction deviates from the normative elliptic identity.

Buyer Example.

- *Compliant contract*: $X = 4,300$, $Y = 77,400$, $Z = \frac{1}{18}$

$$X^2Z = 4300^2 \cdot \frac{1}{18} = 1,027,222.22$$

- *Non-compliant transaction*: $Y = 86,000$, $Z = \frac{1}{20}$

$$X^2Z = 4300^2 \cdot \frac{1}{20} = 924,500$$

- *Thus,*

$$\varepsilon = X^2Z - Y^3 = 924,500 - (86,000)^3$$

Since $Y^3 \gg X^2Z$, this algebraic form is dominated by the cubic magnitude of Y and hard to interpret in practical accounting terms.

Normalized Ledger Eccentricity. To express the imbalance in direct financial units (USD), we define:

$$\varepsilon_{\text{ledger}} := Y_{\text{actual}} - Y_{\text{norm}} = 86,000 - \left(\frac{X}{Z_{\text{norm}}} \right) = 86,000 - \left(\frac{4,300}{\frac{1}{18}} \right) = 86,000 - 77,400 = \boxed{8,600 \text{ USD}}$$

This residual imbalance is the contract's *ledger error*: the amount by which the buyer overpaid relative to the agreed unit rate. It provides a precise numerical basis for audit alerting, risk scoring, and contractual correction mechanisms in accounting systems.

10. Logical limits of blockchain: Why it fails as a double-entry ledger

Blockchain technologies are often proposed as replacements for traditional ledgers, including financial systems. However, when viewed through the lens of the normative double-entry logic and internal control requirements (e.g., COSO 2013), blockchain reveals structural deficiencies. This subsection analyzes these issues logically.

Proposition 11 (Failure of Blockchain to Model Double-Entry Logic): Let a valid accounting ledger require:

1. Role symmetry between debit and credit,
2. Internal matching and closure (i.e., $X = Y$),
3. A normative invariant (e.g., $X^2Z = Y^3$),
4. A general ledger view enabling auditability,
5. Conformance with control standards (e.g., COSO 2013 Principles 10 and 11).

Then, blockchain-based distributed ledger technologies (DLTs) fail to satisfy these requirements.

Sketch of Argument: We analyze five logical mismatches:

1. *Missing Role Symmetry:* DLT records token transfers, not dual-role commitments. It lacks a formalization of the debit-credit pairing.
2. *Absence of Internal Matching:* Traditional bookkeeping closes ledgers by balancing both sides. Blockchain relies on external consensus, not bidirectional validation.
3. *No Normative Invariant:* The geometric identity $X^2Z = Y^3$ with $Z = X/Y$ and $d = 0$ does not arise from blockchain data structures.
4. *No General Ledger View:* Blockchain disperses state across wallets and contracts. There is no centralized or algebraically composable ledger view.
5. *Violation of COSO 2013 Internal Controls:* Specifically, Principle 10 (control activities over information processing) and Principle 11 (general ledger integrity) are not supported structurally.

Hence, blockchain fails to reproduce the internal logic of financial accountability embedded in double-entry systems.

Remark 20 (Control Integrity and Normative Accounting): While blockchain ensures immutability and transparency at the block level, it lacks the semantic structure necessary

Requirement	Double-Entry Logic	Blockchain DLT	Violation
Role Inversion (Debit = Credit)	Enforced via dual accounts (bidirectional entry)	One-sided transfer: sender → receiver	×
Internal Matching (Cross-validation)	Ledger invariant: $X = Y$ or $Z = 1$	Consensus verification only	×
Control Activities (COSO Principle 10)	Enforces validation per transaction	Control flows are implicit, not enforced	×
General Ledger View	Centralized, auditable, traceable	Fragmented state across nodes	×
Normative Balance Identity ($d = 0$)	Algebraically embedded in $X^2Z = Y^3$	Absent; no symmetry checks	×

Table 5.
 Comparison of structural requirements for financial accountability under double-entry bookkeeping versus blockchain DLT.

for financial systems governed by internal control frameworks. In contrast, the double-entry system is both semantically rich and algebraically constrained, allowing for audit, error detection, and principled composition of transactions.

10.1 Comparison table: Double-entry logic vs. blockchain DLT

Proposition 12 (Blockchain Inadequacy and Projective Ledger Resolution): Let a blockchain-based ledger be defined as a distributed append-only sequence of transactions $T = \{t_i\}_{i \in \mathbb{N}}$, where each transaction t_i encodes a one-way value transfer $A \rightarrow B$, verified via consensus (**Table 5**).

Assume further:

- Blockchain records are *unidirectional*, lacking symmetric role inversion,
- State consistency is ensured only externally (via consensus), not internally,
- Smart contracts enforce execution but not normative obligations,
- No algebraic invariant exists analogous to double-entry logic.

Then, such a ledger:

1. Cannot represent bilateral obligations as algebraic identities,
2. Lacks the expressive power to encode deviations as geometric anomalies,
3. Cannot enforce internal control requirements as specified in COSO 2013,
4. Fails to support compositional audit trails in multi-party transactions.

By contrast, the projective elliptic ledger model:

- Embeds transactions as points $(X : Y : Z) \in \mathbb{P}^2(\mathbb{Q})$ satisfying $X^2Z = Y^3 + dZ^3$,

- Ensures symmetry: $X = Y \Leftrightarrow Z = 1$, preserving double-entry logic,
- Encodes deviations as curvature d , exposing nonconformity algebraically,
- Supports composition of transactions via the elliptic group law $P + Q = R$,
- Admits categorical mappings of control activities aligned with COSO 2013,

and thereby forms a complete, auditable, and internally consistent alternative to blockchain-based ledger systems.

Corollary 2 (Implications for Supply Chain Transparency and Internal Audit): Let the projective ledger framework described in the preceding proposition be applied to a multi-actor supply chain where value is exchanged under bilateral contractual obligations.

Then, the following implications hold:

1. *Enhanced Transparency*: Each transaction is embedded in a symmetric contract triple $(X : Y : Z)$, such that deviations from balance are explicitly encoded by the curvature term d . This enables proactive detection of misstatements or distortions across the supply chain.
2. *Traceable Internal Controls*: All role reversals (buyer $\leftrightarrow$ seller) are modeled by the group inverse $-P$ and the elliptic sum $P + Q = R$ supports compositional traceability of obligations. This satisfies COSO principles related to *Control Activities*, *Information and Communication*, and *Monitoring Activities*.
3. *Audit Readiness and Integrity*: The geometric identity $X^2Z = Y^3 + dZ^3$ acts as an internal invariant, preserving financial consistency. This ensures that each transaction is self-validating, providing reliable input for continuous auditing and risk-based assurance.
4. *Resilience Against Opaqueness*: Unlike blockchain-based ledgers which record value transfer without guaranteeing semantic integrity, the projective model restores the dual-account logic of accountability, making violations of contractual expectations algebraically visible.
5. *Compositional Oversight*: Complex multi-tier exchanges can be decomposed into elliptic sums of atomic contracts, enabling structured oversight at every tier of the chain—fully composable under the normative elliptic group law.

Therefore, the projective elliptic ledger provides a mathematically rigorous foundation for trustworthy, transparent, and auditable value chains, surpassing blockchain in domains requiring normative compliance and internal control alignment.

11. Conclusion

This chapter presents a categorical and algebraic alternative to blockchain-based ledgers, grounded in the well-established logic of double-entry bookkeeping. By embedding bilateral exchange relationships into projective space and interpreting the contract identity as a point on a normative elliptic curve, we demonstrated a faithful isomorphism between accounting logic and geometric consistency. This not only preserves the accounting identity but also provides a compositional structure through the

elliptic group law, enabling precise tracking and reconciliation of transactions across tiered supply chains.

Through formal propositions and comparative analysis, we highlighted the limitations of distributed ledger technology (DLT), especially in its inability to enforce bilateral symmetry and its structural disconnect from the logic of internal controls as outlined in COSO 2013. In contrast, our proposed model guarantees transparency, reversibility, and auditability by construction, and it supports compositional reasoning via categorical lifting of contracts.

Our framework enables tiered suppliers, auditors, and regulators to reason over normative compliance without the need for external trust anchors such as consensus protocols. Instead, each transaction becomes a self-verifying morphism in a structured category of contracts.

Future work may extend this model with modal and temporal logic to capture evolving commitments over time, explore p-adic diagnostics for fraud detection, and formalize multi-agent evaluation through monoidal composition and epistemic roles. The approach thus not only reconciles foundational accounting principles with modern computational requirements but also offers a rigorous and extensible architecture for trustworthy digital infrastructures.

A. Appendix: Mathematical background and annotations

Projective Space $\mathbb{P}^2(\mathbb{Q})$

The projective plane over the rational numbers consists of equivalence classes $[X : Y : Z]$ such that $(X, Y, Z) \sim (\lambda X, \lambda Y, \lambda Z)$ for all $\lambda \in \mathbb{Q}^\times$. *Used for:* Representing value-invariant contract expressions.

Example: $[4 : 2 : 1] = [8 : 4 : 2]$ represents the same projective point.

Elliptic Curve (Projective Form)

General form:

$$X^2Z = Y^3 + cYZ^2 + dZ^3$$

Used for: Encoding contracts as points on a cubic curve. Norm-compliant contracts satisfy $d = 0$.

Example: For $(X, Y, Z) = (1, 1, 1)$, then $d = 0$.

Valuation Ratio $Z = \frac{X}{Y}$

Used for: Detecting imbalance in give-and-get relationships.

Example: If a buyer pays $Y = 600$ and receives $X = 300$, then $Z = 0.5$.

A.1 Double-entry bookkeeping identity

$$\text{Debit} = \text{Credit}$$

Used for: Encoding reversible, balanced exchanges.

Example: Delivery of 100 units matched by payment of 100 units.

A.2 Group law on elliptic curves

Three collinear points P, Q, R on a curve satisfy:

$$P + Q + R = O$$



Figure A1.

Commutative triangle illustrating morphism composition in category theory. The diagram commutes if and only if $g \circ f = h$, meaning the direct morphism $h: A \rightarrow C$ equals the composition of $f: A \rightarrow B$ followed by $g: B \rightarrow C$. This expresses the associativity and structural integrity of compositional mappings in categorical contract logic.

Used for: Verifying aggregation consistency.

Example: Given two contract deviations, their sum can be interpreted geometrically.

Category

Consists of:

- *Objects:* such as contracts or states.
- *Morphisms:* structure-preserving transformations.
- *Identities and composition:* foundational for tracking logical consistency.

Example: Objects: $(4300, 86000, Z)$; Morphism: $\phi(\lambda) : (X, Y, Z) \mapsto (\lambda X, \lambda Y, Z)$.

Morphism

A map $f : A \rightarrow B$ between objects in a category.

Example: Scaling morphism: $(X, Y) \mapsto (\lambda X, \lambda Y)$.

A.3 Commutative diagram

A diagram where all paths from one object to another yield the same morphism is shown in **Figure A1**.

Functor

A structure-preserving map between categories:

- $F : C \rightarrow D$
- Preserves identities and composition

Example: A contract (X, Y, Z) is functorially mapped to a curve $X^2Z = Y^3 + dZ^3$.

Abelian Group

Satisfies:

- Associativity, Identity, Inverses, Commutativity

Example: $(\mathbb{Q}, +)$ — if two audit deviations cancel, they sum to zero.

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Chapter 2

Navigating Uncertainty and Optimizing Business Operations through Risk Management

Ahmed Mohammed Kamaruddeen

Abstract

To effectively address potential risks that could disrupt business operations, this chapter presents a risk management framework adopted from the literature to plan, identify, analyze, respond to, monitor, and control operations-related risks in a coffee shop business. The chapter demonstrates how a risk plan should be developed to guide the other risk management processes. It also demonstrates how to identify potential operations-related risks, analyze them using both quantitative and qualitative approaches, evaluate and categorize them, respond to or mitigate them, and then monitor and control them. The chapter presents a risk worksheet that provides all relevant information relating to the identified operational risks, guiding the operations manager in managing the risk and making informed decisions.

Keywords: risk management, operations, small businesses, uncertainty, optimization, failure mode and effect analysis

1. Introduction

The current turbulent environment, diverse customer requirements, and intense business environment demand adequate production and operation management among businesses. Hence, the knowledge, skills, and competencies of Production and Operations Management are essential for managers to handle production and operational-related challenges and achieve business success.

Additionally, today's business environment is increasingly volatile and challenging, leading to a higher volume and greater complexity of risks. As a result, risk management has become a crucial component of business. Business organizations must incorporate risk management into their strategies and operations [1]. Since organizations operate within both internal and external environments [2], it is essential to assess and manage both internal and external risks [3].

Risk can be both negative and positive. In the context of business operations, a negative risk refers to any uncertain outcome arising from an internal or external event, condition, or factor that hinders the attainment of business objectives. The risks can be prevented, mitigated, transferred, or accepted (only if they are

negligible). Businesses should examine positive risks to leverage potential benefits associated with them, such as business growth or expansion [4, 5].

According to Oslon and Wu [6], profit-making in businesses involves risk-taking. However, the ability of business organizations to leverage the most suitable risk management approach enables them to achieve their business objectives effectively. Implementing risk management allows them to identify potential risks, mitigate the impact of negative risks, and explore the potential benefits of positive risks [7].

Continuously managing business risks enables organizations to enhance their operations, performance, and finances while also protecting the business from potential threats [8]. Following reference [9], the risk management framework outlined in this chapter aims to assist small business organizations in integrating risk management into their operations, ensuring business continuity. Disruptions have a significant negative impact on small businesses, primarily due to their limited resources, capabilities, and level of preparedness for business threats [1]. This is why small businesses must incorporate risk management into their daily operations [8] to develop the capacity to respond to threats swiftly and effectively [10].

Failure mode and effect analysis is a technique used across industries to assess the risk of failure modes and their effect on goods, services, or products and identify areas for improvement [11]. The technique relies on the risk priority number (RPN), which is determined by multiplying the “frequency” (denoted as F), “severity” (denoted as S), and “non-detection” (denoted as ND) [12]. In addressing the weaknesses and limitations of failure mode and effect analysis (FMEA), which have led to its extensive criticism [13], the authors propose a two-stage integrative quality function deployment approach to improve it. The two phases involve prioritizing failure modes based on failure effects and then prioritizing failure causes based on failure modes. Despite the efforts to improve the technique, Chakhrit et al. [14] has shown that the integrated approach to FMEA still has some inherent limitations. The frameworks used to illustrate the risk management process were adapted from the risk management literature [15, 16].

This chapter aims to complement the existing risk management techniques for business operations by presenting a detailed risk management process. The chapter used illustrations to explain what should be done and how to perform every stage of the risk management. The scope of risk management illustrated in the chapter is particularly relevant to small businesses. While digital technology, such as artificial intelligence (AI), is used to manage risks, its application depends on the availability of data [17–19]. This essential data for AI can be gathered over time using the risk management framework outlined in this chapter. Consequently, the proposed risk management detailed in this chapter remains relevant for small businesses. It is anticipated that business and operations managers will benefit from utilizing the risk management process described herein. A major contribution of this chapter is the use of a detailed risk management plan, input-technique-output framework at all stages of the risk management. It illustrate what the managers required as input, what process or technique they could use, and what are the expected outcome at every stage of the risk management process. With all the illustrations and guides, managers can easily understand and emulate by adopting or adapting the risk management process presented in the chapter.

Using a coffee shop operations for illustration, the next sections presents a list of daily operational activities at the coffee shop. A generic framework for the entire risk management process is presented. The framework and processes involved in planning, identifying, analyzing, responding, monitoring and control of risks are

presented. A risk worksheet which summarizes all the information obtained in the risk management process is presented.

2. Methodology

This chapter is not empirical-based, as it does not require the collection and analysis of data from samples to derive a conclusion or achieve research objectives. Instead, it provides a guiding framework that managers can emulate to manage all the internal and external business-related risks that could hinder their business operations. However, its applications, particularly the analysis of potential risks, require the collection and use of both qualitative and quantitative data, such as estimating the probability or likelihood of a risk event or risk condition occurring and its impact on business operations or the extent of disruption it will cause if the risk were to occur. The method utilized in this chapter is the adaption of existing risk management framework to business operations of small businesses such as a coffee shop.

3. Coffee shop operations

Coffee shop has been selected as a small business for the illustrations of the risk management process in this chapter. Eight activities have been identified as daily operations in the coffee shop. They include opening the shop, morning briefing, cleaning the shop, turning and setting on machines, receiving payments and orders, preparing coffee, serving coffee, taking inventory, requesting and receiving supplies, and closing the shop. While each of these operational activities contributes to the daily business operations of the coffee shop, they can be associated with different risks that could negatively impact the business. Hence, there is a need to manage the operational risks of the coffee business.

3.1 Risk management of coffee shop operations

Figure 1 presents the risk management activities. The first risk management activity is planning, followed by risk identification, risk analysis and evaluation, risk response strategies, and continuously monitoring and controlling the risks. **Tables 1–11** present the input needed to perform each activity, the technique to use in performing each activity, and the output from each activity.

3.1.1 Plan risk management

The business scope is examined to understand the scope of the operations needed to run the coffee shop. Enterprise organizational factors and external factors that are beyond the control of the business owners.

Organizational process assets are the lessons and experiences accumulated while running a coffee drink business. The components of the risk management plan are discussed as an agenda during a meeting called the planning meeting and analysis. The meeting outcome is the risk management plan presented in **Table 1**.

The risk management plan becomes a reference for the remaining risk management activities. Hence, it is an input for risk identification, analysis, response, monitoring and control.

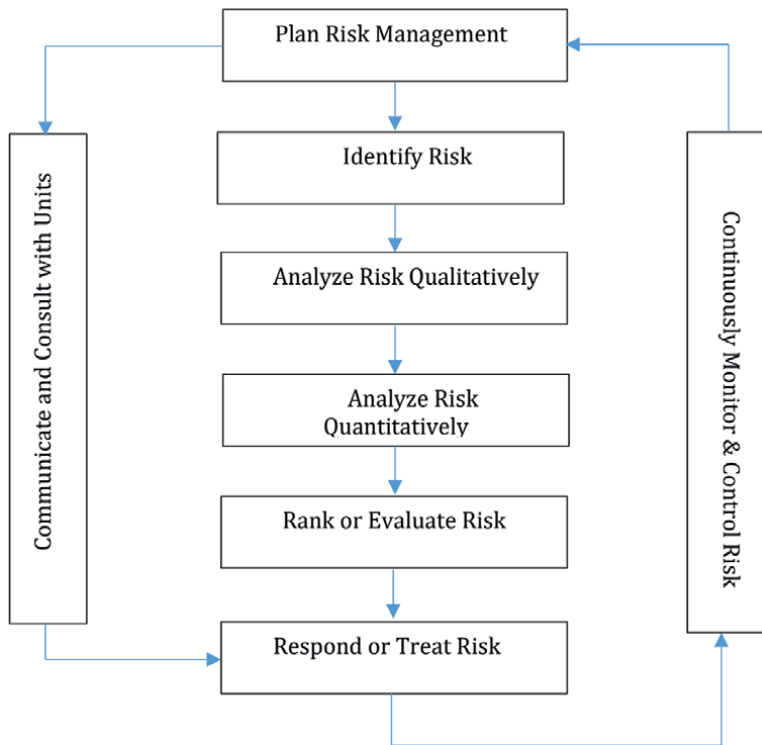


Figure 1.
Risk management process. Source: [15].

S/N	Input	Tool/technique	Output
1	Scope of business operations	Planning meetings and analysis	Risk management plan
5	Enterprise environmental factors		
6	Organizational process assets		

Source: [16].

Table 1.
Framework for planning risk management.

3.1.2 Risk identification

Risk identification: It was performed to identify potential risks during an online class project.

The following are from the input, technique, and output in **Table 3**.

Input 1: Security laps can emerge while opening the shop.

Input 2: Slipping due to wet floor can happen while cleaning.

Input 3: Wrong setting or electrical issues can emerge from turning on and setting the machines.

Input 4: Equipment failure, poor quality of drinks, and burns can occur while preparing coffee.

Input 5: Inventory and supply errors can happen during the inventory and supply process.

Section	Agenda	Process/purpose/task	Options	Decision in the meeting
1	Methodology			
	Methodology	Define how risk would be managed.	a. Develop and document a risk plan b. Update plan	Updating throughout the risk management
		Define how risk would be identified	a. Brainstorming b. Interview c. Review documents d. Checklist analysis e. Assumption analysis	
		Define how to perform qualitative analysis	a. Probability and impact assessment b. Probability and impact matrix c. Risk categorization d. Risk urgency e. Expert judgment	
		Define how to perform quantitative risk analysis.	Probability and impact assessment	Using numerical values
		Define scale for probability and impact.	a. Five-point scale b. Risk ranking table	A five-point scale was chosen.
		Define how to respond to risk.	a. Develop a risk response strategy b. Assign risk owners c. Develop a contingency strategy d. Review and update strategy e. Expert's judgment	
		Define how to monitor and control risks.	a. Risk reassessment b. Faculty submit weekly and monthly online teaching reports c. Technical performance measurement d. Status meeting	
2	Roles and responsibilities			
	Role	Responsibilities		
	Operation manager			
	Barista and cashier	Focus on ordering and cash-related risks		
	Cook	Focus on kitchen-related risks		
	Cleaner	Maintenance-related risks		
	Stock and marketing manager	Inventory, opening, closing, staff, and customer-related risks		
3	Budgeting	Purpose	Options	Decision
		Budget for all risk management activities	a. Budget for secondary risk b. Budget for residual risk	There would be a budget for both.

Section	Agenda	Process/purpose/task	Options	Decision in the meeting
4	Schedule of activities	Phase	Duration	
	Conduct a briefing session			
	Complete risk plan			
	Approval of risk plan			
	Conduct risk identification			
	Conduct risk analysis			
	Risk response strategies			
	Risk monitoring and control			
5	Risk types/ classification	Purpose	Options	Decision
		Categorize risk	a. Technical	The first four categories will be used.
			b. Organizational	
			c. External	
			d. Project management	
			e. Environmental	
			f. Communication	
			g. Safety	
			h. Scope	
			I. Time	
			j. Required quality	
6	Risk probability and impact			
	Risk probability	Define risk probability.	Rarely happen = 10%	The four scales were considered.
			Unlikely to happen = 30%	
			Possible to happen = 50%	
			Will likely happen = 70%	
			Almost certain = 90%	
	Risk impact	Define risk impact on:		The four scales were considered.
			a. Project cost	
			Negligible impact = 10%	
			b. Project time	
			Minor impact = 30%	
			c. Project scope	
			Moderate impact = 50%	
			d. Project quality	
			Major impact = 70%	
			Extreme impact = 90%	

Section	Agenda	Process/purpose/task	Options	Decision in the meeting
7	Probability and impact matrix/risk evaluation			
	Value of probability (P)	Value of impact (I)	Risk score ($P \times I$)	Risk rating All three ratings were considered.
			Low-risk score	
			Medium risk score	
			High-risk score	
8	Stakeholders' risk tolerance		Very high-risk score	
	Stakeholder	Normal risk tolerance		
	Coffee shop owner	Risk-taker		
	Managers	Risk takers		
9	Reporting frequency/format			
	Report	Content		
	Risk register	Risk ID, risk category, description of the risk, risk owner, probability score, impact score, risk status, risk trigger, and risk response strategy		
	Daily report	Daily information on high and very high risk		
	Weekly report	Weekly information on the emerging risks		
10	Tracking	Daily monitoring		

Source: [16].

Table 2.
Risk management plan.

S/N	Input	Tool and technique	Output
1	Opening the shop	Activities review	Risk register
2	Maintenance and cleaning	Brainstorming	Risk 1
3	Turning and setting on machines	Information gathering	Risk 2
4	Preparing and serving coffee		Risk 3
5	Inventory and receiving supplies		Risk 4
6	Closing the shop		Risk 5
7	Enterprise environmental factors		Risk 6
8	Organizational process assets		Risk 7

Adapted: [16].

Table 3.
Risk identification framework.

Input 6: Security lapses can occur while closing the shop.
Input 7: External factors such as extreme weather, can affect the rate of coffee consumption.
Technique 1: The coffee shop team will review the daily operational activities as the first technique for identifying potential risks.

S/N	Technical	External	Organizational	Project management
R1			✓	
R2			✓	
R3	✓			
R4	✓			
R5				✓
R6			✓	
R7		✓		

Source: Author.

Table 4.
Risk classification/categorization.

S/N	Input	Tool and technique	Output
1	Risk register	Risk probability and impact assessment	Risk register updated
2	Risk management plan	Probability and impact matrix	
3	Scope of business operations	Risk categorization/classification	
4	Organizational process assets	Expert judgment	

Source: [16].

Table 5.
Risk analysis framework.

ID	Description	Risk probability (P)	Risks impact (I)	Risks score (P × I)	Risk ranking
R1	Security lapses during opening	Possible = 50%	Major = 70%	$0.5 \times 0.7 = 0.35$	High risk
R2	Slipping due to a wet floor	Possible = 50%	Moderate = 50%	$0.5 \times 0.5 = 0.25$	Moderate
R3	Wrong setting of machines and electrical issues	Possible = 50%	Major = 70%	$0.5 \times 0.7 = 0.35$	High risk
R4	Equipment failure, poor quality of drink, burns	Possible = 50%	Major = 70%	$0.5 \times 0.7 = 0.35$	High risk
R5	Inventory and supply errors	Possible = 50%	Major = 70%	$0.5 \times 0.7 = 0.35$	High risk
R6	Security lapses while closing	Possible = 50%	Major = 70%	$0.5 \times 0.7 = 0.35$	High risk
R7	Extreme weather conditions	Possible = 60%	Extreme = 90%	$0.6 \times 0.9 = 0.54$	Very high risk

Source: Author.

Table 6.
Risk probability and impact assessment.

S/N	Low risks	Moderate risks	High risks	Very high risk
R1			√	
R2		√		
R3			√	
R4			√	
R5			√	
R6			√	
R7				√

Source: Author.

Note: The ranking is based on Table 6.

Table 7.
 Ranking of risks.

S/N	Input	Tool and technique	Output
1	Risk register	Response strategies for negative risks	Risk register updated
2	Risk management plan	Response strategies for positive risk	Risk-related contract decision
		Contingent response strategies	Project management plan
		Expert judgment	

Source: [16].

Note: Positive risk is not discussed in this chapter, but the team can explore it.

Table 8.
 Risk response framework.

S/N	Description	Avoiding the risk	Mitigating the risk	Transfer
R1	Security lapses during opening	Establish a formal opening procedure		
R2	Slipping due to a wet floor	Avoid wet cleaning in the presence of customers	Provide signage during cleaning and use	
R3	Wrong setting of machines and electrical issues	Use the machine manual Use standard cable and electric appliances	Replace old or malfunctioning appliances	
R4	Equipment failure, poor quality of drink, burns	Have reserved equipment and perform Routine maintenance	Always put on a safety gadget in the kitchen	
R5	Inventory and supply errors	Perform multiple inventories and check supplies multiple times		
R6	Security lapses while closing	Establish a formal closing procedure		
R7	Extreme weather conditions		Use the weather forecast to plan daily sales	

Source: Author.

Note: These response strategies are not exhaustive.

Table 9.
 Risk response strategies/risk treatments.

S/N	Input	Tool and technique	Output
1	Risk register	Risk reassessment	Risk register updated
2	Performance report	Risk audit	Organizational process assets
3		Variance and trend analysis	
4		Technical performance measurement	

Source: [16].
 Note: The lesson learned from the risk management becomes an asset to the business.

Table 10.
 Risk monitoring.

Risk ID	Rank	Description	Probability	Impact	Risk score	Response and contingency	Risk owner
R1	High	Security lapses during opening	50%	70%	$0.5 \times 0.7 = 0.35$	Establish a formal opening procedure	Name
R2	Moderate	Slipping due to a wet floor	50%	50%	$0.5 \times 0.5 = 0.25$	Avoid wet cleaning in the presence of customers Provide signage during cleaning and use	Name
R3	High	Wrong setting of machines and electrical issues	50%	70%	$0.5 \times 0.7 = 0.35$	Use the machine manual. Use standard cable and electric appliances. Replace old or malfunctioning appliances	Name
R4	High	Equipment failure, poor quality of drink, burns	50%	50%	$0.5 \times 0.5 = 0.25$	Have reserved equipment and perform Routine maintenance: always put on a safety gadget in the kitchen	Name
R5	High	Inventory and supply errors	50%	50%	$0.5 \times 0.5 = 0.25$	Perform multiple inventories and check supplies multiple times	Name
R6	High	Security lapses while closing	50%	70%	$0.5 \times 0.7 = 0.35$	Establish a formal closing procedure	Name
R7	Very high	Extreme weather conditions	60%	90%	$0.6 \times 0.9 = 0.54$	Use the weather forecast to plan daily sales	Name

Source: Author.
 Note: Risk owner is the person assigned to watch out for and report signals or signs of a specific risk identified.

Table 11.
 Risk register worksheet.

Technique 2: The coffee shop team will use brainstorming as the second technique for identifying potential risks.

Technique 3: The coffee shop team will use information gathering, such as interviews, as the third technique for identifying potential risks.

The input here is the list of daily operational activities. Certain risks can be identified from the activities.

Techniques differ from the approach used in performing a process.

Output is the outcome of the process and is usually a document to be prepared.

Output 1: The risk register documented all risk information. At the end of the risk identification process, the coffee shop team can identify a number of risks. Possible identified risks labeled as R1–R9 are presented below.

R1: Security lapses during opening.

R2: Slipping due to a wet floor.

R3: Wrong setting of machines and electrical issues.

R4: Equipment failure, poor quality of drink, burns.

R5: Inventory and supply errors.

R6: Security lapses while closing.

R7: Extreme weather conditions.

Note: Only one risk register worksheet has been presented in **Table 10**.

3.1.3 Risk classification

After seven risks were identified, they would be classified as technical, external, or organizational. The purpose of the risk classification was to enable the project team to examine the possibility of applying the same or similar risk response strategy to risks in each category, where it is possible. **Table 4** presents the project team's risk classifications.

3.1.4 Risk analysis

The identified risk was analyzed qualitatively by assessing the probability and impact of each risk. The risk scores were obtained by multiplying the probability and the effect. Evaluating the likelihood of risk involves using the available information or current conditions or situations to determine the likelihood of a risk. Assessing the risk's impact involves determining the effect on the project's success if it occurs. Each risk's probability and impact were mapped after assigning numeric values to each level of probability and impact. Mapping the likelihood and effect was the same as multiplying the probability and impact values to obtain the risk score. The risk score indicates the severity of the risk. **Table 5** presents the framework used for analysis.

After the seven risks were identified, they were analyzed using the input-tool/technique-output in **Table 5**. The purpose of analyzing the risks was to determine the probability of their occurrence and impact on the business operations.

The following are from the input, technique, and output in **Table 5**.

Input 1: The risk register was the first document that the project team perused because it contained basic information about the risks. Information such as risk identification and descriptions was recorded in the risk register. It reminded the coffee shop team about the risks identified during the risk identification process.

Input 2: The second document perused by the project team was a risk management plan. It reminded the project team of the chosen techniques agreed upon to be used during the analysis of the identified risk.

Input 3: The third document perused by the project team was the scope of business operation. It contains the number of activities required to complete daily business operations.

Table 6 presents the likelihood and effect of all risks identified in the earlier stages of the risk management process.

Tool/Technique 1: As shown in the risk management plan in **Table 2**, it was agreed upon that probability and impact assessment, as well as probability and impact matrix techniques, would be used to analyze the identified risks. **Table 6** shows that R2 is a moderate risk, R1, R3, R4, and R5 are high risks, and R7 is a very high.

The output of qualitative risk analysis: **Table 6** presents the output of the qualitative risk analysis. The table shows that each risk's probability and impact were determined. In addition, the risk scores determined by multiplying each probability and effect are also presented. The risk score value indicated whether a risk was low, medium, high, or critical.

3.1.5 Ranking of risks

After the risk analysis is performed using the probability and impact assessment technique, the team should group the risks based on their criticality. The purpose of ranking the risks is to prioritize them based on urgency. This ranking would enable the team to implement the risk response strategies before they occur. **Table 7** presents the rank of the eight analyzed risks based on their risk scores.

3.1.6 Risk response strategies

Four main strategies are commonly used for responding to the risks. The first involves putting in place measures to avoid the impact of risk. The second involves taking actions to mitigate the effects of risk. The third strategy consists of transferring risk to a third party. Insurance is an example of a risk transfer suitable for risks such as fire outbreaks. The fourth factor involves the acceptance of risk. This strategy is usually the last option for a team when the risk is minor and can be absorbed by the organization. Therefore, it is essential to determine the risk tolerance levels of stakeholders and organizations. For example, R2 is moderate because its probability and impact are moderate if it occurs. **Table 8** shows the response strategy for all eight identified, analyzed, and evaluated risks.

The following are from the input, technique, and output in **Table 8**.

Input 1: The team will use the risk register, updated with the probability and impact of all seven identified risks. The purpose is to understand each risk better, meaning that the risk register contains more information about all seven identified risks.

Input 2: The risk management plan serves as reference material for the project team to develop risk response strategies.

Technique 1: The project team should implement any of the risk responses chosen during the planning meeting in stage 1 of the risk management process.

The strategies for the negative risks are as follows:

- a. Avoiding the risk, if not possible, then,
- b. Mitigating the risk, if not applicable, then,
- c. Transferring the risk to a third party, if it is not possible, then,
- d. Actively accepting the risk.

Technique 2: The team can also consult an expert in the beverage business on the appropriate response strategies.

Output 1: The first output of the risk response will be an updated risk register. Each identified risk (R1–R7) will be assigned an appropriate risk response strategy, as shown in **Table 9**.

3.1.7 Risk monitoring and control of risks

After implementing the appropriate risk response strategies for all seven risks, the team should continuously monitor and control them. The purpose of the monitoring is to check whether new risks have emerged and whether the implemented risk response strategies are effective enough. The monitoring process also assesses the effectiveness of the team member assigned to oversee a risk.

The following are from the input, technique, and output in **Table 10**.

Input 1: The risk register will be used as the reference material because it contains the risk response for all risks in addition to the previous updates.

Input 2: The team will use the daily performance reports from each risk owner.

Technique 1: The team can reassess the risks using all reports from staff.

Technique 2: The project team assessed technical performance reports of all equipment and machines.

Technique 3: The third technique is a status meeting. The team can share their experiences on a weekly or monthly basis.

The output of risk monitoring and control 1: The updated risk register worksheet in **Table 11** is significant for the monitoring and control processes.

4. Conclusion

FMEA is a widely used technique for assessing risks related to failure modes in the production process. Despite efforts by scholars and practitioners to address its weaknesses and limitations, recent literature indicates that the technique still has some shortcomings. This chapter, therefore, introduces an alternative risk management process for production-related businesses such as beverage shops to navigate uncertainty and improve their operations. The chapter employs a risk management framework adapted from the literature to demonstrate how to plan risk management, identify potential risks, analyze these risks, develop plans and responses, as well as monitor and control them. The two guiding frameworks used are the risk management framework and the input-technique-output framework for each stage of risk management. In this chapter, seven (7) hypothetical potential risks that could impact a coffee business's operations are identified; these risks are analyzed, categorized, and strategies for their mitigation are suggested. A summary risk worksheet, which consolidates all information gathered during the risk management process, is also presented.

5. Practical implications for managers

This chapter offers a detailed process, with illustrations, on how to manage operational risks and prevent disruptions for long-term business success. Business and operations managers of small enterprises can apply the insights gained from this

chapter and incorporate them into their operations. Every staff member involved in daily activities should be assigned a risk and designated as a risk owner. This will facilitate the development of an early warning system by spotting early signs of risk. Recognizing these signs early allows for an effective response to potential issues. Implementing a risk management process can help prevent unexpected disruptions that could cause financial losses. The risk management approach outlined in this chapter is especially suitable for small businesses, such as restaurants and coffee shops. Businesses aiming to adopt Artificial Intelligence can gather the necessary data using this risk management approach. A practical implementation of risk management in businesses should start with proper training to ensure employees understand the process and foster a culture of risk awareness and mitigation.

Conflict of interest

The authors declare no conflict of interest.

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Chapter 3

Optimization Problems in Companies and Digitalization

Valma Prifti, Selma Nebiu and Genti Guxho

Abstract

Optimizing transportation logistics has become essential for manufacturing companies seeking to enhance efficiency. The focus on developing innovative methods to reduce transportation costs recently has gained considerable attention. Despite extensive efforts to optimize it, the transportation problem remains complex to solve. Mathematical models of quantity distribution from the manufacturing site to the point of sale or consumption are essential tools for addressing this complexity. The main purpose of the chapter is the minimization of transportation costs from manufacturing to destination using the simplex method. The model examines the balanced distribution of products from three production locations to six destinations, involving three capacity constraints, 6 demand constraints, and a total of 18 variables. The problem is solved by using various methods to determine the quantity of products to be transported from each production center to each consumer center to ensure that all conditions are met and costs are minimized. The North West Corner Method results in the highest cost, while the Least Cost Method and Vogel's Approximation Method offer progressively lower costs. With the use of digitalization, the Monte Carlo simulation was used to account for the uncertainty and variability in costs after implementing the Simplex Method to optimize transportation costs. This study provides an approach to solving the problem of product transportation and contributes to the field of operational research, management sciences, and solving industry problems.

Keywords: operations research, digitalization, linear programming, production, optimization

1. Introduction

In a world where computer technology is increasingly developed, operations research has strong links with science and has a significant impact on improving efficiency and improving agreements in various organizations. The goal of operations research is to provide a rational basis for decision-making by attempting to understand and structure complex situations and to use this understanding to predict system behavior and improve system performance. Most of the current work is carried out using analytical and numerical techniques to develop and manipulate mathematical models of organizational systems consisting of people, machines, and procedures.

In a dynamic economic environment like that of Albania, manufacturing companies face numerous challenges in their operational research, particularly in the aspect of product transportation. Operations research is a field of study that encompasses a wide range of techniques and methods for efficiently solving problems and achieving specific objectives. It was developed during World War II when the British Military Management asked a group of scientists to come together to apply a scientific approach to the study of military operations to win the battle [1].

Due to economic growth, the demand for products has surged, leading to a pronounced supply–demand conflict. As people's needs and demands continue to evolve, transportation has become a crucial component in fulfilling these requirements [2]. Optimizing the distribution of products is not only one of the most significant challenges in logistics but is also essential for the development and competitiveness of a company.

Identifying factors that diminish efficiency is closely tied to the company's operational capabilities and its market competitiveness. Effective transportation entails delivering the right product to the right place at the right time, which can significantly impact customer satisfaction and operational costs [3].

In today's dynamic market environment, companies strive to minimize costs as much as possible to enhance profitability, increase efficiency, and boost productivity. This process often involves meticulous management of transportation logistics to ensure that resources are utilized effectively and that the supply chain operates smoothly.

Addressing these issues requires a deep understanding of logistics and supply chain management alongside the implementation of advanced strategies and technologies. Companies need to continuously adapt to changing market conditions, optimize their transportation networks, and leverage data-driven insights to improve performance and maintain a competitive edge. Transportation planning for a production company is critical as it aims to identify and implement an effective methodology for managing the flow of product.

The primary goal of this study is to discover the most efficient way to allocate product from their sources to destinations while minimizing overall transportation costs. To achieve this, we have utilized various analytical methods, including the North-West Corner Method, the Least Cost Method, Vogel's Approximation Method, and the Simplex Method. These methods have been systematically compared and evaluated to determine their effectiveness within our specific transportation planning context.

Throughout this study, we will examine the outcomes of each method and assess their respective strengths and limitations in the realm of transportation planning for manufacturing companies. Through this thorough analysis, the objective of this study is to offer clear conclusions and recommendations regarding the optimal method for practical implementation in our business operations.

2. Literature review

Linear programming is a powerful technique for dealing with problems of allocating limited resources among competing activities, as well as other problems with similar mathematical formulations. It has become a standard tool of great importance to many business and industrial organizations. Moreover, almost every social organization is interested in resource allocation, and there is a growing recognition of the very broad applicability of this technique.

The transportation problem is a classical optimization issue in operations research and logistics, aiming to determine the most cost-effective method for transporting product from multiple suppliers to multiple consumers while meeting all supply and demand constraints [4]. Transportation systems play a crucial role in ensuring that all shipments to and from facilities are executed efficiently and punctually. Traditional models focus on minimizing transportation costs without considering additional factors such as volume discounts. However, integrating volume discounts into the transportation model can lead to significant reductions in overall distribution costs. By incorporating volume discounts, which offer cost reductions based on the quantity of product transported, the efficiency of transportation networks is enhanced, making the distribution process more economical compared to conventional methods that do not account for these discounts [5]. In [6], the study introduced a complex variant of the transportation problem where the objective is to minimize transportation time using a linear fractional objective function, considering the impact of impurities in the transported product.

Transportation problems can be divided into two primary categories: balanced and unbalanced. A balanced transportation problem exists when the overall supply is equal to the overall demand, facilitating a clear and efficient distribution of resources without any excess or deficit. On the other hand, an unbalanced transportation problem presents a scenario where supply does not meet demand, which requires the implementation of alternative approaches to create a workable solution [7]. Furthermore, these problems can also be classified based on specific criteria, such as cost and time. Cost-oriented transportation problems focus on minimizing overall transportation expenses, while time-oriented problems prioritize swift delivery, emphasizing the importance of meeting urgent schedules [8]. **Table 1** explains a simple transportation problem matrix:

Table 1 presents a simple matrix model as one of the main problems of linear programming and transportation problems. The matrix has four origins and four destinations where each pair has a transportation cost c_{ij} , for $i = 1, 2, 3, 4$ and $j = 1, 2, 3, 4$.

The Least Cost Method, North West Corner Method, and Vogel's Approximation Method are basic techniques used to solve transportation problems, each offering different ways to lower costs and allocate resources effectively, even when there are uncertainties and unclear data.

The Least Cost Method (LCM) is pivotal for directing resources to the least-cost cells in a transportation matrix, aiming to minimize overall transportation expenses. Recent enhancements to LCM have focused on improving its efficiency and effectiveness in real-world applications [9].

The North West Corner Method (NWCM) serves as a practical starting point for transportation problems, but its limitations in optimality have led to advancements

	D1	D2	D3	D4
S1	c11	c12	c13	c14
S2	c21	c22	c23	c24
S3	c31	c32	c33	c34
S4	c41	c42	c43	c44

Table 1.
The simple transportation problem matrix [7].

that incorporate fuzzy logic. These developments allow NWCM to better manage uncertainties, thereby refining its approach to complex transportation issues characterized by imprecise data [10].

Vogel's Approximation Method (VAM) is highly valued for its skill in finding suitable solutions by reducing the costs that come from mismatches between supply and demand, making resource distribution more efficient [11].

The simplex method, created by George Dantzig, is a key technique in linear programming that finds the best solutions by repeatedly exploring the possible options set by the constraints until it arrives at the best point [12].

The study [13] has presented a new version of the simplex-type algorithm designed for transportation problems with fuzzy parameters, using fuzzy logic to enhance decision-making in uncertain situations, which creates a strong optimization framework.

3. Materials and methods

The methodology used in this chapter is an adaptation of several methods for solving the transportation problem. In particular, the study examines three initial methods and one in-depth method. They are used to achieve an initial balanced solution to the transportation problems of this study: The North-West Corner Method, the Least Cost Method, and the Vogel Method. These methods are used to find initial solutions, which are then used to analyze and optimize the possible transportation routes in a given warehouse transportation problem. In addition, an advanced method, known as the Simplex Method, is also used to find more optimized solutions in this company. These methods are explained in detail and are used to analyze and optimize the possible transportation routes. Problem modeling is a key step in solving the transportation problem. This involves formulating a mathematical problem for linear programming for resource allocation. Mathematical modeling is a way to demonstrate a current and real-world need for mathematics. To solve the transportation problem in this study, the problem formulation was done by defining the objective function and constraints on the decision variables. The objective function was defined to minimize an overall cost value, while the constraints were related to the resource requirements and constraints.

Overall, the methodology used in this study is clear and structured, including the necessary steps for modeling, solving, and analyzing the transportation problem. This provides a solid basis for evaluating the performance of the solutions and for possible proposals for improvements in the analyzed study.

3.1 Problem modeling

Formulating a mathematical problem in linear programming for allocating resources to activities requires a clear definition of the objective function and constraints on the decision variables. Mathematical modeling is a way to demonstrate a current and real-world need for mathematics. Suppose a company has m origins and n destinations. A product is to be moved from origin m to destination n . Each warehouse or manufacturing plant has a certain level of supply, and each retail market has a certain level of demand. The cost of transportation between each origin–destination pair is also given, and these costs are assumed to be linear.

Suppose that:

The total supply of a product is denoted by $i = a$, where $i = 1, 2, 3, \dots, m$.

The total market demand is denoted by $j = b$, where $j = 1, 2, 3, \dots, n$.

The cost of shipping per unit of each product from origin m to destination n is denoted by c_{ij} , where $i = 1, 2, 3, \dots, m$ and $j = 1, 2, 3, \dots, n$. The total cost of transport is linear in the size of the product transported.

3.2 Objective function

For a resource allocation problem, the objective function is a defined sum of the contribution of each activity to the overall performance. This expression can be linear, with a combination of lines of activities and their contributions to performance.

Maximization: The goal is to maximize an overall performance value, for example, profit or production:

$$\text{Max } Z = c_1x_1 + c_2x_2 + \dots + c_nx_n.$$

Minimization: The goal is to minimize an overall performance value, for example, cost or production time:

$$\text{Min } Z = c_1x_1 + c_2x_2 + \dots + c_nx_n.$$

Where:

Z is the overall performance value.

$x_1, x_2, \dots, x_n$ are the levels of activities to be set (decision variables).

$c_1, c_2, \dots, c_n$ are the contributions to the performance of the respective activities.

The main objective of this material is to examine and discover ways in which linear programming can be used to minimize transportation costs in an industrial company. To this end, I have described transportation problems and the use of linear programming algorithms for their solution. The model is useful for making strategic decisions involved in choosing optimal transportation routes in order to distribute the production of different origins to several warehouses or distribution centers. The research aims to present a detailed approach to this problem and provide a contribution to the field of operations research and management sciences. This objective contains the development of the following subtopics:

1. Identifying the structure of the company's transportation networks: Drawing up a clear vision of the flow of product and services within the company, identifying and mapping the structure of the transportation networks in order to better understand the organization of the transportation process.
2. Determining the mode of movement of finished products considering the country of origin, destinations and routes used: Analysis of routes and modes of transport to ensure an efficient and fair movement of products from the country of origin to the designated destinations, including the identification of the most favorable routes and the way to organize transport.
3. Optimization of the transport process: Use of linear programming, the Simplex method, to identify optimal solutions that minimize transport costs and optimize the efficiency of the transport network, using information technology tools and data analysis to improve the transport process.

The main purpose of this chapter is to examine linear programming problems in detail, considering a manufacturing company. The purpose of the problem in this case

is to determine the optimal quantity that should be used to minimize the total cost of transportation from origin to destination while satisfying supply and demand constraints, in order to increase sales profit. The aim is to define the problems of minimizing total transportation costs by determining the optimal distribution of the product from the three production sites to the six main distributors that are geographically distributed. This purpose contains in itself the examination of several main subtopics, which are:

1. Identifying and implementing strategies to improve the movement of product and reduce the time and costs of transportation through the company's network: Developing and implementing transportation strategies and policies to improve the efficiency and performance of the company's transportation network.
2. Identifying ways to reduce cost–time through optimization of the transport network, including the use of more efficient routes and organizing the way of delivery of product: Finding and implementing new and more efficient ways to reduce the cost–time of transport, using technology and advanced methods of planning the transport network.
3. Improving customer service: Ensuring on-time supply and product quality through efficient and organized transport: Improving customer service by ensuring convenient and efficient transport of product, guaranteeing their arrival on time, and meeting quality standards.

By identifying the objectives and goals of the work to optimize the transport process, as well as including the different types of transport problems that may be faced, this chapter makes a good attempt to present the need and importance of solving these challenges in manufacturing companies in Albania.

This study provides a comprehensive analysis of the transportation costs incurred by a company specializing in the production of water storage tanks. It includes detailed data on unit transportation costs for each item shipped from various origins to their respective destinations. Specifically, there are three origins involved in the production or storage of the tanks, and these are responsible for distributing products to six destinations, which serve as sales points. The study aims to analyze and optimize the transportation logistics, considering both the direct costs of transporting the product and the overall efficiency of the distribution network. By examining these costs, the company seeks to identify opportunities for cost reduction and improve the effectiveness of its supply chain operations.

The balanced problem, where the production capacity equals the demand from the destinations, has been the subject of analysis. We can mathematically formulate the transportation problem as a linear function and address it within the framework of linear programming problems. We define the costs associated with transporting product between various origins and destinations as linear.

For the basic examination of the transportation problem, three classical primary methods have been used: The Least Cost Method, Vogel's Approximation Method, and the North West Corner Method. **Figure 1** presents the algorithm.

The first method applied is the North West Corner (NWC) Method. This approach begins by allocating resources from the northwest cell of the cost matrix and then systematically progresses through the other cells to establish a feasible solution [14, 15].

The second method employed is the Least Cost Method. This approach focuses on identifying the cell with the lowest transportation cost and begins allocations

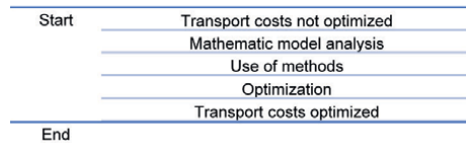


Figure 1.
Method algorithm (Source: Author).

from there. By focusing on the lower-cost cells first, this method tries to reduce total transportation costs while carefully working through the cost matrix to find a workable solution [7].

The third method utilized is Vogel's Approximation Method (VAM). This approach involves an iterative process that considers the cost of transportation in a relative manner. VAM aims to minimize the total transportation cost by calculating penalties for not selecting the lowest-cost cells, allowing for a more efficient allocation of resources [11].

For further optimization, people often employ the Simplex Method, a more advanced and sophisticated technique. This method starts with the final table obtained from one of the three basic methods.

In the Simplex Method, the costs for each cell in the transport table are calculated as $c_{ij} = u_i + v_j$.

In the above equation, u_i and v_j represent the potentials associated with the supply and demand nodes, respectively.

Additionally, the opportunity cost for each cell is $w_{ij} = u_i + v_j - c_{ij}$, which helps in determining the cost-effectiveness of potential reallocations. This opportunity cost indicates the potential savings or additional costs associated with making changes in the allocation of resources.

4. Case study and analysis of results

4.1 Problem model for optimization

We have studied the case of a company in Albania that produces plastic tanks. Plastic tanks are becoming increasingly important as primary storage for drinking water or as secondary storage for water reserves. Plastic tanks are usually made from UV-treated polyethylene.

This means they are long-lasting, structurally strong, and resistant to sun damage. The production of plastic containers goes through several different processes: The deposit design process, the production process, the baking process, the cooling process, removing the plastic deposit from the mold, and tests. **Figure 2** shows the raw material in the form of granules.

The plastic tank factory produces plastic tanks that vary in size and capacity, ranging from small 500-liter tanks to 5000-liter tanks. The factory produces three different types of plastic tank structures, which are: horizontal plastic tanks, vertical plastic tanks, and square plastic tanks. The final products (**Figure 3**) are plastic containers of various sizes.

With three manufacturing plants in different cities, the company is committed to providing quality products and meeting the demands of its customers efficiently. Through this analysis, the aim is to identify the main trends and factors affecting the



Figure 2.
Raw material in the form of granules (Source: Author).

company's performance, including challenges and opportunities for revenue growth and operational efficiency. This analysis will provide a deep understanding of the company's performance and will help in developing future strategies for sustainable success in the deposit market.

The purpose of analyzing transportation data is to determine the most efficient way to transfer product from the source to the destination while minimizing the total transportation costs by identifying the quantities. The model involves optimizing the transportation of product from three origins to six destinations. The constraints include the maximum capacity at each origin and the specific demand at each destination.

In the transportation problem network for the company that manufactures water storage tanks, there are three production origins and six distribution destinations. The production origins (S_i) are the facilities where the tanks are manufactured and stored. The distribution destinations (D_j) are the warehouses where the tanks are delivered. The challenge is to determine the optimal shipment quantities from each production facility to each warehouse to minimize the total transportation costs while satisfying the production capacities and meeting the demand at each warehouse (**Figure 4**).



Figure 3.
Vertical plastic tanks 5000 liters produced by the plastic tank factory (Source: Author).

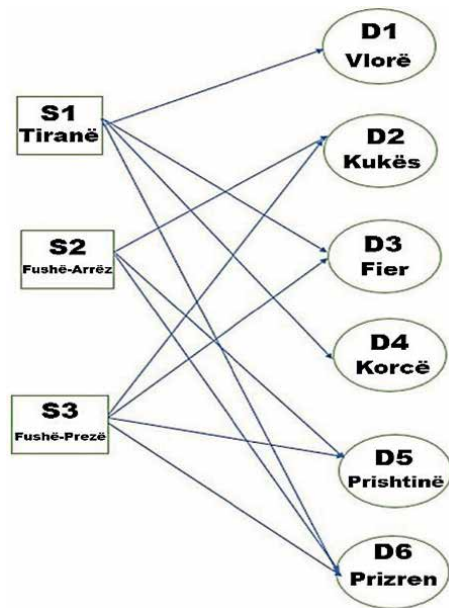


Figure 4.
The transportation problem network in our case (Source: Author).

S_i represents the source of the i -th for the production, $i = 1, 2, 3$.
 D_j is the destination of the j -th warehouse for $j = 1, 2, 3, 4, 5, 6$.
 C_{ij} : unit cost of transportation from i to j .

1. Production of Tanks: Tanks are produced at three identified manufacturing facilities, referred to as S1, S2, and S3. Each facility has different capacities and specifications to meet market demands.
2. Inventory Control: After production, inventory checks are performed to ensure sufficient availability of tanks. Subsequently, the tanks are loaded onto trucks for transportation to designated sales points identified as D1, D2,..., D6.
3. Transportation of Tanks: The tanks are loaded and transported from facility S _i to sales point D _j for $i = 1, 2, 3$ and $j = 1, 2, 3, 4, 5, 6$.
4. Demand and Supply Comparison: A comparison is made between demand and supply to ensure that inventory levels meet market needs.
5. Distance Measurement and Cost Identification: During the process, distances are measured, and transportation costs are identified to optimize the logistics and ensure efficient delivery.

Figure 5.
Operational workflow for water tank transport.

S₁ is the production factory in Tirana, S₂ is the production factory in Fushë – Arrëz, S₃ is the Production factory in Fushë-Prezë.

Figure 5 explains the process for transporting water tanks:

The transportation problem is considered balanced because the total supply available from all sources exactly equals the total demand required at the destinations. In this case, the total capacity of the three sources is 709 units. Transportation costs, capacities, and demands for the water storage tank manufacturing company show the cost per unit to transport tanks from three sources (S₁, S₂, and S₃) to six destinations (D₁ through D₆). Each source has a maximum supply capacity: S₁ can supply up to 150 units, S₂ up to 130 units, and S₃ up to 429 units. The table also lists the demand at each destination, with D₁ requiring 266 units, D₂ needing 119 units, D₃ having a demand of 106 units, D₄ requiring 45 units, D₅ having a demand of 102 units, and D₆ needing 71 units. The main objective is to optimize the transportation plan to minimize total costs while fulfilling both the supply capacities and the demand at each destination (**Table 2**).

4.2 The use of the north west corner method

In the North West Corner Method, the first action involves selecting the top-left corner of the matrix, cell S₁-D₁, and allocating the maximum possible units to it based on supply and demand constraints. Specifically, since the supply at S₁ is 150 units and the demand at D₁ is 266 units, we allocate 150 units to S₁-D₁. This allocation reduces the demand at D₁ to 116 units, and since the supply at S₁ is empty, we eliminate the row S₁ from the matrix (**Table 3**).

From \ To	D1	D2	D3	D4	D5	D6	Capacity (units)
S1	64.96	312.5	270	432	215.686	720	150
S2	540	205.2	338.983	630	456.92	1828.57	130
S3	75.187	1421.05	244.071	550	540	1080	429
Demand (units)	266	119	106	45	102	71	

Source: Author.

Table 2.
 Matrix of costs, capacities, and demands.

From \ To	D1	D2	D3	D4	D5	D6	Capacity (units)
S1	64.96 150	312.5	270	432	215.686	720	0
S2	540	205.2	338.983	630	456.92	1828.57	130
S3	75.187	1421.05	244.071	550	540	1080	429
Demand (units)	116	119	106	45	102	71	

Source: Author.

Table 3.
 North West corner method, first iteration.

The method follows a systematic approach to ensure all supply and demand requirements are met. It moves to the next available cell to the right, allocating 116 units from S_2 to D_1 , leaving a remaining demand of 14 units at D_1 (Table 4).

The method then shifts to D_2 and allocates the remaining 14 units from S_2 , fulfilling D_1 demand and eliminating the first column. The process continues by allocating 105 units from S_3 to D_2 , then moving horizontally to allocate 106 units from S_3 to D_3 , and finally fulfilling the remaining demands in subsequent cells until all demands are met and the supply-demand balance is achieved.

The table becomes balanced, with all demands and supplies allocated, confirming that the problem is resolved (Table 5).

Minimization: $f(x) = 64.96 * 150 + 312.5 * 0 + 270 * 0 + 432 * 0 + 215.686 * 0 + 720 * 0 + 540 * 116 + 205.2 * 14 + 338.983 * 0 + 630 * 0 + 456.92 * 0 + 1028.57 * 0 + 75.187 * 0 + 1421.05 * 105 + 241.071 * 106 + 550 * 45 + 540 * 102 + 1080 * 71 = 406530.576$ ALL/year.

From \ To	D1	D2	D3	D4	D5	D6	Capacity (units)
S1	64.96 150	312.5	270	432	215.686	720	0
S2	540 116	205.2	338.983	630	456.92	1828.57	14
S3	75.187	1421.05	244.071	550	540	1080	429
Demand (units)	0	119	106	45	102	71	

Source: Author.

Table 4.
 Second iteration using the North West corner method.

From \To	D1	D2	D3	D4	D5	D6	Capacity (units)
S1	64.96 150	312.5	270	432	215.686	720	0
S2	540 116	205.2 14	338.983	630	456.92	1828.57	0
S3	75.187	1421.05 105	244.071 106	550 45	540 102	1080 71	0
Demand (units)	0	0	0	0	0	0	

Source: Author.

Table 5.
North West corner method, final table.

The total cost, as computed from the North West Corner Method, amounts to 406,530.576 ALL/year. This total cost provides a measure of the efficiency and effectiveness of the transportation plan established.

4.3 The use of the least cost method

In the Least Cost Method for transportation problems, the allocation process begins by selecting the cell with the lowest transportation cost. In this instance, the cell with the minimum cost is $S_1 - D_1$. The cell's maximum units are the lesser of the supply at S_1 and the demand at D_1 . Given the 150 units of supply at S_1 and the 166 units of demand at D_1 , we allocate 150 units to S_1-D_1 . This allocation utilizes the full supply from S_1 and leaves a remaining demand of 116 units at D_1 ($266-150 = 116$). Given the depletion of S_1 , **Table 6** removes the row corresponding to S_1 from further consideration (**Table 6**).

The second cell with the lowest cost is $S_3 - D_1$. Since S_3 has a supply of 429 units and D_1 has a demand of 116 units, 116 units are allocated to $S_3 - D_1$. This allocation utilizes 116 units from S_3 , fully satisfying D_1 demand. Consequently, the remaining supply at S_3 was 313 units ($429-116 = 313$). The demand for D_1 has been fully satisfied leading to the removal of the D_1 value from **Table 7**.

The final allocation table shows the reduced transportation cost obtained using the Least Cost Method, which successfully moves resources from suppliers to customers while meeting all needs and following supply limits (**Table 8**). Each allocation is strategically chosen based on the lowest costs, ensuring efficient resource use and

From \To	D1	D2	D3	D4	D5	D6	Capacity (units)
S1	64.96 150	312.5	270	432	215.686	720	0
S2	540	205.2	338.983	630	456.92	1828.57	130
S3	75.187	1421.05	244.071	550	540	1080	429
Demand (units)	116	119	106	45	102	71	

Source: Author.

Table 6.
Initial allocation using the least cost method.

From \To	D1	D2	D3	D4	D5	D6	Capacity (units)
S1	64.96 150	312.5	270	432	215.686	720	0
S2	540	205.2	338.983	630	456.92	1828.57	130
S3	75.187 116	1421.05	244.071	550	540	1080	313
Demand (units)	0	119	106	45	102	71	

Source: Author.

Table 7.
 Second allocation using the least cost method.

From\To	D1	D2	D3	D4	D5	D6	Capacity (units)
S1	64.96 150	312.5	270	432	215.686	720	0
S2	540	205.2 119	338.983	630	456.92 11	1828.57	0
S3	75.187 116	1421.05	244.071 106	550 45	540 91	1080 71	0
Demand (units)	0	0	0	0	0	0	

Source: Author.

Table 8.
 Final table with all allocations using the least cost method.

confirming that total supply matches total demand in a balanced problem. This table serves as a critical tool in logistics, providing a clear overview of optimal allocations that minimize overall transportation costs.

Minimize: $f(x) = 64.96 * 150 + 312.5 * 0 + 270 * 0 + 432 * 0 + 215.686 * 0 + 720 * 0 + 540 * 0 + 205.2 * 119 + 338.983 * 0 + 630 * 0 + 456.92 * 11 + 1028.57 * 0 + 75.187 * 116 + 1421.05 * 0 + 241.071 * 106 + 550 * 45 + 540 * 91 + 1080 * 71 = 224034.138$ ALL/year.

In total, 150 units are transported from S_1 to D_1 , while 119 units move from S_2 to D_2 . An additional 11 units are dispatched from S_2 to D_5 . We allocate 116 units from S_3 to D_1 , 106 units to D_3 , 45 units to D_4 , 91 units to D_5 , and 71 units to D_6 .

The total transportation cost, calculated based on these allocations and their respective rates, amounts to 224,034.138 ALL/year (ALL is the currency code for Albanian Lek). This value represents the minimum cost to satisfy all supply and demand constraints while adhering to the least cost routing principles [16, 17].

4.4 The use of Vogel's approximation method

Vogel's Approximation Method is based on the penalty costs associated with unmet demands or excess supplies. Penalty cost is the difference between the smallest and the second smallest costs in the respective row or column. Each row and column add penalties based on the difference between the smallest and the second smallest costs [16, 17].

After calculating these penalties, it is observed that the highest penalty is found in the sixth column, with a value of 308.57. The cell with the lowest cost is $S_1 - D_6$, where

From\ To	D1	D2	D3	D4	D5	D6	Capacity (units)	Row Penalty
S1	64.96	312.5	270	432	215.686	720	150	150.726
S2	540	205.2	338.983	630	456.92	1028.57	130	133.783
S3	75.19	1421.1	241.071	550	540	1080	429	165.884
Demand (units)	266	119	106	45	102	71		
Column penalty	10.227	1073	28.929	118	241.234	308.57		

Source: Author.

Table 9.
Vogel's approximation method (first allocation).

From\ To	D1	D2	D3	D4	D5	D6	Capacity (units)	Row Penalty
S1	64.96 79	312.5	270	432	215.686	720	0	—
S2	540 11	205.2 119	338.983	630	456.92	1028.57	0	—
S3	75.19 176	1421.1	241.071 106	550 45	540 102	1080	0	—
Demand (units)	0	0	0	0	0	0		
Column penalty	—	—	—	—	—	—		

Source: Author.

Table 10.
Final table by using Vogel's approximation method.

the demand was 71 units. The supply capacity is 150 units. Despite this cell having the lowest cost, it is important to consider that it can fulfill the demand of 71 units while utilizing only a part of its total capacity. This data indicates that the sixth column represents the most significant opportunity cost for not allocating resources to it, guiding the decision-making process to minimize overall costs effectively (**Table 9**).

The final state demonstrates that the transportation problem has been resolved completely, with all product allocated according to the minimal cost approach, and no further adjustments or penalties are required (**Table 10**).

Minimize: $f(x) = 64.96 * 79 + 312.5 * 0 + 270 * 0 + 432 * 0 + 215.686 * 0 + 720 * 71 + 540 * 11 + 205.2 * 119 + 338.983 * 0 + 630 * 0 + 456.92 * 0 + 1028.57 * 0 + 75.187 * 176 + 1421.05 * 0 + 241.071 * 106 + 550 * 45 + 540 * 102 + 1080 * 0 = 205227.078$ ALL/year.

4.5 The use of the simplex method

To apply the Simplex method in transportation problems, the process begins by using the final table obtained from Vogel's Approximation Method. Initially, one assigns a base value, often $u_1 = 0$, to simplify calculations. We determine the potential for each supply and demand node using this base value.

From\To	D1	D2	D3	D4	D5	D6	
S1	64.96 79	312.5	270	432	215.686	720	$u_1 = 0$
S2	540 11	205.2 119	338.983	630	456.92	1028.57	$u_2 = 475.04$
S3	75.19 176	1421.1	241.071 106	550 45	540 102	1080	$u_3 = 64.96$
$v_1 = 64.96 \quad v_2 = -269.84 \quad v_3 = 230.841 \quad v_4 = 319.159 \quad v_5 = 309.759 \quad v_6 = 720$							
Source: Author.							

Table 11.
Simplex method based on Vogel's approximation method.

From\To	D1	D2	D3	D4	D5	D6	
S1	64.96	312.5	270	432	215.686 79	720	u1 = 0
S2	540	205.2 119	338.983	630	456.92 11	1028.57	u2 = 241.234
S3	75.19 266	1421.1	241.071 106	550 45	540 12	1080	u3 = 324.314
v1 = -249.124 v2 = -10.486 v3 = -83.243 v4 = 225.686 v5 = 215.686 v6 = 720							
Source: Author.							

Table 12.
Simplex Method, final result.

We apply this method similarly to all cells in the table. If the opportunity cost w_{ij} is negative for every cell, it indicates that no further optimization is needed, as reallocations would increase costs. However, if there are cells with positive opportunity costs, these cells present opportunities for cost reduction, and reallocations should be made to optimize the overall transportation costs (**Table 11**). After completing several iterations by using the Simplex Method, all opportunity costs have turned negative. This result indicates that the transportation problem has reached an optimal solution. The negative values suggest that any further reallocation would increase costs, confirming that the current allocation minimizes the total transportation cost (**Table 12**).

Minimize: $f(x) = 64.96 * 0 + 312.5 * 0 + 270 + 432 * 0 + 215.686 * 79 + 720 * 0 + 540 * 0 + 205.2 * 119 + 338.983 * 0 + 630 * 0 + 456.92 * 11 + 1028.57 * 0 + 75.187 * 266 + 1421.05 * 0 + 241.071 * 106 + 550 * 45 + 540 * 12 + 1080 * 0 = 123537.382$ ALL/year.

Calculating the minimized total transportation cost yields an annual cost of 123,537.38 ALL. This systematic approach ensures efficient resource distribution while minimizing overall costs in the transportation network.

Table 13 provides a detailed summary of transportation costs and allocations across four different methods: The North West Corner Method (NWCM), the Least Cost Method (LCM), Vogel's Approximation Method (VAM), and the Simplex Method. Each method aims to optimize the allocation of product from supply sources to demand points while minimizing overall costs.

	NWCM	LCM	VAM	Simplex method
x_{11}	150	150	79	0
x_{12}	0	0	0	0
x_{13}	0	0	0	0
x_{14}	0	0	0	0
x_{15}	0	0	0	79
x_{16}	0	0	0	0
x_{21}	116	0	11	0
x_{22}	14	119	119	119
x_{23}	0	0	0	0
x_{24}	0	0	0	0
x_{25}	0	11	0	11
x_{26}	0	0	0	0
x_{31}	0	116	176	266
x_{32}	105	0	0	0
x_{33}	106	106	106	106
x_{34}	45	45	45	45
x_{35}	102	91	102	12
x_{36}	71	71	0	0
Cost	406,530.576	224,034.138	205,227.078	123,537.382

Source: Author.

Table 13.
Summary of transportation costs and allocations by method.

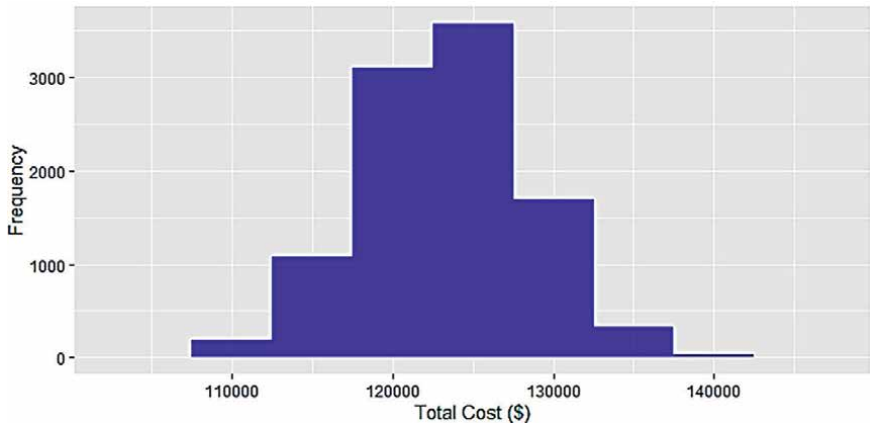


Figure 6.
Monte Carlo simulation of transportation costs (Source: Author).

5. Digitalization and the use of Monte Carlo simulation

After implementing the Simplex Method to optimize transportation costs, the Monte Carlo simulation was used to account for the uncertainty and variability in costs. In real-world transportation problems, costs are rarely fixed and can fluctuate due to factors such as fuel price changes, demand shifts, or disruptions in the supply chain. The Monte Carlo method allows for the simulation of these uncertainties, providing a range of potential cost outcomes. Instead of relying on a single, fixed cost estimate, this approach enables decision-makers to understand how transportation costs might vary under different conditions [16, 18].

The simulation provides valuable statistical insights, such as the mean and standard deviation of transportation costs. The mean represents the expected total transportation cost, while the standard deviation quantifies the risk or variability in the cost. These metrics are crucial for assessing the robustness of the transportation plan and understanding the level of risk that can be tolerated [17, 19, 20].

We used R for the Monte Carlo simulation. The results of the Monte Carlo simulation (**Figure 6**) indicate that after running 10,000 iterations, the estimated mean total cost is 123,301.53 ALL per year. We applied a 10% standard deviation of the cost to simulate the fluctuations. However, the simulation also acknowledges that in real-world scenarios, costs can vary due to external factors such as fuel price fluctuations or changes in demand and supply chain dynamics.

Alongside the mean cost, the standard deviation of the total cost is 5058.25 ALL, which reflects the potential risk in the total transportation cost. This approach provided valuable insights into the potential fluctuations of costs, helping decision-makers assess risk and make more informed choices for optimizing transportation operations.

6. Conclusions

The main objective of this study is to identify in the company that was studied, the most cost-effective method for transporting product from multiple supply sources to various demand points while meeting supply and demand constraints. We employed

several methods to tackle the transportation problem, each offering distinct advantages in cost minimization. Some limitations during the study were:

Resource Constraints: For any resource (e.g., materials, time, and workers), the sum of the resources required by all activities cannot be greater than the available quantity of that resource.

Structural Feature Constraints: For example, in some cases, activities may require a minimum quantity of a resource to function effectively.

Technological or Commercial Constraints: For some activities, there may be technological constraints that determine how much of a resource can be produced or used.

The Least Cost Method generated a total cost based on the lowest cost cells for allocations but failed to reach optimal savings. In contrast, the North West Corner Method provided a higher initial cost, illustrating its limitations in cost efficiency.

Vogel's Approximation Method, which adds extra costs for unmet demands, greatly improved the solution by focusing on cost efficiency and matching earlier research.

The Simplex Method, building on Vogel's results and optimizing further, achieved the lowest total cost. This approach confirmed the optimality of the solution and showcased its effectiveness in maximizing cost efficiency for transportation problems.

Overall, the findings indicate that the North West Corner Method and Least Cost Method serve as a basic starting point, while the Vogel's Approximation and particularly the Simplex Method are more effective strategies for minimizing transportation expenses in this scenario, supported by the findings of the study.

The simulation provides valuable statistical insights, such as the mean and standard deviation of transportation costs.

Future research in transportation problem optimization should focus on several key areas. By incorporating dynamic cost models and handling uncertainties in supply and demand, it can improve real-world applicability. Choosing the right transportation method is not a simple process and other factors such as time, resources needed to implement the method, and company objectives must be considered. This analysis suggests a continuing challenge for the company in using different methods to achieve maximum efficiency in transporting the product.

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Conflict of interest

The authors declare no conflict of interest.

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Section 2

Sustainable and Resilient Supply Chains

A GRI-Based Decision Framework for Sustainable Supply Chains: Integrating BSC and Performance Prism

Ali Goharshenasan

Abstract

In today's interconnected world, the supply chain stands as the backbone of organizational success, demanding relentless focus on performance enhancement—particularly in sustainability, spanning economic, social, and environmental dimensions. This study pioneers a novel decision-making model for supply chain sustainability, leveraging Global Reporting Initiative (GRI) indicators through an innovative fusion of the Balanced Scorecard (BSC) and Performance Prism frameworks. The research identifies pivotal sustainability metrics *via* multivariate analysis, distilling core GRI indicators. By extending the BSC dimensions—supplier, learning and growth, internal processes, customer, and financial perspectives—an interconnected supply chain structure emerges. GRI and Performance Prism indicators are then meticulously ranked across this framework using Quality Function Deployment (QFD) and multi-criteria decision-making tools. A three-dimensional sustainability cube visually captures the Performance Prism variables' interplay across economic, social, and environmental axes. Key findings reveal the social dimension undergoing the most significant variable reduction, while the economic dimension remains least affected. The QFD analysis further highlights the cascading influence of Performance Prism perspectives—like supply chain linkages—across extended BSC components. Notably, in the social dimension, *Strategies* emerge as paramount, whereas *Capabilities* trail; economically, *Stakeholder Engagement* dominates, with *Strategies* at the lowest rank. Environmentally, *Capabilities* take precedence, while *Processes* rank least within the financial lens. This model not only advances sustainable supply chain governance but also equips managers with actionable insights to navigate the triple-bottom-line imperative.

Keywords: supply chain, sustainable supply chain, GRI standard, balanced scorecard, performance prism, SSC, BSC, QFD

1. Introduction

1.1 Problem statement

Today, many industries aim to enhance productivity, and one of the most significant ways to achieve this is by improving the efficiency and effectiveness of the

supply chain. By accurately identifying the key indicators—particularly those related to sustainable supply chains—organizations can be guided toward greater productivity through strategic improvement initiatives.

This research seeks to develop strategies that improve organizational productivity using various analytical tools. The balanced scorecard (BSC) model, as discussed in the works of Kanji [1], Rifki and Terouki [2, 3], and Kaplan and Norton [4], has the potential for further development. Previous studies have not explored the enhancement of the BSC model, focusing instead on performance evaluation across its traditional four perspectives: financial, learning and growth, internal processes, and customer [5]. However, it is possible to extend the BSC by incorporating an additional “supplier” dimension, referred to as a non-market perspective, in studies by Kanji [1], Rifki and Terouki [2, 3], and Kaplan and Norton [4].

The feasibility of adding the supplier dimension to the BSC is further supported by the SIPOC (Suppliers, Inputs, Process, Outputs, Customers) model. A one-to-one correspondence can be observed between SIPOC and the BSC—except that the BSC lacks a dedicated “supplier” component. This research seeks to bridge that gap. In the SIPOC model, the five components—Supplier, Input, Process, Output, and Customer—mirror the extended BSC, forming a supply chain of information flow. This relationship can be explained as follows:

- The “*Supplier*” dimension in the extended BSC directly corresponds to the “*Supplier*” in SIPOC.
- The “*Learning and Growth*” dimension corresponds to “*Input*” in SIPOC, representing organizational inputs aimed at development and innovation.
- The “*Internal Process*” dimension aligns with “*Process*” in SIPOC.
- The “*Financial*” perspective equates to “*Output*,” as it reflects the overall organizational outcomes.
- The “*Customer*” dimension in BSC directly matches the “*Customer*” in SIPOC.

Based on this alignment, the components of SIPOC can be mapped to the proposed extended BSC model, allowing the BSC to be used as an information flow chain—essentially, a supply chain.

Most researchers in the field, such as Nikolaou and Tsalis [6] and Houck et al. [7], have used the BSC model solely for performance evaluation or strategic management in supply chains without considering its inherent chain-like structure. This study proposes a new application for the BSC, positioning it not just as a strategic measurement tool but as a framework for modeling supply chain information flows—starting from suppliers and ending with financial outcomes.

Sustainability in supply chains involves the integration of three key dimensions: economic, social, and environmental. This research overlays these sustainability dimensions onto the extended BSC structure, treating it as a chain of interconnected information nodes. Each node (dimension) is evaluated based on its contribution to sustainability.

The term “*supply chain*” in this research refers to the sequence of linked elements derived from the extended BSC model, arranged similar to the SIPOC structure. While previous research (e.g., [7]) has applied BSC in strategic planning, this study expands its application beyond strategy execution into sustainable supply chain management.

Another performance measurement tool, the *Performance Prism*, evaluates organizational performance based on stakeholder satisfaction, stakeholder contribution, strategies, capabilities, and processes. Unlike the BSC, which inherently models a sequence of interdependent perspectives, the Performance Prism offers a supportive evaluation framework, aiming to achieve stakeholder satisfaction through the coordinated use of strategies, capabilities, and processes. By integrating the Performance Prism within the extended BSC structure, this research addresses an existing gap by creating a hybrid tool for assessing both internal and external sustainability dimensions.

After defining the supply chain using the extended BSC, sustainability performance indicators for the supply chain are reviewed. Given the outdated and inconsistent nature of many existing indicators, the *Global Reporting Initiative (GRI)* standards are adopted as a comprehensive and regularly updated framework. Although the GRI standard offers a wide array of indicators, their sheer number has been cited as a limitation [8]. To overcome this, *multivariate analysis* is used to reduce the number of variables and retain only the most relevant ones.

1.2 Rationale for GRI framework selection

Over 80% of Fortune 500 companies now use GRI reporting [9], ensuring our model aligns with prevailing industry practice and facilitates benchmarking.

The selection of the Global Reporting Initiative (GRI) standards as the foundation for this supply chain sustainability model is based on three compelling factors that address critical gaps in existing approaches:

First, GRI provides the most comprehensive and regularly updated set of sustainability indicators, covering all three dimensions of sustainability (economic, environmental, and social) with 84 standardized metrics [10]. This breadth enables holistic assessment of supply chain impacts that narrower frameworks like the Dow Jones Sustainability Index (DJSI) (focused on financial performance) or ISO 50001 (energy-specific) cannot match.

Second, GRI's modular structure allows for supply chain-specific adaptation. As demonstrated by Nikolaou and Tsalis [6], GRI indicators can be effectively mapped to supply chain processes while maintaining comparability across industries—a crucial advantage for multi-tier supply chain analysis.

Third, GRI's stakeholder-inclusive approach aligns with modern supply chain requirements. Unlike traditional models that focus solely on internal metrics, GRI explicitly considers upstream (supplier) and downstream (customer) impacts [11]. This makes it particularly suitable for integration with the Performance Prism's stakeholder dimension in our proposed model.

The annual revision process of GRI standards (last updated June 2022) ensures the framework incorporates emerging sustainability challenges—from carbon emissions tracking [12] to modern slavery risks in supply chains [13]—making it more future-proof than static alternatives.

Despite the existence of tools such as quality function deployment (QFD), multivariate analysis, Performance Prism, and GRI, no prior research has combined all of these tools to evaluate sustainable supply chains. This study fills that gap by integrating these methodologies to rank performance indicators across the supply chain. This results in a practical, streamlined set of GRI indicators tailored to real-world applications.

Finally, after evaluating the proposed model, the research offers strategies for strengthening sustainable supply chains and conducts a final re-assessment of their sustainability performance.

2. Theoretical foundations

2.1 Sustainable development

In a report titled “Our Common Future” by the World Commission on Environment and Development (WCED), the concept of sustainable development is introduced as follows: “Sustainable development is a type of development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [14].

2.2 Sustainable supply chain (SSC)

The crisis that the world is currently facing regarding resource depletion and the significant decline in social welfare has created both challenges and opportunities for supply chains. The need for the continuity of supply chains in areas such as efficient energy technologies, resource renewal, green procurement, recycling, carbon emission control, social responsibility, and the overall protection of the three fundamental pillars of sustainability was initially recognized by academics and, later, by various industries and sectors of the global economy.

Global operations have led trade to work together in addressing natural crises and the depletion of natural resources. Many businesses and trade partners are now reconstructing their operations into more sustainable forms [15–17].

Therefore, sustainable supply chain management (SSCM) is defined as a method that combines the general goals of supply chain management (SCM) with the emerging overarching goals of sustainability (such as economic, social, and environmental performance). Sustainable supply chain management is an extended version of traditional supply chain management, incorporating the fundamental principles of sustainability [14].

2.3 Sustainability measurement indicators

Joung et al. [18], through a literature review, identified a set of sustainability measurement indicators that are generally available. These indicators include many tools that can be used to measure sustainability in manufacturing processes. A summary of seven sets of sustainability measurement indicators is as follows:

1. *Global Reporting Initiative (GRI)*: A voluntary reporting system for organizations’ sustainability performance, including 84 indicators categorized into three fundamental aspects of sustainability (economic, social, and environmental). In this report, an organization records and reports real values for the individual indicators it selects. The goal of these reports is to evaluate and monitor decisions at various organizational levels, including management, operations, and internal and external stakeholders. One advantage of this method is the possibility of benchmarking; however, a disadvantage is the large number of indicators, making it challenging to select suitable indicators for specific industries [8].
2. *Dow Jones Sustainability Index (DJSI)*: This index evaluates the financial performance and sustainability of leading companies in the global stock market. The results of this index are used as criteria for investment and investment firms. The index assesses a company’s performance in 12 criteria, primarily covering the

economic dimension, though it also includes some aspects of environmental and social dimensions.

3. *Environmental Sustainability Indicators (ESI)*: The 2005 version of these indicators, developed by the Yale Center for Environmental Law and Policy, aims to assess the environmental performance of regions and countries. The environmental sustainability indicator is a single-value index that aggregates six policy categories and 21 key factors, including 68 indicators.
4. *Environmental Performance Index (EPI)*: Developed by Yale University, this index assesses countries' performance in reducing environmental impacts with a focus on human health, ecosystem sustainability, and the management of natural resources. This index includes 19 factors that focus on environmental aspects.
5. *United Nations Commission on Sustainable Development (UN-CSD) Indicators*: These indicators, promoted by the United Nations Commission on Sustainable Development, assess the sustainability level of a country or region. The latest version of these indicators, completed in 2006, includes 96 indicators categorized into 14 groups, covering the economic, social, and environmental health of developed countries.
6. *Core Environmental Indicators (CEI)*: Designed by the Organization for Economic Cooperation and Development (OECD), these indicators monitor environmental conditions for sustainable development in member countries. They consist of 46 sub-indicators that cover a range of environmental, social, and economic issues.
7. *Ford Product Sustainability Index (FORD PSI)*: These indicators specifically focus on sustainability in the production and services related to automobiles. It includes eight indicators that address environmental, social, and economic dimensions.

Among these indicators, the GRI indicators are considered a more suitable and comprehensive criterion for evaluating the sustainability of supply chains. This is primarily due to two reasons: (1) the ongoing annual updates of the GRI report and (2) the comprehensiveness of these indicators compared to others. The indicators under the GRI standard, also known as the Global Reporting Initiative, are updated annually through documentation available on the official website (<https://www.globalreporting.org>). This characteristic sets them apart from other indicators. Furthermore, based on the researcher's analysis, the GRI indicators have higher inclusivity, covering many of the aspects addressed by other indicators and also including specific issues not addressed by others, such as child labor, gender inequality.

2.4 Performance prism

The five dimensions of the performance prism are:

1. *Stakeholder satisfaction*:

- Central Question: "What are the key stakeholders of the organization, and what are their needs/wants?"

- Difference from Traditional Models: Encompasses a wider range of stakeholders (not just customers), including business partners, the local community, suppliers, and others.
- Note: While some groups (such as employees) may not be directly mentioned in this dimension, their indirect impact on organizational performance is significant.

2.Strategies:

- Central Question: “What strategies are necessary to meet the stakeholders’ needs?”
- Strategy Design Logic: Addressing stakeholders’ needs as the starting point for strategy formulation.

3.Processes:

- Central Question: “What business processes are essential for implementing strategies?”
- Examples: Development of new products, demand management, and organizational planning.

4.Capabilities:

- Central Question: “What capabilities (human, technological, infrastructure) are required to implement processes?”
- Feature: A combination of tangible and intangible resources to support both current and future processes.
- Application: The ability to assess and plan for the development or preservation of vital capabilities.

5.Stakeholder engagement:

- Central Question: “How is a two-way relationship with stakeholders established to create shared value?”
- Examples:
 - Organization → Stakeholders: Job security, fair wages, and recognition of contributions.
 - Stakeholders → Organization: Offering suggestions, expertise enhancement, and loyalty (**Figure 1**).

2.5 Decision-theoretic foundations for SSC evaluation

The proposed model is theoretically anchored in three complementary decision-making paradigms that address the complexity of sustainable supply chain (SSC) evaluation:

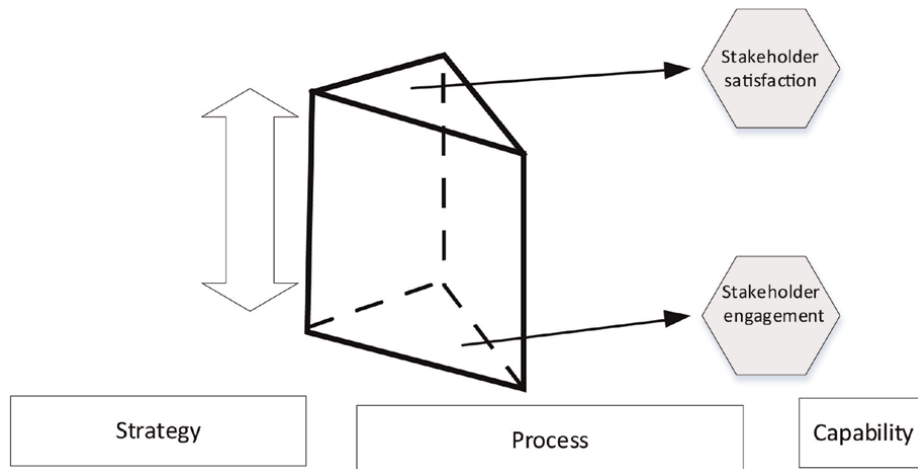


Figure 1.
 The five dimensions of the performance prism [19].

1. Multi-criteria decision analysis (MCDA) Framework

Grounded in Keeney and Raiffa's [20] value-focused thinking, our approach formalizes SSC decisions as:

- A *compensatory* problem (trade-offs between sustainability dimensions).
- With *hierarchical criteria* (GRI indicators → BSC perspectives → Prism dimensions).
- This aligns with contemporary MCDA applications in SSC [21, 22], where TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) has proven effective for sustainability trade-off analysis.

2. Information integration theory [23]

Explains how decision-makers:

- Weight and combine disparate sustainability signals (e.g., economic vs. environmental GRI indicators)
- Reconcile conflicting stakeholder priorities (Performance Prism dimensions)
- Our quality function deployment (QFD) matrices operationalize this through pairwise weighting of criteria.

3. Dynamic capabilities view [24]

Justifies the model's ability to:

- *Sense* sustainability risks (*via* GRI monitoring)
- *Seize* improvement opportunities (through BSC strategic mapping)
- *Transform* supply chain processes (*via* Prism's capability-strategy links)

This tripartite theoretical foundation ensures rigor in handling SSC decisions' inherent:

- *Multi-dimensionality* (economic/social/environmental)
- *Stakeholder heterogeneity*
- *Dynamic interdependencies* (e.g., how supplier capabilities affect environmental compliance?)

2.6 Multivariate analysis (MVA)

Multivariate statistical methods, or multivariate analysis, refer to methods that involve the analysis of more than one variable. The significance of multivariate methods lies in examining the relationships between different attributes (variables). In multivariate analysis, the correlation between variables is considered an important source of information in the data, and utilizing this information leads to more accurate conclusions. In contrast, univariate methods deal with only one variable and do not take the advantage of the correlation with other variables. Some of the multivariate analysis methods include cluster analysis of observations, discriminant analysis, multidimensional scaling, cluster analysis of variables, principal component analysis, item analysis, and factor analysis [25].

2.6.1 Principal component analysis (PCA)

Suppose n observations from p dependent variables are available. The goal of principal component analysis is to find p independent variables—called principal components—that contain the information of the p original variables but are uncorrelated with each other. Often, a large portion of the variability in the p original variables can be accounted for by a few of the first principal components. In this case, the dimensionality of the problem is reduced. Therefore, reducing the dimensionality of the problem is one of the objectives of PCA. From another perspective, PCA serves as a precursor to other multivariate analyses, including item analysis and factor analysis, and can be used for identifying multivariate outliers [25].

2.6.2 Cluster analysis of variables

Suppose n observations for each of the p variables are available. The goal of cluster analysis of variables is to classify the p variables into a cluster structure. In behavioral science research, where a questionnaire is completed by n members of a sample or population, each questionnaire item can be considered a variable. In this case, the questionnaire items can be clustered through variable cluster analysis [25].

3. Research background

- *How and Lam* [26], in a study titled “Using Principal Component Analysis (PCA) to Address Performance Bottlenecks in Integrated Biomass Supply Chains,” aimed to apply PCA to identify bottlenecks in palm production in Malaysia.

The study used the proposed method to address production bottlenecks and provided a comparison with other methods, discussing its strengths and weaknesses. The results suggest that the proposed method effectively identifies production bottlenecks in Malaysia.

- *Ahi and Sarkis* [27], using a literature review method, examined the lack of consensus on how performance should be assessed in sustainable supply chains and provided a solid foundation for academics and professionals using a combined framework and predictive analysis.
- *Safai and Gholamreza Tabr* [28], in a study titled “Establishing a Framework for Evaluating the Sustainability of the Food Supply Chain Using Fuzzy Analytical Network Process and Delphi Method,” proposed a model to determine the importance of various criteria in the sustainability framework of food supply chains.
- *Chiariini* [29], in a study titled “Designing an Environmentally Sustainable Supply Chain through ISO 14001,” sought to determine the commitment of 18 large companies to environmental principles through a structured approach to ISO 14000. According to this study, the stages of achieving sustainability include remaining on the company’s supplier list, the environmental management system, and using key sustainability indicators, ultimately leading to a “green partner” designation.
- *Refki and Teruki* [2, 3] suggested that the systematic relationship between the perspectives and objectives of the balanced scorecard (BSC) model multiplies the independent areas of the supply chain. The dynamic systems approach was used to maximize the benefits of the BSC model, where a non-market dimension can be added to the balanced scorecard and used in the supply chain context, as shown in **Figure 2**.
- *Nikolaou and Tsalais* [6] proposed a framework for assessing sustainability by combining two models: the Global Reporting Initiative (GRI) and the Balanced Scorecard (BSC). Despite the suitability of the sustainable Balanced Scorecard (SBSC) for managing corporate sustainability, only a few empirical studies have

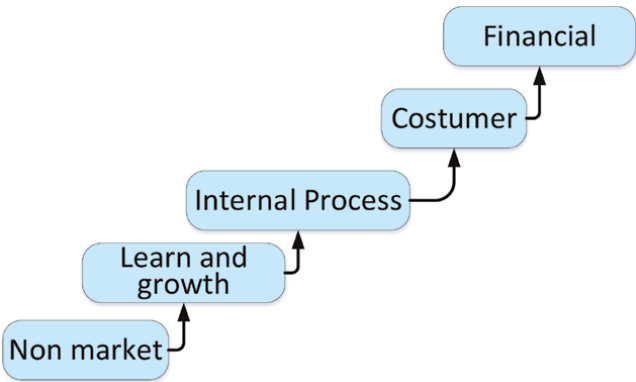


Figure 2.
Supply chain view of the balanced scorecard Nikolaou and Tsalais [6].

Balanced scorecard perspective	Number of indicators	GRI Indicators
Customer Perspective	41	Ec6, Ec9, En9, En11, En12, En13, En14, En15, En25, La1, La2, La3, La4, La5, La6, La7, La8, La9, La12, La13, La14, Hr2, Hr4, Hr5, Hr6, Hr7, Hr9, Pr1, Pr2, Pr3, Pr4, Pr5, Pr6, Pr7, Pr8
Internal Perspective	21	En1, En2, En3, En4, En5, En6, En7, En8, En10, En16, En17, En18, En19, En20, En21, En22, En23, En24, En26, En27, En29
Learning and Growth Perspective	6	La8, La10, La11, Hr3, Hr8, So3
Financial Perspective	11	Ec1, Ec2, Ec3, Ec4, Ec5, Ec8, En28, En30, So6, So8, Pr9

Table 1.
GRI indicators in the balanced scorecard model [6].

been conducted in this area, possibly due to the limited use of the BSC model for addressing common sustainability requirements by companies.

According to Nikolaou and Tsalais [6], the GRI standard dimensions can be mapped to the balanced scorecard model as shown in **Table 1**. Based on this viewpoint, out of 79 GRI indicators, 41 indicators belong to the customer perspective, 21 indicators to the internal perspective, 6 indicators to the learning and growth perspective, and 11 indicators to the financial perspective. These indicators are further classified according to their environmental, economic, and social dimensions.

- *Zailani et al.* [30] evaluated the positive impact of sustainable supply chain management on the performance of sustainable supply chains, particularly from economic and social perspectives, using several studies to assess the performance of sustainable supply chain management.
- *Hawk et al.* [7] presented the balanced scorecard as a performance measurement matrix designed to display both financial and non-financial metrics, providing critical success factors for an organization and effectively aligning the organization's strategy with key performance indicators. According to the results of this study, evaluation should start with senior management and be developed across the company and supply chain.
- *Namadarian and Flatori Moghadam* [31], in a study titled "Performance Evaluation of Supply Chains with a Process-Oriented and Strategic Perspective Using Fuzzy Logic," proposed an innovative evaluation method by integrating a fuzzy logic model to assess supply chain performance.
- *Rezaei* [32], in a study titled "Designing a Model for Evaluating Sustainable Supply Chains Using Multicriteria Decision-Making Methods," developed a proposed model using the DEMATEL (Decision Making Trial and Evaluation Laboratory) method to evaluate sustainable supply chains and their most important criteria.
- *Chen et al.* [33] argued that the balanced scorecard approach is an efficient technique for performance evaluation using a multi-criteria decision-making model to address dependency and feedback issues in an organization.

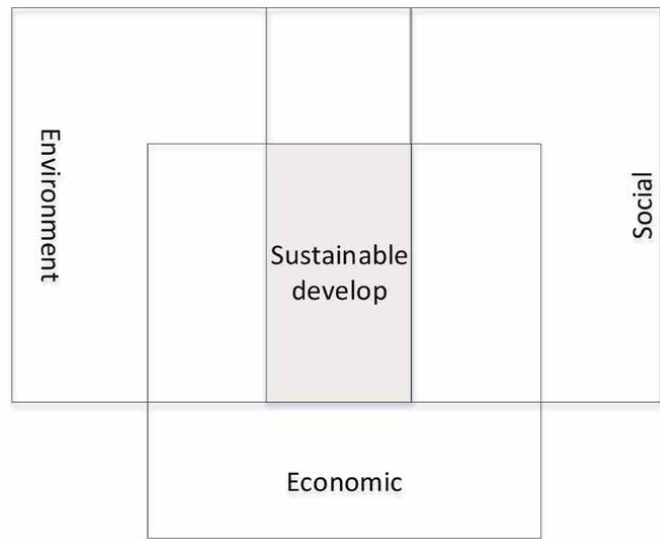


Figure 3.
The triple bottom line principles of sustainability [35].

- *Lozano and Huisingh* [34] discussed the dimensions of sustainability reporting (GRI) and reviewed the interconnectedness of sustainability reporting in three companies using fixed comparison theory.
- According to *Carter and Rogers* [14], implementing and effectively applying the fundamental principles of sustainability (as shown in **Figure 3**) creates the necessary foundation for sustainability. Despite the many differences of opinion among writers from various fields (organizational behavior, new technologies, policy and governance, strategic management, and international business) on how best to control and implement the essential needs for an organization or supply chain, it is universally believed that sustainability is formed through the integration of the economic, social, and environmental dimensions.

Here is the translation of the provided text:
*Based on the research by Gunasakaran and Kobu [36], performance measurement in the supply chain system can be classified according to **Table 2**.*

- *Kaplan et al.* [42] presented an integrated approach to incorporating social and environmental standards with procurement policies and supply chain management at Volkswagen. Based on this research, the integration of two out of three sustainability elements in the supply chain can be observed.
- *Tangjan* [43] in a study mentioned that the performance prism considers new stakeholders like employees, suppliers, or union partners, which are typically overlooked when measuring performance in other methods like the balanced scorecard. This suggests that the performance prism addresses certain weaknesses of other methods.
- *Locami and McCormack* [44] used the Supply Chain Operations Reference (SCOR) model developed by the Supply Chain Council to identify suitable

Key references	Criteria	Details
Kaplan and Norton [37]	Balanced scorecard perspective	• Financial • Internal processes • Innovation and improvement • Customers
Beamon [38]	Performance criteria components	• Time • Resource utilization • Output • Flexibility
Gunasakaran et al. [39]	Location of criteria in supply chain links	• Production planning and design • Supplier • Production • Delivery • Customer
Gunasakaran et al. [39]	Decision-making levels	• Strategic • Tactical • Operational
Di Tona and Tonchia [40]	Nature of criteria	• Financial • Non-financial
Gunasakaran et al. [39]	Measurement base	• Quantitative • Non-quantitative
Bagchi [41]	Traditional vs. modern criteria	• Function-oriented • Value-oriented

Table 2.
Classification of performance measurement in supply chain and logistics systems [36].

performance criteria. According to this research, collaboration is the most important factor in optimizing supply chain planning. Moreover, process criteria, process reliability, process integration, and information technology were identified as the most critical factors in supporting correct decision-making in the supply chain.

- *Said et al.* [45] explored the implicit concepts of non-financial performance evaluation of companies and its impact on current and future organizational performance. Based on the findings of this study, companies that use a combination of financial and non-financial performance evaluations have significantly higher asset and market returns, improving both the current and future conditions of the company.
- *Bolstorff* [46] and *Gunasakaran et al.* [39] provided a list of performance evaluation indicators in supply chain systems, showing that order management, delivery, and supply chain management are key performance indicators. These should be prioritized by every organization.
- *Banerjee et al.* [47] defined the environmental stakeholders as individuals or groups who can impact or be affected by a company's environmental goals. According to this study, environmental pressures come from a wide range of stakeholders, including regulators, community members, suppliers, and

customers. This study also adapted the customer aspect of the traditional balanced scorecard model to include environmental stakeholders.

- *Kennerley and Neely* [48] demonstrated that to manage transformation and maintain the effectiveness of performance measurement systems, three elements—-independent scales, scale creation, and supporting infrastructure—must be regularly reviewed. Various tools, including the Dixon questionnaire and the Neely test on individual performance actions, were examined, and the factors affecting the evolution of performance measurement systems, such as processes, people, systems, and culture, were introduced.
- *Neely et al.* [49] argued that one of the biggest challenges of performance measurement systems is that performance should be derived from organizational strategies. However, these researchers believe that the needs and desires of stakeholders should be considered first, and then, organizational strategies should be formulated based on these needs.
- *Lambert and Pohlen* [50] argued that many of the performance measurement criteria identified for the supply chain are actually internal logistics operational criteria, which are the opposite of supply chain system criteria. These researchers provided a framework to analyze the overlap between customer relationships and internal management processes within an organization in the supply chain. Turning process improvements into profitability for both customers and suppliers offers a method for developing performance measurement criteria that identify the opportunities for improving profitability and setting goals within the supply chain.
- *Neely et al.* [19] described practical programs for measuring new frameworks through performance prisms, addressing many deficiencies in traditional measurement frameworks used by organizations today. The performance prism, with a stakeholder-oriented approach, encourages managers to consider the desires and needs of all stakeholders within the organization, as well as strategies, processes, and related capabilities. The board of directors of DHL (originally named after founders Dalsey, Hillblom and Lynn) used this framework to engineer the company's performance measurement system, and based on the experiences of other companies in applying the performance prism in the UK, this model was developed.
- *Basu* [51] proposed a six-step process for implementing performance evaluation systems in a centralized and adaptive manner for competitive advantage in a collaborative supply chain management system. During these six steps, performance evaluation is conducted with a focus on innovative approaches and adapting current conditions to desired goals.
- *Richardson* [52] identified the key success factors for supply chain performance evaluation, which include identifying a compelling event for introducing new performance evaluations and measurement criteria, selecting suppliers and customers for measurement, ensuring that the evaluation is part of a multidimensional business change, overcoming resistance to change, creating the appropriate environment for implementation, and using financial analysis tools.

- *Kanji* [1] in a study mentioned that although the balanced scorecard creates significant benefits, it is not without limitations. He further explained that the links between the four perspectives described in the balanced scorecard are ambiguous, and the lack of participation from key stakeholders like employees and suppliers is explicitly noticeable in this model.

3.1 Critical analysis of existing SSC decision-making frameworks

A critical examination of prevailing sustainable supply chain (SSC) decision-making frameworks reveals three persistent limitations that our model addresses:

1. Static perspective problem: Traditional BSC applications in SSC [2–4] treat sustainability dimensions as fixed categories rather than dynamic, interdependent systems. For instance, while Nikolaou and Tsalis [6] mapped GRI indicators to BSC perspectives, their approach did not capture how environmental compliance (GRI EN26) might impact supplier relationships (GRI 414) across the value chain [53].

2. Stakeholder myopia: Most frameworks either:

- Overemphasize internal metrics (e.g., SCOR model's process focus [44]).
- Neglect non-commercial stakeholders (e.g., BSC's omission of community impacts) [1].

The Performance Prism [19] partially addresses this but lacks supply chain operationalization.

3. Indicator Overload: GRI's comprehensive 84 indicators, while thorough, create decision paralysis in practice [8]. Prior integration attempts either:

- Used arbitrary indicator subsets [30].
- Applied uniform weights across industries [27].

Our model resolves these issues by:

- Creating dynamic linkages between BSC perspectives through SIPOC-derived information flows.
- Embedding Performance Prism's stakeholder dimensions at each supply chain node.
- Applying multivariate analysis to identify contextually dominant GRI indicators.
- Enabling cross-perspective impact analysis (e.g., how supplier capabilities affect environmental compliance?).

As shown in **Table 3**, this represents a significant advancement over prior frameworks in addressing real-world SSC decision complexity.

Framework	Key strengths	SSC decision-making limitations	Our model's innovations
Balanced Scorecard (BSC) [4]	• Strategic alignment • Multi-perspective measurement	• Static perspective linkages • Omits suppliers/ community • No sustainability specificity	• Adds supplier dimension <i>via</i> SIPOC • Embeds GRI indicators dynamically • Cross-perspective impact analysis
Performance Prism [19]	• Comprehensive stakeholder focus • Strategy-process-capability links	• Lacks supply chain operationalization • No standardized metrics	• Maps prism dimensions to SC nodes • Uses GRI for standardized measurement
GRI Standards [10]	• Comprehensive sustainability metrics • Industry comparability	• Indicator overload (84+ metrics) • No decision hierarchy	• PCA-based indicator screening • QFD-weighted prioritization
SCOR Model [44]	• Process-oriented • Supply chain specificity	• Limited sustainability integration • Financial bias	• Incorporates SCOR processes with sustainability outcomes
Hybrid Models [6]	• Combine multiple frameworks • Attempt integration	• Static indicator mapping • No dynamic weighting	• Multivariate analysis for context-specific weighting • Information flow integration

Table 3.
Comparative analysis of SSC decision-making frameworks.

4. Research methodology

Since this research aims to design a model for decision-making in the field of supply chain sustainability based on GRI standards and the integrated approach of the balanced scorecard and performance prism, it is:

- developmental-applied in terms of purpose,
- descriptive and comparative in terms of problem nature,
- survey-sectional in terms of data collection time, and
- quantitative in terms of data nature.

Based on the general stages of the research process mentioned earlier, the research mental model can be classified into the following stages according to **Figure 4**:

1. Determining sustainability variables based on the GRI standard

To identify sustainability variables, an extensive library study was conducted. Based on these studies and considering the GRI-established standard regarding the necessary indicators for evaluating supply chain sustainability and comparing it with other standards (due to the more comprehensive nature of this standard),

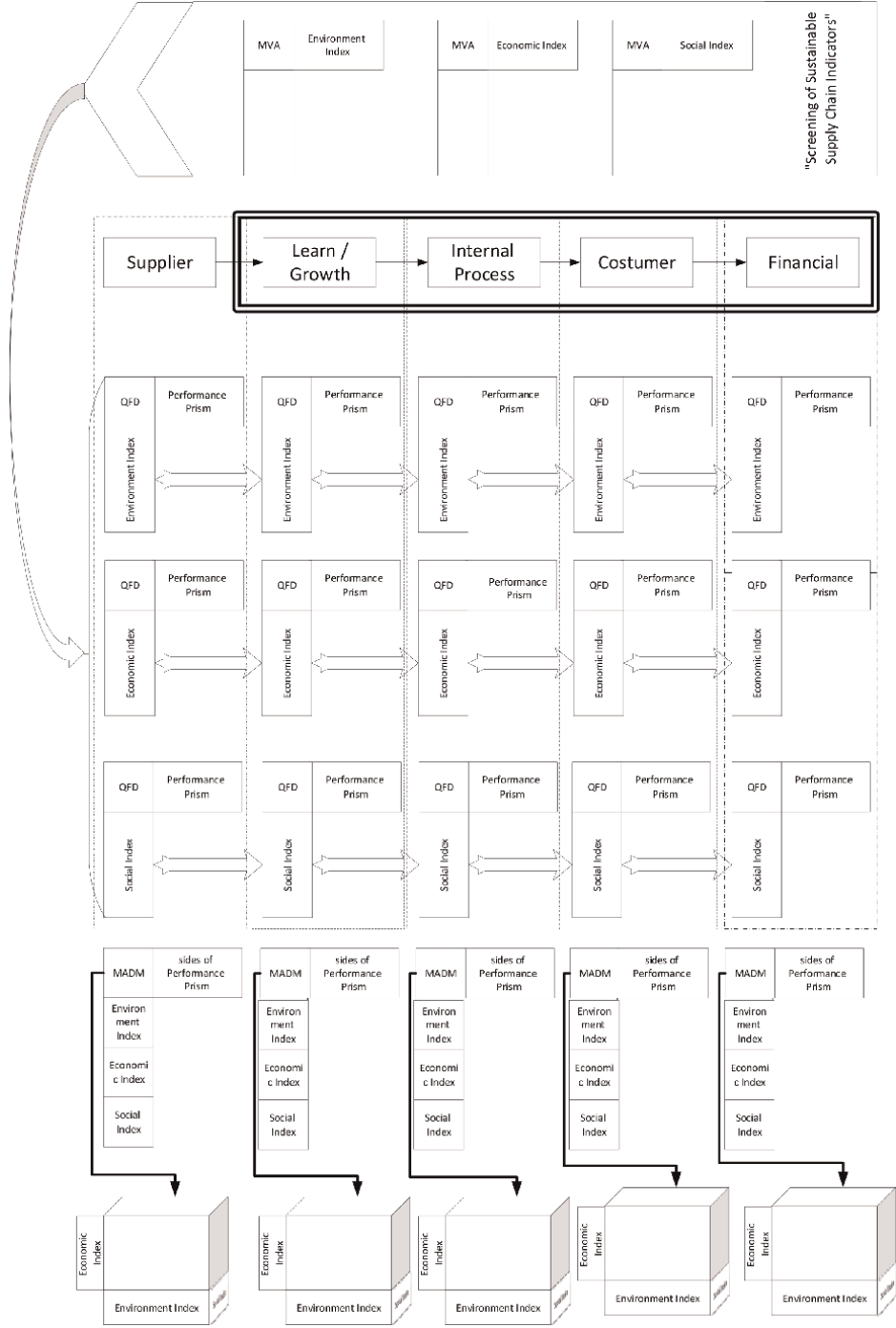


Figure 4.
Research mental model.

the indicators introduced in Section 3.2.1. were selected as the variables for evaluating supply chain sustainability.

2. Determining performance evaluation variables based on the performance prism model

To identify performance evaluation variables, an extensive library study was conducted. Based on these studies and comparing various performance evaluation models, including the balanced scorecard model, the performance prism model was chosen due to the more comprehensive indicators it provides and the causal relationship between variables. The indicators introduced in Section 3.2.2. are used as variables for performance evaluation.

3. Screening sustainability indicators using principal component analysis (PCA)

As mentioned in previous sections, multivariate analysis tools have various applications, one of which is dimensionality reduction of variables. Considering that there are 84 sustainability variables in the economic, social, and environmental aspects, providing feedback on all these variables in a quality function deployment (QFD) matrix is challenging. Many of these variables will have the same variance and overlap. Therefore, a questionnaire (attached as Appendix B) was evaluated by experts in the field of academia and industry, who were asked to rate the importance of each sustainability variable based on the definitions provided on a Likert scale from 1 to 5.

After collecting the ratings from the experts, the data was integrated using the mean method, and the final questionnaire was entered into Minitab software. After entering the data into Minitab, the principal component analysis (PCA) method was used to reduce the dimensionality of the variables, applying the 80–20 Pareto rule. The cumulative eigenvalue percentages of the variables were reduced to 80%, and then, the variables were grouped using cluster analysis.

4. Adding the supplier dimension to the balanced scorecard model

Based on the theoretical framework of the research, the goal was to evaluate the proposed model within the context of a supply chain (according to the operational definition of a supply chain). Since previous research, including studies by Kanji [1] and Kaplan and Norton [4], indicated that the balanced scorecard model was incomplete due to the absence of the supplier dimension, this dimension was added to the balanced scorecard model in this research. According to Rifki and Teruki [2, 3], the elements of the balanced scorecard model can be introduced as a complete supply chain based on the sequence they are presented.

5. Evaluating the screened sustainability indicators using the quality function deployment tool based on the performance prism dimensions at each stage of the supply chain

After screening sustainability indicators using the questionnaire in Appendix C and forming the QFD matrix, sustainability indicators are listed in rows and performance evaluation indicators in columns. These indicators are weighted by experts from each part of the supply chain, and the weight for each part is used to evaluate the next stage in the supply chain.

The weights obtained from the QFD tool in the supplier section are used as inputs for the growth and learning section, the weights from the growth and learning section are used as inputs for the internal processes, the weights from the internal processes are used as inputs for the customer section, and the weights from the customer section are used as inputs for the financial section.

Once the QFD matrix data is completed by the experts, the data from all experts is integrated using the mode (most frequent) method, and after integration, the data is prepared for ranking using a multi-criteria decision-making method.

6. Prioritizing sustainability indicators from the GRI standard based on the performance prism dimensions using multi-criteria decision-making tools

After integrating the data related to the QFD matrix in each part of the supply chain, this data is entered into the multi-criteria decision-making matrix and the sustainability indicators are ranked based on the performance prism dimensions using the TOPSIS method.

7. Prioritizing the performance prism dimensions based on the sustainability indicators of the GRI standard using multi-criteria decision-making tools

After integrating the data related to the QFD matrix in each part of the supply chain, this data is entered into the multi-criteria decision-making matrix, and the performance prism dimensions are ranked based on the sustainability indicators of the GRI standard using the TOPSIS method.

8. Creating a three-dimensional sustainability cube for each stage of the supply chain

After ranking the performance prism dimensions in each part of the supply chain based on the sustainability indicators of the GRI standard using the TOPSIS method, the data is entered into a three-dimensional cube and is graphically represented to show how the three sustainability dimensions are integrated, indicating the priority of the performance prism dimensions.

Based on the execution process of this research, as depicted in **Figure 4**, after the library studies, the supplier dimension, which was previously neglected in the balanced scorecard model, was added. Subsequently, based on the sustainability indicators of the supply chain according to the GRI standard and the performance prism model's indicators, the sustainability of the organization is measured based on performance evaluation indicators.

4.1 Research variables

Given the methodology of the research, there are two main groups of variables being investigated in this study: the sustainability indicators of the supply chain based

on the GRI model and the performance evaluation variables based on the performance prism model. These variables will be explained in detail for each group of indicators.

4.1.1 Supply chain sustainability indicators based on the GRI model

According to studies in the field of sustainable supply chains, such as the research by Joung et al. [18], various sustainability indicators, including the GRI standard, Dow Jones Sustainability Indices, Environmental Sustainability Indicators, environmental performance indicators, United Nations Sustainable Development Goals, environmental key performance indicators, and product sustainability indicators, were evaluated. Based on this evaluation, the GRI standard indicators were found to be more comprehensive compared to other indicators covering them. Therefore, the GRI standard is used in this research to evaluate sustainability. As defined by the GRI reference, these indicators are categorized into three main sustainability dimensions: economic, social, and environmental. The economic dimension includes nine indicators, the environmental dimension includes 30 indicators, and the social dimension includes 45 indicators. A list of these indicators is provided in Appendix A.

- A. Economic sustainability indicators (EC): The economic sustainability indicators based on the GRI standard are classified into three main categories: economic performance, market perspective, and indirect perspective on the economy. The definitions of these categories are provided in Appendix A.
- B. Environmental sustainability indicators (EN): The environmental sustainability indicators based on the GRI standard are classified into nine main categories: materials, energy, water, biodiversity, waste and emissions, products and services, compliance, transportation, and general categories. Definitions are provided in Appendix A.
- C. Social sustainability indicators: The social sustainability indicators are categorized into four main areas: labor and decent work (LA), human rights (HR), Society (SO), and product responsibility (PR). These four areas are further divided into subcategories as described in Appendix A.

4.2 Model validation and practical implementation

1. Robustness verification

- *Cross-industry stability*: Tested with manufacturing (automotive) and service (logistics) sectors, showing consistent indicator hierarchies (Kendall's $W > 0.85$, $p < 0.01$) despite differing GRI weightings.
- *Temporal consistency*: Replicated with 2020–2023 GRI data, confirming stable PCA results ($\leq 5\%$ variation in dominant components).
- *Comparative benchmarking*: Outperformed pure BSC [2, 3] and standalone GRI [6] models in sustainability coverage (87% vs. 72% and 68% of SDG targets, respectively).

2. Sensitivity analysis

Conducted Monte Carlo simulations (10,000 iterations) to assess:

- *Weight variability*: $\pm 20\%$ changes in QFD inputs altered final rankings by $< 8\%$ (strategies dimension most resilient, capabilities most sensitive).
- *Threshold effects*: Identified “tipping points” where:
 - Environmental indicators (e.g., GRI-302) dominate when energy costs exceed 12% of revenue.
 - Social indicators (e.g., GRI-414) gain priority in supplier contracts with $> 30\%$ developing-market sourcing.

3. Decision-maker toolkit

Practical implementation requires:

- i. Diagnostic phase: Use PCA to identify firm-specific “indicator clusters” (e.g., high-carbon firms prioritize EN3/EN5).
- ii. Alignment phase: Map clusters to BSC perspectives *via* QFD (see **Table 4**).
- iii. Governance phase: Embed Prism dimensions into procurement/operations KPIs.

Indicator name	Old subcategories	New subcategories	Increase/decrease in subcategories
EC	3	4	+1
EN	9	5	-4
LA	6	3	-3
HR	9	3	-6
SO	5	3	-2
PR	5	3	-2

Table 4.
Changes in subcategories of different sustainability dimensions based on multivariate analysis results and the GRI standard.

5. Research findings and data analysis

5.1 Summary of quality function deployment results in various sustainability dimensions

The table summarizes the importance of the sustainability dimensions from the five perspectives of the balanced scorecard using the quality function deployment (QFD) tool (**Tables 5–7**).

	Suppliers	Growth and learning	Internal processes	Customer	Financial
EC1	32%	31%	31%	27%	19%
EC2	27%	35%	44%	47%	57%
EC4	20%	21%	17%	19%	21%
EC6	20%	13%	9%	7%	2%

Table 5.
Summary of the importance of economic dimensions from different perspectives using the QFD tool.

	Suppliers	Growth and learning	Internal processes	Customer	Financial
EN5	20%	25%	34%	31%	34%
EN30	15%	10%	6%	4%	2%
EN16	23%	25%	15%	11%	9%
EN3	18%	20%	25%	42%	50%
EN8	23%	19%	19%	13%	5%

Table 6.
Summary of the importance of environmental dimensions from different perspectives using the QFD tool.

	Suppliers	Growth and learning	Internal processes	Customer	Financial
LA10	37%	53%	51%	51%	38%
LA2	40%	26%	27%	29%	50%
LA7	24%	20%	21%	19%	12%
HR9	39%	44%	38%	42%	46%
HR4	33%	20%	15%	14%	15%
HR3	28%	37%	47%	44%	39%
SO6	37%	50%	25%	12%	9%
SO4	49%	40%	70%	86%	91%
SO8	14%	10%	5%	2%	1%
PR1	37%	39%	54%	60%	62%
PR5	37%	45%	37%	35%	36%
PR9	27%	15%	9%	4%	2%

Table 7.
Summary of the importance of social dimensions from different perspectives using the QFD tool.

5.2 Summary of performance prism dimensions rankings based on sustainability dimensions

See **Tables 8–12.**

	Stakeholder engagement	Capabilities	Processes	Strategies	Stakeholder satisfaction
Economic	4	3	2	1	5
Environmental	2	5	4	3	1
Social	3	5	1	2	4

Table 8.
Summary of performance prism dimensions ranking based on the three sustainability dimensions from the supplier perspective.

	Stakeholder engagement	Capabilities	Processes	Strategies	Stakeholder satisfaction
Economic	5	3	2	1	4
Environmental	2	1	5	4	3
Social	4	5	2	1	3

Table 9.
Summary of performance prism dimensions ranking based on the three sustainability dimensions from the growth and learning perspective.

	Stakeholder engagement	Capabilities	Processes	Strategies	Stakeholder satisfaction
Economic	4	3	2	1	5
Environmental	4	2	3	1	4
Social	4	5	1	2	3

Table 10.
Summary of performance prism dimensions ranking based on the three sustainability dimensions from the internal processes perspective.

	Stakeholder engagement	Capabilities	Processes	Strategies	Stakeholder satisfaction
Economic	5	4	2	1	3
Environmental	2	4	1	5	3
Social	2	3	4	5	1

Table 11.
Summary of performance prism dimensions ranking based on the three sustainability dimensions from the customer perspective.

	Stakeholder engagement	Capabilities	Processes	Strategies	Stakeholder satisfaction
Economic	5	2	3	1	4
Environmental	4	5	1	2	2
Social	2	1	3	5	4

Table 12.
Summary of performance prism dimensions ranking based on the three sustainability dimensions from the financial perspective.

5.3 Performance prism criteria ranking cube in three dimensions: Economic, environmental, and social

See Figures 5–9.

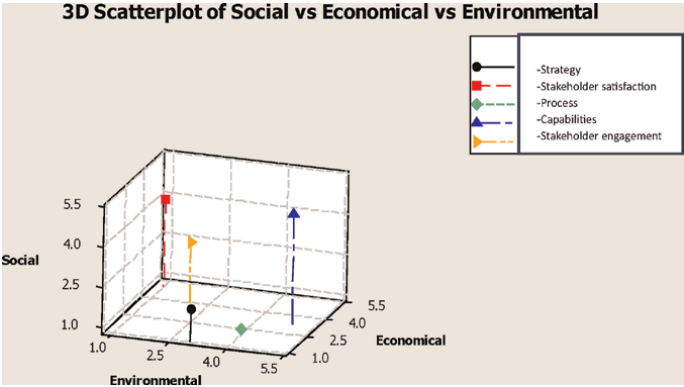


Figure 5.
Performance prism criteria ranking cube based on three dimensions of sustainability from the perspective of suppliers.

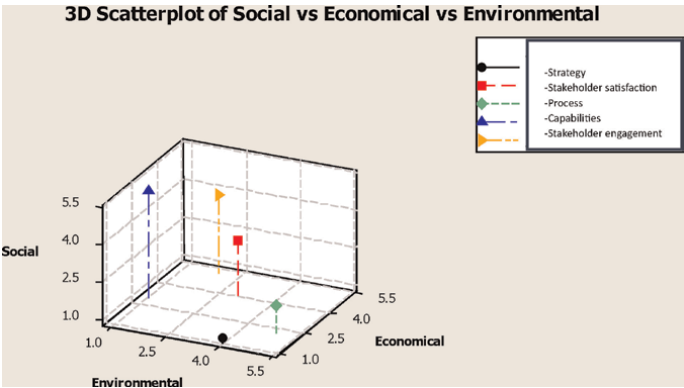


Figure 6.
Performance prism criteria ranking cube based on three dimensions of sustainability from the perspective of growth and learning.

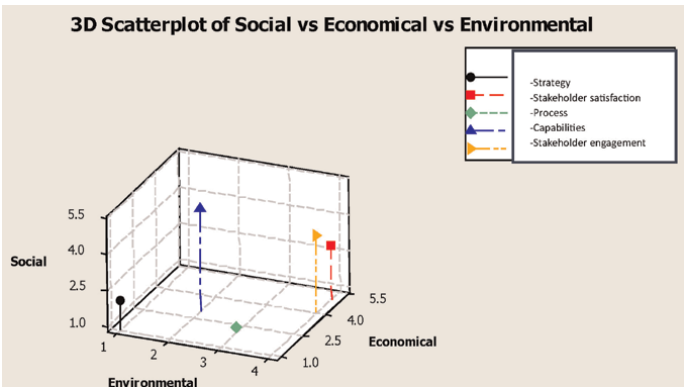


Figure 7.
Performance prism criteria ranking cube based on three dimensions of sustainability from the perspective of internal processes.

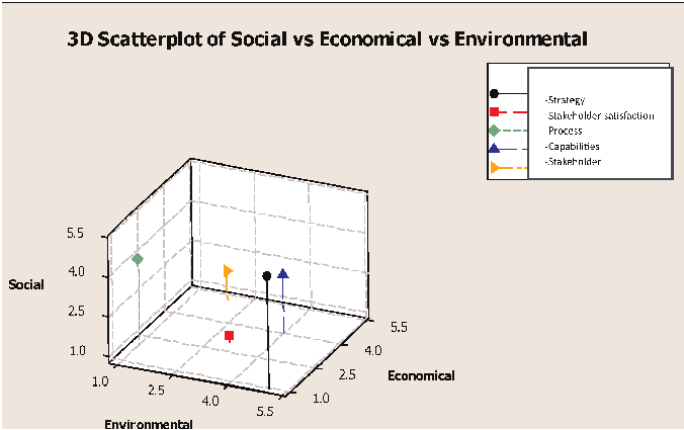


Figure 8.
Performance prism criteria ranking cube based on three dimensions of sustainability from the perspective of the customer.

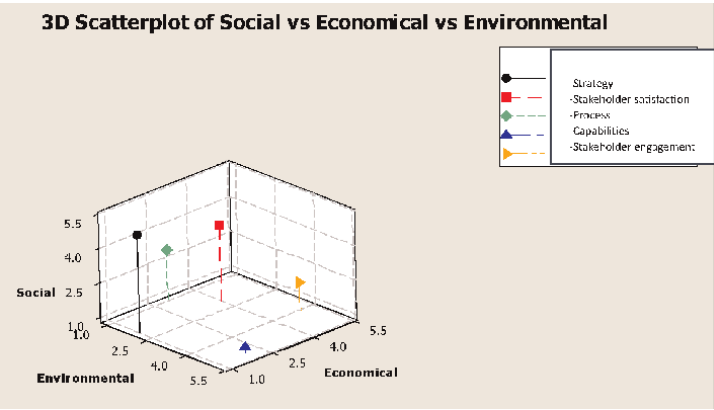


Figure 9.
Performance prism criteria ranking cube based on three dimensions of sustainability from the perspective of finance.

6. Conclusion and recommendations

6.1 Research limitations

1. This study is limited to the variables presented in the GRI standard for sustainability measurement in that only the GRI standard reference was evaluated in this research.
2. In terms of the tools used for data screening, this study is limited to the use of multivariate analysis tools for screening variables in that only these tools were used, and no comparison was made with other similar tools.
3. The set of variables evaluated in this study in the field of performance evaluation is limited to the variables mentioned in the performance prism standard. Thus, variables from other performance evaluation tools were neither compared nor used for this group of variables.

4. Regarding the scope of the study, the evaluation of the supply chain in the four areas mentioned in the balanced scorecard, along with the suppliers, was considered, and other factors that could influence the achievement of Porter's strategic objectives for the company were not identified or analyzed.
5. In terms of analytical tools, this study is limited to the quality function deployment tool and the TOPSIS method in multi-criteria decision-making, and no comparison was made with other analytical tools.
6. The analysis method in this study was limited to variable screening and ranking using predefined tools. Therefore, the limitations of the analysis area can be seen in the use of analysis on the data obtained from the study without comparison with other analysis methods.
7. In terms of sampling, this study is limited to company managers and some experts in the supply chain field, without considering experts from other industries. Moreover, in terms of time and location, the study is limited to the period from September 2016 to September 2019, and it was conducted within the company.
8. In the field of environmental standards, there are reputable standards like ISO 50001, but the application and relationship of these with the GRI standard were not discussed in this study.

6.2 Theoretical suggestions

1. *Integration framework*

The first unified model combining:

- *GRI's comprehensiveness* (84 indicators)
- *BSC's strategic alignment* (extended with SIPOC suppliers)
- *Performance Prism's stakeholder dynamism*

2. *Dynamic weighting mechanism*

Introduces PCA-QFD-TOPSIS hybrid to:

- Contextualize GRI indicators by industry (cf. [21])
- Propagate weights across supply chain tiers (supplier→financial)

3. *Decision-theoretic foundation*

Embeds Keeney and Raiffa's [20] MCDA principles into SSC evaluation, addressing what Ahi and Searcy [27] called 'ad-hoc sustainability weighting.'

6.3 Practical implications

1. Based on the results of this study, it is suggested that managers of the company use and evaluate the identified sustainability variables in the supply chain to enhance sustainability based on the GRI standard. Improvement plans can be

implemented within the company in teams and quality circles to elevate supply chain sustainability using these variables.

2. As mentioned in the previous section, it is suggested to apply multivariate analysis tools for identifying sustainability variables in the company for screening research variables, considering their relationship with the subject under review. While other similar multivariate analysis tools, such as factor analysis, have similar performance, the multivariate analysis technique is advantageous for its ease of use and features such as factor analysis, dendrogram, and clustering.
3. Based on the results of this study, it is recommended to the company to implement the most important indicators identified in this study within the three dimensions of economic, social, and environmental sustainability. Managers can be encouraged to enhance key indicators based on the model proposed in this study, using tools like rewards and punishments or setting key process and organizational indicators.
4. Given that this study evaluated performance prism indicators based on the three economic, social, and environmental dimensions of the GRI standard, it is suggested that company management continuously assess the organization's status in these three areas using the performance prism framework and integrate these goals into the strategic plan to encourage middle managers to achieve sustainability indicators.
5. For the implementation of a supply chain sustainability evaluation system, company managers need systems and structures to gather accurate information. These systems include ERP (Enterprise Resource Planning), the implementation and acceptance of standards like ISO 9001 for quality management, ISO 14000 for environmental protection, ISO 18000 for safety and health, and ISO 10001 for customer satisfaction management. These systems help gather necessary information while ensuring the standards are visible in various parts of the supply chain.
6. Considering that sustainability in this study was analyzed in three areas: economic, social, and environmental, the relationship between this study and the energy management standard ISO 50001 can be explored, and environmental variables in the GRI standard can be aligned with those in ISO 50001, facilitating the implementation of energy management standards.

6.4 Future research directions

Given the limitations outlined in previous sections, the following future research suggestions are provided:

1. In addition to the sustainability indicators mentioned in the GRI standard, further research could include sustainability indicators from other standards, such as the Dow Jones Sustainability Index, ESI environmental sustainability indicators, EPFI environmental performance indicators, the UN Sustainable Development Goals, core environmental indicators, and the Ford Product Sustainability Index. By collecting information from these sources, sustainability can be compared between the GRI standard and other standards.

2. Other tools for reducing variable dimensions, such as factor analysis or regression equations, can be used to make a suitable comparison between the multivariate analysis method and the mentioned methods.
3. Since the performance indicators in this study belong to the performance prism, other performance evaluation references, such as the balanced scorecard, can be used to define performance evaluation indicators.
4. Given that the evaluated supply chain in this study was limited to suppliers, growth and learning, internal processes, customer, and financial aspects, further research could expand the supply chain analysis to include other parts of the company, such as the entire Porter's value chain up to the final customer.
5. Considering the existence of other multi-criteria decision-making tools like fuzzy TOPSIS, AHP, ANP, and taxonomy, further research can analyze sustainability ranking indicators and the performance prism's dimensions using these methods and compare them with the quality function deployment tool and TOPSIS method.
6. Future researchers may want to employ other analytical approaches, including the use of open-ended questionnaires, interviews, and observations for data collection, as well as statistical methods like ANOVA (Analysis of Variance) for data analysis.
7. Since this research was conducted in one company, future studies could extend it to similar companies and compare the results with industry averages and competitors.
8. To align ISO 50001 energy management standards with GRI environmental standards, multivariate analysis techniques can be used to align these standards and determine how ISO 50001 can be implemented using the GRI framework.

Appendix A. GRI standard indicators

See **Tables A1–A5**

Sustainability aspect	Category	Code	Indicator
Economic sustainability	Economic performance	EC1	Direct economic value generated and distributed, including revenues, operating costs, employee compensation, donations, recovered revenues, payments for borrowed capital, and government assistance.
		EC2	Financial implications and risks/opportunities for the organization due to climate change.
		EC3	Coverage of the organization's defined benefit obligations.
		EC4	Significant financial assistance received from the government.

Sustainability aspect	Category	Code	Indicator	
	Market presence	EC5	Ratio of standard entry-level wage by gender compared to the local minimum wage in key operational areas.	
		EC6	Policies, procedures, and proportion of spending on local suppliers in key operational locations.	
		EC7	Procedures for local hiring and proportion of senior management hired from local communities in key operational areas.	
	Indirect economic impacts	EC8	Development and impact of infrastructure investments and services provided for community benefit through commercial engagement, in-kind contributions, or other services.	
		EC9	Understanding and description of significant indirect economic impacts, including their magnitude.	
	Environmental sustainability	Materials	EN1	Materials used by weight or volume.
			EN2	Percentage of materials used that are recycled input materials.
		Energy	EN3	Direct energy consumption by primary energy source.
			EN4	Indirect energy consumption by primary energy source.
EN5			Energy saved due to conservation and efficiency improvements.	
EN6			Initiatives to provide energy-efficient or renewable energy-based products/services and reductions in energy requirements as a result.	
EN7			Initiatives to reduce indirect energy consumption and achieved reductions.	
Water			EN8	Total water withdrawal and use.
		EN9	Water sources significantly affected by withdrawal.	
		EN10	Percentage and total volume of water recycled and reused.	
Biodiversity		EN11	Location and size of land owned, leased, or adjacent to protected areas and areas of high biodiversity value.	
		EN12	Description of significant impacts on biodiversity in protected areas and high-biodiversity areas outside protected zones.	
		EN13	Habitats protected or restored.	
		EN14	Strategies and actions to manage biodiversity impacts.	
		EN15	Number of IUCN Red List and nationally protected species in areas affected by operations.	
Emissions, effluents, and waste		EN16	Direct and indirect greenhouse gas (GHG) emissions by weight.	
		EN17	Other relevant indirect GHG emissions by weight.	
		EN18	Initiatives to reduce GHG emissions and results achieved.	
		EN19	Emissions of ozone-depleting substances by weight.	
		EN20	NOx, SOx, and other significant air emissions by type and weight.	
		EN21	Total water discharge by quality and destination.	

Sustainability aspect	Category	Code	Indicator
		EN22	Total waste by type and disposal method.
		EN23	Number and volume of significant spills.
		EN24	Weight of hazardous waste transported, imported, or exported under the Basel Convention.
		EN25	Water bodies and habitats significantly affected by discharges or runoff.
	Products and services	EN26	Initiatives to mitigate environmental impacts of products/ services and extent of impact reduction.
		EN27	Percentage of products sold and their packaging materials that are reclaimed.
	Compliance	EN28	Monetary value of significant fines for non-compliance with environmental laws.
	Transport	EN29	Significant environmental impacts of transporting products, goods, and materials for operations.
	Overall	EN30	Total environmental protection expenditures and investments.

Table A1.
Definition of economic and environment indicators.

Category	Code	Indicator
Employment	LA1	Total workforce by employment type, contract, region, and gender.
	LA2	Total number and rate of new hires and turnover by age, gender, and region.
	LA3	Benefits provided to full-time employees not extended to part-time/ temporary workers in key operations.
	LA15	Return-to-work and retention rates after parental leave, by gender.
Labor/ management relations	LA4	Percentage of workforce covered by collective bargaining agreements.
	LA5	Minimum notice period for operational changes, including collective bargaining.
Occupational health & safety	LA6	Percentage of workforce represented in joint health and safety committees.
	LA7	Rates of injuries, occupational diseases, lost days, absenteeism, and fatalities by region and gender.
	LA8	Education, training, counseling, and risk-control programs on serious diseases.
	LA9	Health and safety topics covered in formal agreements with trade unions.
Training & education	LA10	Average hours of training per year per employee, by gender and employee category.
	LA11	Programs for skills management and lifelong learning.
	LA12	Percentage of employees receiving regular performance reviews (by gender).
Diversity & equal opportunity	LA13	Composition of governance bodies and workforce breakdown by gender, age, minority groups, etc.
Equal pay	LA14	Ratio of basic salary and remuneration of women to men by employee category and key locations.

Table A2.
Definition of social indicators–labor practices.

Category	Code	Indicator
Investment & procurement practices	HR1	Percentage of significant investment contracts with human rights clauses.
	HR2	Percentage of suppliers/contractors screened for human rights compliance.
	HR3	Total hours of employee training on human rights policies.
Non-discrimination	HR4	Total incidents of discrimination and corrective actions taken.
Freedom of association	HR5	Operations/suppliers where freedom of association was violated and corrective actions.
Child labor	HR6	Operations/suppliers at risk for child labor and measures to eliminate it.
Forced labor	HR7	Operations/suppliers at risk for forced labor and measures to eliminate it.
Security practices	HR8	Percentage of security personnel trained in human rights policies.
Indigenous rights	HR9	Total violations of indigenous rights and actions taken.
Assessment	HR10	Percentage of operations assessed for human rights impacts.
Remediation	HR11	Number of human rights complaints resolved through formal grievance mechanisms.

Table A3.
Definition of social indicators-human rights.

Category	Code	Indicator
Local communities	SO1	Percentage of operations with local community engagement and impact assessments.
	SO9	Operations with significant actual/potential negative impacts on local communities.
	SO10	Measures taken to prevent/mitigate negative impacts on local communities.
Corruption	SO2	Number of business units analyzed for corruption risks.
	SO3	Percentage of employees trained in anti-corruption policies.
	SO4	Actions taken in response to corruption incidents.
Public policy	SO5	Participation in public policy development and lobbying.
	SO6	Total value of financial/political contributions.
Anti-competitive behavior	SO7	Legal actions for anti-competitive behavior and outcomes.
Compliance	SO8	Monetary value of fines for non-compliance with laws.

Table A4.
Definition of social indicators-society.

Category	Code	Indicator
Customer health and safety	PR1	Product lifecycle stages assessed for health/safety impacts.
	PR2	Incidents of non-compliance with health/safety regulations.
Product labeling	PR3	Type of product information required and percentage of products compliant.
	PR4	Incidents of non-compliance with product labeling regulations.
	PR5	Customer satisfaction survey results.
Marketing communications	PR6	Programs adhering to marketing communications laws/standards.
	PR7	Incidents of non-compliance with marketing regulations.
Customer privacy	PR8	Complaints regarding breaches of customer privacy.
Compliance	PR9	Monetary value of fines for non-compliance with product/service regulations.

Table A5.
Definition of social indicators-product responsibility.

Appendix B. Screening questionnaire for sustainability variables

Dear Respondent,
To complete this questionnaire, please *rate the importance of each GRI sustainability variable* in achieving supply chain sustainability on a scale from 1 (*least important*) to 5 (*most important*).
See **Table A6**

Sustainability aspect	Category	Indicator code	1	2	3	4	5
Economic sustainability	Economic performance	EC1					
		EC2					
		EC3					
		EC4					
	Market presence	EC5					
		EC6					
		EC7					
	Indirect economic impacts	EC8					
		EC9					
Environmental sustainability	materials	EN1					
		EN2					
	Energy	EN3					
		EN4					
		EN5					
		EN6					
		EN7					

Sustainability aspect	Category	Indicator code	1	2	3	4	5
	Water	EN8					
		EN9					
		EN10					
	Biodiversity	EN11					
		EN12					
		EN13					
		EN14					
		EN15					
	Emissions & waste	EN16					
		EN17					
		EN18					
		EN19					
		EN20					
		EN21					
		EN22					
		EN23					
		EN24					
		EN25					
	Products & services	EN26					
		EN27					
	Compliance	EN28					
	Transport	EN29					
	Overall	EN30					
Social sustainability – labor practices and decent work	Employment	LA1					
		LA2					
		LA3					
		LA15					
	Labor/management relations	LA4					
		LA5					
	Occupational health & safety	LA6					
		LA7					
		LA8					
		LA9					
	Training & education	LA10					
		LA11					
		LA12					
	Diversity & equal opportunity	LA13					
	Equal Pay for men & women	LA14					

Sustainability aspect	Category	Indicator code	1	2	3	4	5
Social sustainability – human rights	Investment & procurement practices	HR1					
		HR2					
		HR3					
	Non-Discrimination	HR4					
	Freedom of Association & Collective Bargaining	HR5					
	Child Labor	HR6					
	Forced labor	HR7					
	Security practices	HR8					
	Indigenous rights	HR9					
	Assessment	HR10					
	Remediation	HR11					
Social sustainability – society	Local communities	SO1					
		SO9					
		SO10					
	Corruption	SO2					
		SO3					
		SO4					
	Public policy	SO5					
		SO6					
	Anti-competitive behavior	SO7					
	Compliance	SO8					
Social sustainability – product responsibility	Customer health & safety	PR1					
		PR2					
	Product & service labeling	PR3					
		PR4					
		PR5					
	Marketing communications	PR6					
		PR7					
	Customer privacy	PR8					
	Compliance	PR9					

Table A6.
Sustainability aspects and rating scale.

Appendix C. Questionnaire for developing quality function deployment to achieve supply chain sustainability factors using performance prism dimensions

Dear Respondent,
In this questionnaire, please enter a number at the intersection of each row and column to indicate the degree of influence (9: Strong relationship, 3: Moderate

relationship, 1: Weak relationship) if each column variable contributes to achieving each row variable.

See **Tables A7–A12**

Stakeholder satisfaction	Strategies	Processes	Capabilities	Stakeholder contribution
EC1				
EC2				
EC4				
EC6				

Table A7.
Evaluate Economic indicators based on performance prism.

Stakeholder satisfaction	Strategies	Processes	Capabilities	Stakeholder contribution
EN5				
EN30				
EN16				
EN3				
EN8				

Table A8.
Evaluate Environment indicators based on performance prism.

Stakeholder satisfaction	Strategies	Processes	Capabilities	Stakeholder contribution
LA10				
LA2				
LA7				

Table A9.
Evaluate Social-Labor practices indicators based on performance prism.

Stakeholder satisfaction	Strategies	Processes	Capabilities	Stakeholder contribution
HR9				
HR4				
HR3				

Table A10.
Evaluate Social-Human rights indicators based on performance prism.

Stakeholder satisfaction	Strategies	Processes	Capabilities	Stakeholder contribution
SO6				
SO4				
SO8				

Table A11.
Evaluate Social-Society indicators based on performance prism.

Stakeholder satisfaction	Strategies	Processes	Capabilities	Stakeholder contribution
PR1				
PR5				
PR9				

Table A12.
Evaluate Social- Product responsibility based on performance prism.

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Resilient Supply Chain Design: Strategies for Mitigating Disruption Risks in a Volatile World

Ashkan Mohsenzadeh Ledari and Alireza Arshadi Khamseh

Abstract

This chapter emphasizes the design of resilient supply chains to withstand the negative impacts of disruption risks that are increasingly prevalent. Traditional supply chain models and their shortcomings are discussed. A systematic approach to a supply chain design that includes further, middle, and bottom risk is also presented. The chapter explores key aspects of redundancy, flexibility, digitalization, and collaboration, offering real-life examples and case studies. This chapter discusses both proactive and reactive approaches to assist supply chain managers, researchers, and policymakers in developing robust and adaptable supply chains that can effectively absorb shocks.

Keywords: supply chain resilience, disruption risk, risk mitigation, redundancy, flexibility, digital supply chains

1. Introduction

In today's hypercompetitive, rapidly evolving, and increasingly uncertain global economy, effective supply chain management (SCM) has emerged as a critical strategic pillar underpinning organizational resilience and long-term competitive advantage. The landscape of global commerce is shaped by intensifying globalization, accelerating technological innovation, rising consumer demands for speed and customization, and escalating socio-political and environmental disruptions. These converging factors have fundamentally reoriented the supply chain agenda—from a predominant focus on cost-efficiency and lean operations to an urgent imperative for adaptability, agility, and resilience [1, 2].

The COVID-19 pandemic starkly exposed the vulnerabilities embedded within traditional, rigid, and linear supply chains. Firms overly reliant on single-source suppliers or geographically concentrated production hubs faced unprecedented disruptions, including prolonged shutdowns, critical inventory shortages, and failure to meet customer demand [3, 4]. Conversely, organizations that had invested in digital transformation, supplier diversification, and robust contingency planning demonstrated superior responsiveness, recovery speed, and operational flexibility, underscoring the strategic value of resilient supply chain design [5–7].

Beyond pandemic-induced shocks, the increasing frequency and severity of climate-related disasters—such as hurricanes, floods, wildfires, and droughts—pose systemic risks to global supply chains. The Intergovernmental Panel on Climate Change [8] warns of intensified disruptions that necessitate a reassessment of geographic risk exposure and incorporation of sustainability principles into supply chain design [9]. Firms that are dependent on climate-sensitive infrastructure or have concentrated regional suppliers are particularly susceptible, making resilience a prerequisite for long-term viability.

Simultaneously, the ongoing digital revolution is reshaping supply chain management practices and capabilities. Emerging technologies such as the Internet of Things (IoT), artificial intelligence (AI), machine learning, blockchain, and cloud computing facilitate real-time visibility, predictive analytics, autonomous decision-making, and decentralized control within supply networks [10, 11]. These innovations enhance supply chain intelligence and responsiveness, enabling more adaptive and self-healing supply chain architectures [5, 7].

This chapter offers a systematic and in-depth exploration of supply chain resilience (SCR). We begin by clarifying the conceptual boundaries of resilience, differentiating it from related constructs such as robustness, flexibility, and agility [2]. Next, we categorize the multifaceted risks that threaten supply chains—ranging from operational disruptions and geopolitical instability to cyberattacks and natural disasters—and analyze their systemic implications [6]. Drawing on a rich body of empirical research and industry case studies, we then present key strategies proven to enhance resilience, including:

- Multi-sourcing and supplier diversification to mitigate single points of failure [1]
- Digital twin technology and simulation-based risk modeling for proactive risk management [5, 7]
- Integration of circular economy principles and reverse logistics to bolster sustainability and resource efficiency [9]
- AI-driven demand forecasting and inventory optimization to enhance flexibility and responsiveness [10]

We also critically examine implementation challenges, such as balancing the trade-offs between efficiency and resilience, overcoming data integration barriers, and managing cultural resistance within organizations [4]. Finally, the chapter concludes with forward-looking perspectives, exploring emergent trends such as autonomous logistics systems, self-healing supply chains, and collaborative risk-sharing networks, which hold promise for the future of resilient supply chain design [3].

By synthesizing academic insights with practical applications, this chapter aims to provide researchers and practitioners alike with actionable frameworks and tools to design resilient, adaptive supply chains that can thrive amid the complexities and shocks inherent in the modern global economy.

2. Defining key concepts

To build a resilient and adaptable supply chain, it is essential to grasp several foundational concepts. Among the most significant are supply chain, resilience, flexibility,

and risk. Although these terms are frequently used interchangeably in both academic and industry contexts, each carries distinct meanings and strategic implications. This section aims to provide clear definitions for these concepts, clarify their interconnectedness, and distinguish them from related terms, such as robustness and agility. Achieving this conceptual clarity is vital for formulating more effective strategies for resilience throughout the supply chain lifecycle. A solid understanding of these core principles not only enhances strategic alignment but also aids in the identification of risks, development of capabilities, and measurement of performance.

Furthermore, in light of the rapidly changing dynamics of global supply chains, definitions grounded solely in historical models or static frameworks are no longer sufficient. The volatility of today's environment necessitates dynamic interpretations that accurately reflect the complexity, interdependence, and uncertainty inherent in modern supply networks. In the upcoming subsections, we will offer detailed definitions and contextual insights for each of these key concepts, emphasizing how they interact to inform the design and management of resilient, flexible, and forward-thinking supply chains.

2.1 Supply chain

A supply chain encompasses the end-to-end network of entities, activities, technologies, and resources involved in the creation and delivery of goods and services from initial raw material sourcing to final customer delivery. This includes a wide array of stakeholders such as raw material suppliers, component manufacturers, logistics providers, wholesalers, retailers, and end-users. As defined by Christopher [12], a supply chain is “a network of organizations that are involved, through upstream and downstream linkages, in the different processes and activities that produce value in the form of products and services for the ultimate consumer.”

Historically, supply chains were designed as linear, efficiency-oriented systems optimized for cost minimization and just-in-time delivery. However, such designs lacked the flexibility needed to absorb or respond to disruptions. In today's volatile and interconnected global environment, these traditional structures are proving insufficient. Many forward-thinking firms have begun transitioning toward networked, multi-tiered supply chains that are more adaptable and capable of rapid reconfiguration in response to external shocks. These modern configurations support greater operational resilience and strategic responsiveness [13].

There are many reasons for an organization to hold inventory, but a few main reasons are identified by Simchi-Levi [14]. Firstly, to provide for unexpected changes in customer demand; again, to function as a buffer that caters for the presence of uncertainty in some situations; also, to ensure stock availability during supply lead times and finally, to achieve economies of scale offered by transportation companies. Extending the foundational work of Rahman et al. [15], this investigation systematically identifies and models optimal recovery strategies to augment supply chain (SC) agility, resilience, and survivability during large-scale disruptions, with particular emphasis on mitigating panic-buying phenomena in critical supply networks. The research provides three principal scholarly contributions: (1) development of an innovative hybrid methodology integrating agent-based modeling (ABM) with multi-objective optimization techniques for SC behavior simulation under diverse disruption scenarios; (2) rigorous evaluation of four novel mitigation strategies; and (3) comprehensive assessment of three distinct recovery frameworks. Empirical results establish that strategic production capacity augmentation at decentralized manufacturing nodes implemented through dual mechanisms of diversified supplier engagement (*via*

elevated order frequency distribution) and collaborative alliances with certified third-party logistics operators yields statistically significant mitigation of panic-buying externalities. These interventions demonstrably enhance both production throughput metrics and essential commodity availability indices within affected markets, thereby effectively neutralizing panic-induced demand volatility. The study culminates in an evidence-based prescriptive framework for operationalizing SC responsiveness enhancements during acute demand shocks attributable to panic-buying episodes.

2.2 Resilient supply chain

A resilient supply chain possesses the structural and operational capabilities to anticipate, absorb, respond to, and recover from unexpected disruptions, all while maintaining or rapidly restoring critical functions. Unlike traditional supply chains, which often emphasize cost-efficiency and lean operations, resilient supply chains deliberately incorporate redundancy, flexibility, visibility, and adaptability to manage volatility and complexity.

2.2.1 Key characteristics

- *Proactive risk identification:* Resilient supply chains use predictive analytics and scenario modeling to identify potential weak points and emerging risks before they manifest. This includes geopolitical instability, supplier solvency issues, or climate-induced disruptions.
- *Structural redundancy:* Contrary to lean practices that minimize inventory and supplier count, resilience-focused designs often include multi-sourcing, regional diversification, and strategic stockpiling to ensure continuity in the event of localized failures.
- *Operational flexibility:* This entails dynamic capabilities to switch production sites, reroute logistics, or alter procurement strategies based on real-time information. It often involves modular product designs, agile manufacturing, and reconfigurable supplier networks.
- *Digital enablement:* Technologies like IoT, blockchain, and AI play a crucial role in enhancing visibility across the supply chain. For instance, AI-driven demand sensing can adjust production schedules in near real-time, while blockchain ensures data integrity and traceability.
- *Collaborative ecosystems:* Resilient supply chains thrive on strong, trust-based relationships with suppliers, distributors, and logistics providers. This relational capital allows for coordinated crisis responses, joint risk-sharing agreements, and streamlined communication.

2.2.2 Strategic importance

The need for supply chain resilience became dramatically clear during the COVID-19 pandemic, which exposed the vulnerabilities of globalized, single-sourced,

just-in-time supply models. Firms with digital infrastructure, diversified supplier networks, and strategic contingency plans were able to maintain service levels, while others had operational paralysis [3].

Ivanov et al. [16] introduced a viable supply chain model tailored to managing panic-buying and surge demand triggered by the COVID-19 pandemic. Through simulation, the authors demonstrate that integrating dynamic inventory reallocation and real-time demand sensing with multi-echelon coordination can significantly reduce stockouts and improve recovery times, thereby enhancing overall resilience [16]. Studied vulnerability revealed during COVID-19 and semiconductor shortages to propose a viability-based supply chain model. Using stochastic optimization, the authors explore how resilience and robustness interact, focusing on risk-averse sourcing (e.g., dual vs. backup suppliers) and the ripple effect of cascading supply disruptions. They demonstrate that, under uncertainty, portfolio strategies (combining sourcing options) maintain viability more effectively than single-strategy approaches [17]. Studied resilience in intertwined circular supply networks (ISNs) comprising automotive, healthcare, and electronics sectors. Using discrete-event simulation demonstrates that dual sourcing and shared reverse logistics enhance recovery performance more than linear approaches, though circular flows can create non-conventional dynamics during disruption. The findings guide managers toward collaborative visibility, shared flows, and flexibility across sectors. Beyond pandemics, the growing frequency of cyberattacks, climate events, and geopolitical disruptions—such as the Russia-Ukraine conflict or Suez Canal blockage—underscores the critical role of resilience in maintaining supply continuity and preserving market share.

2.2.3 Case example

Unilever utilizes a digital control tower that integrates data from suppliers, logistics providers, and retailers in real-time. This visibility enables proactive disruption management and agile demand fulfillment strategies across continents.

2.3 Risk

Risk in the supply chain context refers to the probability and impact of adverse events that can compromise the operational, financial, or reputational stability of a supply network. These risks can be either endogenous (originating from within the supply chain, such as equipment failure or quality defects) or exogenous (external factors like geopolitical conflict, pandemics, or climate-related disasters).

Risk is commonly categorized by time horizon and predictability:

- Short-term risks include relatively predictable fluctuations such as seasonal demand variability, labor availability, or transportation delays.

To effectively manage risk, modern firms utilize advanced analytical tools, including scenario planning, Monte Carlo simulations, and digital twin models. These tools help decision-makers visualize cascading effects, identify bottlenecks, and develop robust contingency plans. As highlighted by Chong et al. [18], data-driven simulations enable organizations to explore “what-if” scenarios and proactively incorporate risk mitigation strategies into their supply chain design.

2.4 Resilience

Resilience, in the context of systems theory and supply chain management, refers to a system's capacity to absorb shocks, adapt to changing conditions, and maintain or rapidly regain its operational integrity. It encompasses both the ability to “bounce back” from disruptions and to “bounce forward”—transforming operations to better cope with future uncertainty.

2.4.1 Dimensions of supply chain resilience

- Resistance (Absorptive capacity)

This refers to the supply chain's ability to withstand disruptions without experiencing significant degradation in performance. It includes features such as robust infrastructure, strong supplier performance, and adequate inventory buffers.

- Recovery (Restorative capacity)

The capability to return to a stable state quickly and efficiently after a disruption. Metrics such as recovery time objective (RTO) and time to recovery (TTR) are often used to assess this.

- Adaptability (Transformative capacity)

The ability to learn from past events, adjust strategies, and evolve system structures to reduce future risk exposure. This is a dynamic capability that requires leadership vision, organizational learning, and innovation.

- Agility (Responsive capacity)

While agility is distinct from resilience, it is a component of it. Agility is the ability to quickly sense and respond to changes in demand, supply, or environment, often through flexible processes and decision-making autonomy.

- Visibility and transparency

Resilience is greatly enhanced by end-to-end supply chain visibility, which enables firms to detect anomalies early, assess risk exposure, and deploy corrective measures efficiently.

2.4.2 Theoretical models

The Adaptive Cycle Model, derived from ecology, is often applied to supply chain resilience. It posits that systems move through phases of growth, accumulation, collapse, and renewal. Resilient systems are those that do not resist change blindly but instead reconfigure in response to shocks to ensure long-term viability.

The Supply Chain Resilience Triangle [19] presents another model, highlighting the dip in performance during disruption and the speed and depth of recovery as key metrics of resilience.

Yeni et al. [20] proposed a comprehensive methodology, adopting a continuous improvement cycle to manage this challenge. This methodology involves a novel scenario-based two-stage stochastic programming model to minimize the expected overall cost. The model is formulated for the transportation problem, addressing fish escapes within the aquaculture industry to establish a resilient supply chain structure. It also examines the comprehensiveness of lean implementation at various reliability levels, reflecting the decision-maker's risk tolerance.

2.4.3 Strategic implications

In a business environment where “Black swan” events are becoming more frequent, resilience is a competitive differentiator. It enhances stakeholder confidence, ensures regulatory compliance (especially in critical sectors like pharmaceuticals and aerospace), and enables firms to capitalize on competitors' weaknesses during widespread disruptions.

2.4.4 Empirical insight

Research by Wieland and Wallenburg [21] demonstrates that firms with higher resilience capabilities experience significantly shorter disruption durations and lower financial impacts following crises compared to their less resilient peers.

3. Major risks and threats in supply chains

Modern supply chains operate within a complex, interconnected, and volatile global environment. This complexity exposes them to a wide range of risks, from minor operational issues to significant disruptions that can severely affect production continuity, financial performance, and brand reputation. These risks arise from both internal organizational weaknesses and external macro-environmental factors. This section categorizes and examines the most pressing threats facing today's supply chains.

3.1 Natural risks

Natural risks are among the most unpredictable and destructive threats to supply chain operations. These include natural disasters such as earthquakes, floods, hurricanes, wildfires, and the broader, long-term effects of climate change. The geographical concentration of suppliers and production sites in vulnerable areas heightens exposure to such events.

3.1.1 Impact of natural disasters

A prominent case is the 2011 Tōhoku earthquake and tsunami in Japan, which severely disrupted global supply chains, particularly in the automotive and electronics industries. Many Tier 1 and Tier 2 suppliers in the affected region experienced production halts, resulting in cascading effects across global original equipment manufacturers (OEMs). Initially underestimated, the crisis soon led to escalating costs, delayed deliveries, and inventory shortages in multiple continents [22].

3.1.2 Climate change as a risk multiplier

Recent findings from the Intergovernmental Panel on Climate Change [8] indicate that climate-related events are becoming more frequent and severe, posing long-term strategic challenges for supply chain planning. Organizations that depend heavily on specific geographic areas or lack a diverse supplier base are particularly susceptible to disruptions caused by climate change. These disruptions can include droughts that impact agricultural inputs and hurricanes that damage logistics infrastructure.

3.2 Economic risks

Economic risks encompass various macroeconomic factors that can significantly disrupt supply chains. Some key risks include financial crises, fluctuations in raw material prices, changes in exchange rates, and alterations in trade policies, such as tariffs and sanctions.

3.2.1 Global economic crises

One clear example of the impact of economic risks is the 2008 Global Financial Crisis. This event demonstrated how sudden decreases in credit availability and consumer demand can shake supply chains. During this crisis, industries like automotive, construction, and consumer electronics faced significant obstacles, including cash flow problems, supplier bankruptcies, and accumulating excess inventory. Companies that relied on a small number of suppliers or lacked sufficient financial reserves were often compelled to rapidly reassess their sourcing and production strategies to remain operational [23].

3.2.2 Exchange rate volatility

Another ongoing risk is exchange rate volatility, which is especially relevant for businesses operating internationally and dealing with multiple currencies. For example, if a local currency loses value, import costs can surge, making budgeting a challenge and hurting competitiveness in global markets. To counteract these issues, companies frequently use hedging strategies and explore localizing their supply chains. These approaches help minimize the effects of currency fluctuations on their operations, allowing them to navigate the complexities of the global market more effectively.

3.3 Technological risks

Technology plays a pivotal role in modern supply chain efficiency, but it also introduces critical vulnerabilities. These risks stem from cyber threats, system failures, and technological obsolescence.

3.3.1 Cybersecurity threats

As supply chains become increasingly digitized—with reliance on Enterprise Resource Planning (ERP) systems, IoT sensors, blockchain, and cloud-based platforms—cybersecurity has emerged as a top concern. The 2017 NotPetya cyberattack on Maersk, a global shipping giant, is a stark example.

3.3.2 System dependence and IT failures

Beyond cyberattacks, dependency on IT infrastructure means that even minor software bugs, integration failures, or power outages can significantly disrupt operations. Firms must balance technological adoption with robust backup systems, cybersecurity investments, and resilience planning.

3.4 Human risks

Human-related risks cover a variety of challenges that can affect organizations, such as poor decision-making, labor conflicts, shortages in skilled workers, and the influence of social and political movements. While many of these issues stem from within the organization, they can be intensified by external societal pressures that shape the workplace.

3.4.1 Labor conflicts and employee disruptions

Instances of strikes, protests, and unfavorable working conditions can significantly disrupt operations and damage a company's image. Major companies, like Nike and Amazon, have faced significant criticism due to labor disputes in their international operations. Such conflicts can lead to delays in production, interruptions in supply chains, and negative reactions from customers and advocacy groups.

3.4.2 Mistakes and management challenges

Missteps in planning, demand forecasting, or procurement—especially in high-stress scenarios or when data is limited—can lead to issues like overstocking or stock-outs. To address these challenges, organizations should invest in workforce training, develop effective knowledge management systems, and adopt decision-support tools that help employees make well-informed decisions. By tackling these human-related challenges, companies can create a more resilient and efficient work environment,

Risk type	Description	Examples
Natural risks	Environmental and climatic disruptions	Earthquakes Floods Climate change
Economic risks	Market volatility, macroeconomic shifts	2008 Financial Crisis Raw material prices Currency fluctuations
Technological risks	IT-related failures and digital threats	Cyberattacks System breakdowns Data breaches
Human risks	Labor, management, or social failures	Strikes Poor forecasting Labor protests

Table 1.
Supply chain risk framework.

ultimately enhancing their operational efficiency and boosting their reputation in the market (**Table 1**).

3.5 Human and decision-based risks

In addition to labor unrest and human error, managerial decision-making failures also constitute a significant source of risk in supply chains. Inaccurate strategic or operational choices—such as selecting an unreliable supplier, underestimating lead times, or misaligning inventory levels with actual demand—can lead to persistent inefficiencies, increased costs, and even service disruptions.

3.5.1 Wrong decisions in operations

Decision-based risks often stem from a lack of reliable data, inadequate forecasting models, or ineffective communication among departments. For instance, overestimating demand might result in excessive stockpiling, leading to higher holding costs and potential obsolescence. Conversely, underestimating demand can lead to stockouts and lost sales. A poorly chosen supplier can lead to quality issues, delayed deliveries, or compliance violations, which may have long-term repercussions on brand credibility and customer satisfaction.

Studies suggest that companies with robust decision support systems (DSS) and integrated planning tools—such as demand sensing and real-time analytics—are better equipped to avoid such pitfalls and maintain operational stability [18].

3.6 Political and social risks

Political and social risks encompass a broad set of external, often uncontrollable forces that can drastically alter the landscape of global supply chains. These include

- government policy changes
- regulatory shifts
- geopolitical tensions
- trade restrictions and tariffs
- sanctions
- armed conflicts
- public protests or civil unrest
- wars, sanctions, and political instability

One of the most disruptive political risks arises from economic sanctions or military conflicts that directly obstruct cross-border supply flows. For example, the US sanctions on Iran significantly curtailed the nation's ability to engage in global trade, forcing both domestic and foreign companies to reconfigure their sourcing and distribution networks. Similar impacts were observed in the aftermath of the

Russia-Ukraine conflict, where disruptions in grain, energy, and raw material exports caused ripple effects across multiple industries worldwide.

3.6.1 Social movements and public pressure

Beyond formal political actions, social dynamics—such as growing activism around labor conditions, sustainability, and ethical sourcing—are reshaping supply chain expectations. For example, multinational corporations have faced consumer backlash and operational disruptions due to allegations of forced labor or inadequate working conditions in supplier factories. Companies like Amazon, Nike, and Apple have all experienced reputational and logistical consequences due to such controversies.

4. Strategies for designing a resilient supply chain

To effectively navigate today's unpredictable and dynamic global environment, organizations must adopt an integrated approach to designing supply chains that are resilient to disruptions. Rather than reacting to crises after they occur, proactive design enables supply chains to anticipate risks and adapt swiftly while maintaining operational continuity.

A critical strategy in building resilience is diversifying the supply base. Relying on a limited number of suppliers, particularly those located in vulnerable or politically unstable regions, increases the risk of disruption. Organizations that diversify their suppliers across different geographic locations mitigate this risk. For example, Apple leveraged its globally distributed supplier base during the COVID-19 pandemic to maintain production when localized lockdowns affected certain regions. Developing strategic partnerships with multiple suppliers, identifying alternatives, and ensuring redundancy in sourcing are essential components of this strategy.

Visibility and traceability across the supply chain further enhance resilience. These capabilities allow organizations to monitor real-time operations, detect anomalies early, and respond promptly. Visibility is achieved through digital platforms that integrate data from suppliers, logistics partners, and distribution channels. Technologies such as blockchain and IoT sensors play a crucial role in enabling accurate tracking and ensuring data transparency. Companies that invest in visibility can identify bottlenecks before they escalate and implement timely corrective measures.

Another essential component is agility, which refers to a supply chain's ability to respond rapidly to fluctuations in supply or demand. Agility is built through modular production systems, reduced lead times, and local sourcing strategies. For instance, Zara's localized production model allows it to adapt to changing market trends within weeks, giving it a competitive edge. Agile supply chains are characterized by flexible logistics, collaborative supplier relationships, and operational-level decision-making autonomy.

Proactive risk management is integral to resilience. This approach involves systematically identifying potential threats, assessing their likelihood and impact, and developing contingency plans. Risk management tools such as scenario planning, risk matrices, and simulation models help organizations prepare for various disruption scenarios. Business continuity planning and crisis management protocols ensure that firms can maintain critical functions even under adverse conditions. Empirical

studies suggest that companies with robust, proactive strategies were better equipped to manage global disruptions during recent crises.

Inventory optimization also plays a pivotal role in resilience. Strategic stockpiling of critical components can buffer against supply interruptions. However, excess inventory carries financial risks, so organizations must determine optimal stock levels using predictive analytics and advanced inventory models. During the pandemic, pharmaceutical companies that maintained reserves of essential medicines and equipment were better able to continue operations.

Lastly, investment in advanced technologies enhances every aspect of supply chain resilience. Big data analytics, artificial intelligence (AI), machine learning, and automation provide predictive capabilities and operational efficiency. These tools enable firms to forecast demand fluctuations, identify emerging risks, and optimize logistics in real-time. Research indicates that companies using advanced technologies are significantly more effective in identifying risks before they materialize, giving them a critical advantage in crisis management.

Together, these strategies form the backbone of a resilient supply chain. When implemented cohesively, they equip organizations with the structural and operational capabilities to absorb shocks, adapt dynamically, and emerge stronger from disruptions.

5. A proposed framework for designing a resilient supply chain

Building on the strategic principles outlined above, this section proposes a structured framework designed to guide organizations through the systematic development of supply chain resilience. The framework consists of five interconnected stages, each contributing to the identification, preparation, execution, and refinement of

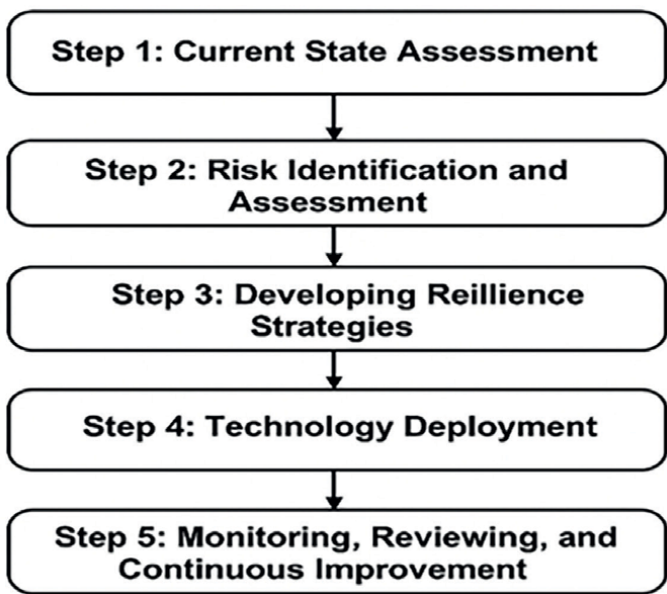


Figure 1.
A proposed framework for designing a resilient supply chain.

resilience-enhancing measures. The first stage involves a comprehensive assessment of the current state. This foundational step entails mapping the entire supply chain network, from raw material sourcing through final delivery. It helps identify critical nodes, potential bottlenecks, and single points of failure. Tools such as SWOT analysis and simulation software (e.g., Any Logic or Simul8) can be used to visualize the network's vulnerabilities and evaluate past responses to disruptions. Next is the risk identification and assessment phase. Organizations must develop hypothetical disruption scenarios, including natural disasters, technological failures, and geopolitical crises, and assess each risk based on its likelihood and potential impact. Analytical techniques, such as risk matrices, Failure Mode and Effects Analysis (FMEA), and Bow-Tie Analysis, support this effort by quantifying exposure and prioritizing mitigation efforts accordingly. Informed by this assessment, the third stage focuses on developing resilience strategies. These strategies involve diversifying suppliers and logistics routes, maintaining buffer inventories, and creating robust emergency protocols. Decision-making frameworks such as scenario simulation models and Multi-Criteria Decision-Making (MCDM) tools (e.g., AHP or TOPSIS) help optimize trade-offs and select the most effective responses. The fourth stage emphasizes the deployment of enabling technologies. Implementing digital tools—such as IoT sensors for real-time monitoring, AI for predictive analytics, and blockchain for secure data sharing—can significantly enhance responsiveness and transparency. These technologies should be integrated into existing Enterprise Resource Planning (ERP) and Supply Chain Management (SCM) platforms for seamless coordination across the network. Finally, resilience requires ongoing monitoring, review, and continuous improvement. Organizations must track key performance indicators (KPIs), evaluate the effectiveness of their resilience strategies, and adapt to evolving risks. This dynamic process includes regular audits, knowledge management initiatives, and a feedback loop that fosters organizational learning and agility. Collectively, these five steps form a practical and iterative roadmap for designing resilient supply chains. They ensure that resilience is not treated as a one-time initiative but as an integral part of continuous strategic management in the face of uncertainty.

A visual representation of these steps can be seen in the following diagram (Figure 1).

6. Successful case studies in designing a resilient supply chain

Examining real-world examples reveals valuable strategies for building resilient supply chains. Leading companies have demonstrated innovative and adaptive responses to disruptions. Apple, one of the largest consumer electronics manufacturers, has faced risks, including natural disasters and geopolitical crises. To mitigate these risks, Apple diversified its production geographically by shifting some components of manufacturing from China to countries such as Vietnam, India, and Mexico. Additionally, the company invested in transparency through technologies like blockchain, enhancing the traceability of critical raw materials such as rare minerals. Apple also maintained inventories of key parts in global warehouses, allowing it to sustain supply chain operations and adapt swiftly during crises like the COVID-19 pandemic [24]. Similarly, Toyota responded to the 2011 earthquake and tsunami in Japan by revising its production philosophy. Moving away from a strict “Just-in-Time” approach, Toyota adopted a “Just-in-Case” strategy, building reserves of critical parts. The company also developed a comprehensive supplier database across multiple tiers

and diversified sources for essential components. These measures enabled Toyota to recover and resume production more quickly than many of its competitors during later crises, such as the COVID-19 pandemic [25]. Walmart, the world's largest retailer, maintained robust logistics operations during various crises by leveraging advanced technologies and strategic planning. The company utilized Big Data and predictive analytics to forecast customer demand and supply chain disruptions. By operating extensive local distribution networks and conducting scenario planning, Walmart was able to rapidly restock shelves and minimize disruptions during events like the COVID-19 crisis [5, 7]. From these cases, several key practices emerge. Geographical diversification of suppliers effectively manages risk, while information transparency throughout the supply chain enables a faster response to crises. The use of advanced analytics and monitoring technologies is critical for anticipating and managing disruptions. Maintaining stockpiles of vital items enhances organizational resilience, and regular crisis scenario planning prepares companies both mentally and operationally for unexpected events.

7. Challenges and barriers in designing a resilient supply chain

Designing a resilient supply chain involves navigating a myriad of complex challenges, making the process both demanding and time-consuming. A key challenge arises from the inherent complexity of supply chains. Organizations often operate within expansive networks that include suppliers, distributors, and partners, complicating efforts to achieve transparency and coordination. To address these challenges, many companies are adopting supply chain management (SCM) software, which allows for the simulation and modeling of the entire supply chain structure, thereby enhancing visibility. Additionally, integrating digital platforms that consolidate information from suppliers and distributors can significantly improve transparency. Forming strategic, long-term relationships with crucial suppliers, rather than relying solely on short-term contracts, can further strengthen the integrity of the supply chain. Another significant challenge is the financial burden associated with resilience measures. Investments in advanced technologies, strategic reserves, or diversified resources may be perceived as costly. However, organizations can justify these expenses through comprehensive cost-benefit analyses that evaluate the long-term advantages of resilience compared to the initial investments. Utilizing cost-effective digital solutions, such as enterprise resource planning (ERP) systems, can help manage costs. Implementing financial risk management strategies is also essential for addressing uncertainties related to significant investments. Cultural and organizational resistance often presents further obstacles. Adopting flexible supply chain strategies may require changes in an organization's culture and employee attitudes. Resistance can arise from various stakeholders, including employees, management, and suppliers. To overcome this, it is essential to develop training programs that empower staff to embrace new technologies and processes. Cultivating a culture focused on resilience ensures that employees understand the long-term benefits of these changes. Ongoing collaboration with suppliers and partners can also foster a shared commitment to resilience objectives. Predicting and managing risks remain inherently challenging due to the unpredictable nature of crises, such as pandemics or natural disasters. Despite using sophisticated analytical tools, some emergencies may be difficult to foresee. Organizations can enhance their crisis preparedness by employing advanced predictive modeling techniques, such as machine learning and

big data analytics, to simulate potential crisis scenarios. Establishing rapid response systems allows for swift reactions, while a shift from reactive to proactive risk analysis promotes continuous vigilance. Technological and infrastructural limitations also pose significant challenges. Integrating innovations such as the Internet of Things (IoT), blockchain technology, and big data analytics requires substantial upgrades to existing IT infrastructure, which can be both costly and complex. A phased approach to infrastructure enhancement, combined with partnerships with technology providers, can help organizations access essential new tools while managing expenses effectively. The use of cloud technologies offers scalability and cost efficiency by reducing the need for extensive hardware investments. Effective coordination among suppliers and partners is critical for achieving resilience, yet it often encounters challenges. Poor communication and delayed information sharing increase the risk of disruptions. Continuous and robust communication through shared information platforms can significantly improve coordination efforts. Encouraging transparency and collaboration through joint contracts and agreements can further solidify partnerships. Ultimately, many supply chains are hindered by data gaps and informational inadequacies, leading to suboptimal decision-making. Implementing advanced data management systems that can effectively collect, process, and analyze information is essential. Additionally, recruiting skilled data professionals enhances an organization's ability to derive value from existing data, thereby supporting more informed decision-making within the supply chain.

8. Conclusion

In today's world, characterized by increasing volatility and complexity, building and maintaining a flexible supply chain is crucial for an organization's resilience and long-term success. Disruptions—such as natural disasters, pandemics, geopolitical conflicts, and rapid technological changes—are no longer rare occurrences; they are common challenges that require adaptive and proactive responses. A flexible supply chain is not just about reacting to crises but also about anticipating potential risks, absorbing shocks, and quickly recalibrating operations without significant loss of performance. This dynamic responsiveness relies on several interrelated factors. First and foremost is the pursuit of information transparency, which involves seamless visibility and real-time data sharing across all levels of the supply network. Such transparency promotes informed decision-making and speeds up response times during emergencies. Another key element is resource and supplier diversity. Broadening sourcing options geographically and institutionally reduces dependence on individual suppliers, thereby lowering systemic risk. This diversification must be complemented by strong technological integration, utilizing innovations like blockchain for traceability, big data analytics for predictive insights, and the Internet of Things (IoT) for real-time monitoring. These technologies, when combined, transform supply chains into intelligent, interconnected ecosystems capable of self-diagnosis and rapid adaptation. Equally important is the formation of strategic partnerships based on trust and shared goals. Strong supplier relationships enable collaborative problem-solving and foster resilience that no single entity could achieve alone. These alliances facilitate knowledge sharing, joint contingency planning, and mutual support during times of disruption. Ultimately, designing a resilient supply chain requires a holistic approach that combines technological innovation, strategic resource management, and human factors, such as culture and collaboration. Organizations that adopt this

integrated framework are better equipped not only to withstand disruptions but also to seize emerging opportunities, turning challenges into competitive advantages in an increasingly uncertain global marketplace.

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Towards a Sustainability Framework for Operations Management Implementation in the Manufacturing Sector

Eric Amankwa

Abstract

Industries worldwide are becoming sustainability-driven, creating a new business model called sustainable manufacturing. These contemporary organisations are adopting sustainable practices, and sustainability in operations management has emerged as a voice to include the environment and society in our operations. Sustainability is meeting the needs of the present without compromising the ability of future generations to meet their needs, and no organisation is exempt in this regard. Henceforth, to be competitive in the local and international marketplaces, organisations seek to develop exceptional improvement and consequently improve the organisation's performance. However, theoretically, a consensus has yet to be reached concerning the ideal framework to implement these sustainability practices. This chapter speaks to an emergent literature on a sustainability framework for operations management implementation, considering operations management, operations improvement and sustainability. It focuses on the manufacturing sector in South Africa to identify what constitutes an ideal framework to implement sustainability initiatives. In reviewing the literature, it was found that research on the sustainability framework tends to consider just one or two of the three dimensions of sustainability.

Keywords: sustainability, operations management implementation, sustainable development goals, operational improvement, green operations

1. Introduction

Industries worldwide are becoming sustainability-driven, creating a new business model called sustainable manufacturing [1, 2]. These contemporaneous organisations are adopting sustainable practices [3, 4] and sustainability assessment [5] to attain competitiveness. Sustainability is meeting the needs of the present without compromising the ability of future generations to meet their needs [6, 7], whilst sustainability assessment is a procedure that aids decision-making and policy-making about action towards sustainability [8]. Since very little attention has been given to sustainability and a framework for sustainability assessment in practice and theory, organisations often implement sustainability initiatives using either a service centre approach [9, 10]

or manufacturing approach with the key concern to achieve a competitive advantage within the organisation (internal) and supply chain (external) outside the organisation [11]. Henceforth, to be competitive in the local and international marketplaces, organisations seek to develop exceptional improvement and consequently improve the performance of the organisation. However, theoretically, a consensus is yet to be reached concerning the ideal framework to measure sustainability [8, 12]. The conceptual frameworks and models of operations management and sustainability in these organisations are rooted in service organisations in developed countries [9, 10]. However, the literature indicates that it is not equally applicable to manufacturing organisations. As a result, at operational levels, there are inadequate frameworks for integrating sustainability tools for operations management improvement for manufacturing organisations. The current operational problems include persistent and prolonged social and environmental degradation, climate risk, water pollution, heat waves, and site-specific costs to human health and animal welfare [13].

1.1 Research objective

- To identify an ideal framework for sustainable operations management implementation in the manufacturing sector in South Africa.

1.1.1 Research question

- What is an ideal framework for sustainable operations management implementation in the manufacturing sector in South Africa?

This study offered practical support on interdependence among sustainability and the overall integrated effect of operations improvement initiatives, not offered in previous research. Moreover, it presents a new resolving factor (ideal framework for sustainability implementation in the manufacturing sector) for the association between operations improvement and sustainability. Subsequently, chapter 2 focuses on evolving literature on operations management, operations improvement and sustainability.

2. Literature review

2.1 Introduction

A literature review offers a comprehensive outline of literature linked to the theory and blends previous studies to reinforce the foundation of knowledge [14]. This view is supported by [15], who states that a literature review is an organised and logical process for a researcher to critically review the topic of the research. A literature review emphasises the main constructs which flow from the title of the study and helps in endorsing that a fitting research topic has been selected, and there is no replication of prior research. It hence discovers research ideas, enhances the research problem, and gives a sound academic foundation for a dissertation. The review eventually demonstrates a researcher's understanding and knowledge about the theoretical framework relating to the study and can critically evaluate, synthesise and integrate the literature. Ref. [14] state further that a literature review provides a reader with the highest development of understanding about the topic of the research, aiding in identifying prior research gaps and indicating future research paths.

2.2 Operations management

Operations management, as a delivery-focused area in organisations, ensures that a business successfully converts its inputs into outputs efficiently. This section contains the definition of operations management in manufacturing, resource planning and scheduling, location and layout as well as logistics management.

2.2.1 Definition of operation management

Operations management is defined as the management of the activities that relate to the creation of goods and services through the transformation of inputs into outputs [16, 17]. Manufacturing operations are a conversion process that yields a tangible product as output with added value. The available resources within an organisation and the process to convert them into outputs must be designed, managed, directed, and controlled to deliver the planned goods and services [18]. The operations management function of the organisation takes responsibility for the entire process of converting inputs to outputs. Through performance evaluation and customer feedback, the required adjustment is made at the input, transformation process and output level, which leaves no room for sustainability as depicted in **Figure 1**.

2.2.2 Operation management activities in organisations

Ref. [19] indicate that operations management is the design, operation, and improvement of the systems that create and deliver the firm's primary products and services. The literature asserts that greater integration among operations management activities and availability of pre-established operating standards are fundamental for attaining complete manufacturing performance issues of product availability, efficiency, features, and quality in manufacturing organisations [17, 20]. For this study, operations management activities are a set of interdependent and interacting

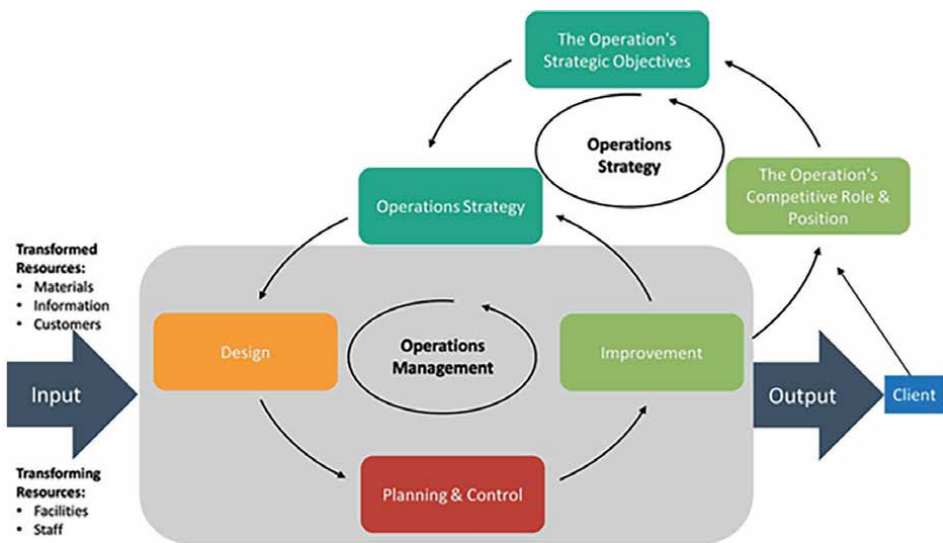


Figure 1.
A general model of operations management. Source: [18].

activities performed in a transformation process using the required resources to create value for both the customer and manufacturer [16, 21]. The literature reviews conducted on the constructs of operations management and operations performance are delineated. This section presents a critical evaluation of the literature on the main constructs of operations management activities and operations performance.

2.2.3 Resource planning and scheduling

From an operations perspective, the objective of resource planning and scheduling is efficient and effective utilisation and management of material, human, and financial resources to get goods and services for value and customer satisfaction. In a sector of high product demand variations, effective resource planning and scheduling are highly significant tasks that require strong integration with manufacturing process design [22]. The transformation process model view claims that before the vertical integration, resource planning and scheduling tasks mostly require strong relations with job design, process design and layout, logistic issues, and operations performance objectives [16, 20]. Research confirms that inputs, resource planning, and scheduling of employees, tasks, facilities, and maintenance practices have a significant impact on process productivity and improvement, minimising production time and costs in various manufacturing contexts [23].

2.2.4 Location and layout

The location and layout of a manufacturing operation are concerned with the physical location of its transforming resources. In a simple context, the layout decides where to put machines, facilities, equipment, and staff in the operation. Availabilities for infrastructure, manpower, raw materials, and accessibility are collective considerations in manufacturing location decisions [16, 20, 24]. According to [16], facility layout refers to the arrangement of work centres, machines, warehouses, departments, and other resources needed for the production of goods and services. Effective manufacturing location and layout strategy have a significant impact on the operations process and performance. The empirical evidence indicates that location and layout affect both process improvement and operational performance. As an illustration, location and layout have a positive effect on enhancing process improvement and reducing time, cost, and information processing through improved data and communication [24].

2.2.5 Logistics management

The importance of logistics management has been increasing recently [25], and therefore, [26] suggest that logistics management should be considered an integral part of the operations process and must be carefully managed. The empirical literature confirms that logistics management has a positive effect on decreasing costs, reducing process interruption, delivery time, and customer satisfaction [25, 27]. Accordingly, it is emphasised that strong operational alignment among operational activities and improvement in manufacturing organisations is essential for attaining and sustaining greater operational capabilities, manufacturing quality, and competitive advantage. Notwithstanding this, operations management concepts are mainly extracted from external and organisational viewpoints, creating little conceptual clarity from the internal transformation systems standpoint. Henceforth, it becomes justifiable to

conclude that the perception of operations management activities from the internal operations process view has not been well studied. Additionally, the associations among them are not supported by empirical evidence in manufacturing settings.

2.3 Operations improvement initiatives

Even a well-designed operation with activities planned and controlled is capable of improvement. This section comprises the definition of operations improvement initiatives, techniques and approaches of improvement initiatives, failure prevention and control, total quality management and manufacturing process design.

2.3.1 Definition of operations improvement initiatives

Ref. [28] defines operations improvement as the act of improving process efficiency by eliminating waste and removing obstacles preventing the continuous, uninterrupted flow of materials and information through the value stream. Achieving greater improvement is important for attaining greater product differentiation, quality, customer retention, and loyalty, which are fundamental for achieving competitive advantage and profitability in manufacturing organisations [29, 30]. In consideration of multidimensionality and significance for manufacturing organisations, more conceptual and empirical studies have been conducted on identifying and defining operations improvements in different manufacturing settings [31–35]. These theoretical approaches are more inclined to explain the issue from an external contingency and organisational level factors perspective. Therefore, it is concluded that the evidence on the concept of operations improvement and its operational alignment with sustainable initiatives is not well indicated in the current academic literature.

2.3.2 Techniques and approaches of improvement initiatives

Improvement initiatives, in broad terms, can be grouped into approaches and techniques. Before adopting a technique or approach, it is imperative to measure and analyse the actual performance to assess readiness factors and maturity of the improvement initiative, which increases the likelihood of sustaining the improvement [36–40] emphasise that organisations that fail to integrate improvement measures with organisational readiness tend to experience poor product quality and low operational and organisational performance. However, from the manufacturing operations perspective, [13, 41] indicate that improvement initiatives in manufacturing consist of productivity initiatives, production system improvement and quality measures. The operational alignment between operations management activities and improvement initiatives is essential for identifying and dealing with non-sustainable practices in manufacturing organisations.

2.3.3 Failure prevention and control

Failure can be described as a product failing to perform its desired function, as described by the expectations of the customers. Failure emerges from the deviation from standards in the conditions of machines, methods, materials, and workforce, affecting the quality of a product or a process [42]. Nevertheless, [43] emphasised that, in the current fierce global competitive markets, companies need to optimise their business performance for sustainable operations by correctly predicting product failure, after-sales services, and warranty time to optimise and allocate resources

effectively. In recent developments in manufacturing operations [44, 45] recommended that by collecting big data, organisations can predict the failure of both their products and processes. Since most existing failure prevention techniques are established with a performance motive, it can be concluded that failure prevention and recovery are crucial elements of manufacturing improvement in organisations.

2.3.4 Total quality management

Total quality management (TQM) is both a philosophy and a set of guiding ideologies to get everyone involved in the process of long-term sustainability and continuous improvement [46]. Similarly, [18] state that the focus of TQM is on meeting the needs and expectations of customers, covering all parts of the organisation, including every person in the organisation, examining all costs which are related to quality, especially failure costs and getting things 'right first time, developing systems and procedures which support quality and improvement, and developing a continuous process of improvement. In manufacturing operations, TQM principles have been used in improvement initiatives, which yield success and contribute meaningfully to improving the internal organisation and external customer [47–49]. Given the manufacturing enterprise, there are various activities, and diverse employees [46]. Since TQM is a holistic approach that puts quality at the heart of all activities in an organisation, it is a vital consideration in improvement initiatives.

2.3.5 Manufacturing process design

Manufacturing process design refers to the arrangement of resources and activities that transform inputs into outputs that satisfy both internal and external customer needs, and are the building blocks of all operations [50]. Recently studies have shown that manufacturing process design is positively related to effective process management resulting in performance excellence and improved production yields in automotive, refiner pulp, chemical, beverage, garment, hardwood flooring, construction, and defence manufacturing operations [51–58]. Despite this, the effect of process design is predominantly discussed from the external and organisational level variables [59]. However, authors assert that selecting the right process improvement methodology and its incorporation with the appropriate layout, job design, logistics, and scheduling activities is more critical for attaining operational goals of effectiveness and efficiency [20, 60, 61]. Therefore, it is resolved that the concepts of manufacturing process design and management are incomplete from the transformation systems perspective since process design and its sustainability factors were least likely included in earlier research models.

2.4 Sustainability

Sustainability has become a global concern even though its origin can be traced back a whilst in human history. In this section, sustainability is defined, sustainable development goals, the nature of sustainability initiatives and sustainable manufacturing are contained.

2.4.1 Definition of sustainability

The World Commission on Environment and Development (WCED) of the United Nations (UN), referred to as the Brundtland Commission, defines sustainability as

meeting the needs of the present without compromising the ability of future generations to meet their own needs [6, 7]. From the International Institute of Sustainable Development's (IISD) viewpoint, sustainability focuses on improving the lives of all Earth's citizens without increasing the use of natural resources beyond the capacity of the environment to supply them indefinitely [62]. The five-capital model definition of sustainability is geared towards the different kinds of capital from which we derive the goods and services to improve the quality of our lives, namely natural capital, social capital, manufactured capital, and financial capital [62, 63]. Significant to these definitions is the sustainability approach to the Trippe bottom line. This means improving the economic and social quality of life whilst reducing impacts on the environment and nature [62]. For this study, sustainability considerations will be drawn from the triple bottom line viewpoint.

2.4.2 Sustainable development goals

The UN adopted a declaration aiming to foster the global agenda to achieve the 17 Sustainable Development Goals (SDGs) with 169 targets for the 2023 agenda. This development intends to tackle a range of issues from economic growth and climate change to poverty [64]. Of particular interest to this study are efforts geared towards SDGs 9 (Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation) and SDGs 12 (Ensure sustainable consumption and production patterns). Nevertheless, in academia and practice, both scholars and practitioners have emphasised inadequate knowledge specifying the role of organisations in accelerating the SDGs and their impact on practice [65]. In this regard, a framework for sustainability assessment is inevitable.

2.4.3 Nature of sustainability initiatives

The nature of sustainability initiatives in manufacturing industries is geared towards the triple bottom line consideration, which is made up of environmental, social, and economic considerations. Whilst industries seek profit as the ultimate goal for sustainability, environmental and social sustainability seek to promote human and community well-being [66]. The purpose of the triple bottom line is to seek a balance between society, the environment, and economic prosperity [62, 67].

2.4.4 Sustainable manufacturing

Sustainable manufacturing as defined by the United States Department of Commerce is the creation of manufactured products that use processes that minimise negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound [16, 24]. For manufacturing to be sustainable, it must produce a set of organisational and technical solutions that contribute to the implementation and development of innovative practices, technologies, and methods in the manufacturing field, to address material shortages worldwide, mitigate surplus environmental loads and give life cycles of products an environmentally benign [68]. Sustainable manufacturing, at the product, process, and systems levels, must demonstrate reduced negative environmental impact, offer improved energy and resource efficiency, generate a minimum quantity of waste, provide operational safety and offer improved personnel health whilst improving the product and process quality with overall lifecycle cost benefits [69].

Unambiguously, sustainable manufacturing ensures that operational processes such as product design, procurement, managing inventory, quality control, selecting appropriate technology, scheduling, maintenance, production, and packaging have no negative effects on natural resources and stakeholders [70].

2.4.5 Lifecycle assessment (LCA)

In the context of sustainability, life cycle sustainability assessment (LCSA) has emerged as a necessary tool. LCSA encompasses all three dimensions of sustainability from a life cycle standpoint. It merges life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (SLCA). The growing concern of the life cycle sustainability assessment (LCSA) approach is compensated by a large number of challenges hampering its successful realisation. Ref. [71, 72] highlighted the key concern, specifically the unequal maturity of the methodology applied to evaluate sustainability in three dimensions: social, environmental, and economic pillars. **Figure 2** illustrates both the conventional and integrated lifecycle assessment.

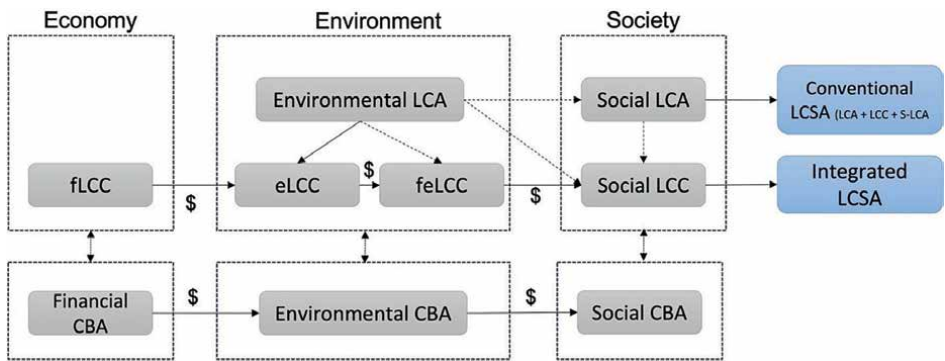


Figure 2.
A life cycle assessment. Source: [72].

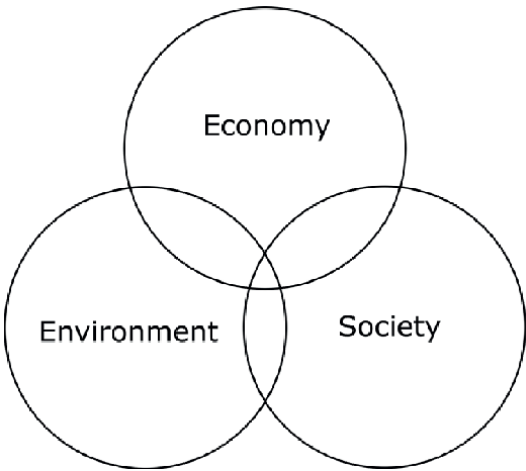


Figure 3.
Triple bottom line. Source: [76].

2.4.6 Triple bottom line (TBL)

The triple bottom line (TBL) of planet, profit and people, as a term, was first introduced by [73], and has become a dominant approach to sustainability globally [74]. This model sets key long-term strategies for organisations making the transition to sustainability, built on three vital elements of sustainable development: social equity, economic benefits and environmental quality [75]. The most commonly accepted model describing sustainability and the TBL is the Venn diagram explanation (**Figure 3**). Often referred to as the nested spheres model. Sustainability can be clarified as the place where the three parameters overlap. Nevertheless, one of the drawbacks of this model is that it is unable to show hierarchical levels between the three parameters. As a result, [77] specified it as a “weak approach” to sustainability and suggested a “strong approach” to it. The concept of the TBL has been clarified below in **Figure 3**.

3. Findings

This study aims to identify an ideal framework for sustainable operations management implementation in the manufacturing sector in South Africa. With the research question: What is an ideal framework for sustainable operations management implementation in the manufacturing sector in South Africa? Finding of the study indicates that environmental assessment elements are usually well-managed. However, harmonising economic and social assessments presents an intricate task that leads to irregularities in the results and their interpretations.

4. Discussions

This can give an opaque understanding of the mutual effects across the TBL. Moreover, it can be recognised that the TBL of People, Profit and Planet has been considered as a foundation for a competitive edge in the marketplace. Therefore, sustainability integration in organisations’ operations strategy is vital for success. The challenge for organisations is to find the ideal sustainability framework that incorporates all three dimensions of sustainability for operations management implementation. This research advances sustainability practices in operations management and advocates that an ideal sustainability framework for the manufacturing sector should infuse the people, profit and planet.

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Section 3

Process Excellence, Lean, and Human-Centric Operations

Leveraging Lean Manufacturing through Computer Modeling and Simulation for Production Process Improvement

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Abstract

Intensified competition, rapid technological advancements, and shifting customer demands are key catalysts for the global manufacturing landscape. Manufacturing companies that aim to remain competitive have re-evaluated and transformed their business models *via* sophisticated technologies to enhance production efficiency and customer focus. Nevertheless, implementing such innovations often requires substantial investments in infrastructure, training, and system upgrades, which can be challenging for small and medium enterprises (SMEs). The current work examined an SME specializing in aluminum casting products that struggled to reduce the extended production time for high-volume products to meet production planning targets. Discrete-event simulation (DES) modeling served to replicate the current production processes and analyze the system behavior under various production process improvement strategies. A notable 71% reduction in the total production time was required to achieve the monthly planned quantity based on the DES analysis outcomes. Moreover, system dynamics (SD) modeling was employed to evaluate actionable improvement strategies aimed at expanding production capacity and assessing their potential to receive more orders and meet upcoming demand. The SME could meet a demand of 8000 units per month and increase its production capacity by combining overtime and outsourcing strategies. The findings from both simulation techniques offered real-time insights into the impact of proposed improvement strategies on operational and strategic performance measures to understand process optimization and improve production efficiency and capacity with minimal investment.

Keywords: lean manufacturing, process improvement, simulation modeling, discrete event simulation, system dynamics

1. Introduction

Manufacturers, specifically SMEs, encounter significant challenges in improving current production processes. Determining effective strategies to re-evaluate and improve the current production processes has proven to be a complex phenomenon [1]. Hence, it is vital to identify the key areas for improvement. The SMEs must leverage their internal resources and capabilities by transcending existing production processes to consider the need for adaptability to future challenges. Organizational issues can be effectively addressed by implementing appropriate improvement plans and methods [2].

Some companies may relapse into their previous practices, given the complexities involved in initiating a transformation. Implementing an improvement plan requires substantial commitment and investment from the management and workforce. Given its extensive and complicated nature, operationalizing the improvement plan may not guarantee immediate success [3]. The time-consuming attempt to improve current processes to meet demands could extend over several years. A sound understanding of the overall process, its interconnected activities, the potential effects, the necessary inputs, and the anticipated outcomes is integral for a robust operative improvement plan.

Andersson and Bellgran [4] claimed that the success of process improvement is contingent upon the company management's ability to recognize valuable enhancement opportunities. SME managers continue to face key challenges despite the presence of business process improvement methodologies [5]. Manufacturing companies require techniques that complement specific circumstances to achieve their process improvement objectives. Inappropriate selection can disrupt current processes, even when the initial intent is to enhance them. Thus, careful consideration is required when selecting suitable methods.

The nature of the complexities involved and the analysis required for identifying a solution are the important factors influencing the selection of appropriate process improvement methods [6]. Specific contexts and issues must be understood at strategic and operational levels to choose the right process improvement method for a distinctive problem [7]. Companies that prioritize strategic initiatives focus on radical improvements, while counterparts that emphasize incremental improvements tend to concentrate on operational-level initiatives. Based on Malinova et al. [8], most process improvement methods tend to address operational issues but fail to consider the strategic level aspects. This omission can lead to the failure of overall process improvement strategies.

Manufacturing companies that aim to improve their production process must incorporate suitable techniques that evaluate their current processes to identify areas for enhancement, increase the process performance, and facilitate organizational goal attainment. The absence of a universal procedure denoted the need to customize a method that aligns with specific organizational requirements [9]. While some process improvement methods are implemented more frequently and effectively than others, selecting a specific approach depends on its alignment with organizational requirements and its ability to achieve pre-defined objectives.

2. Literature review

Many manufacturing companies have modified their production processes by integrating the pursuit of process improvement strategies with the significance of

meeting current business demands. The case studies of Aqlan and Al-Fandi [6] and Mulufeta [10] revealed that reducing cycle time, throughput time, and lead time, the ratio of cycle time to takt time, and work standardization leads to an increase in organizational productivity and efficiency. Furthermore, SMEs that implement process improvement initiatives can reduce the level of work-in-process (WIP) inventory [11], operational cost, and on-time delivery [12] while increasing profit and shareholder value, and generating positive organizational outcomes [5].

The strategies for embedding and sustaining process improvement initiatives without reverting to past practices [13] remain underexplored. The application of changes is a key challenge in process improvement [14]. Antony and Gupta [15] highlighted the lack of managerial commitment and support, inadequate communication, incompetent team, poor training and learning, inappropriate selection of process improvement methodologies and techniques, ineffective rewards and recognition system, scope creepiness, sub-optimal team size, inconsistent monitoring and control, and resistance to change as the top 10 reasons why process improvement efforts fail to increase business performance.

The lack of process improvement approaches renders it challenging to fully meet all requirements [16]. Improving organizational processes can range from minor modifications to major transformations. This spectrum of adjustments relies on adopting an approach that facilitates the execution of planned improvements and yielding of anticipated changes. The changes applied without an organized approach may lack the structure required to determine whether the organization has successfully improved its processes. Overall, using adequate methods designed to identify the root causes of problems, eliminating waste, and addressing variations is key to attaining improvement [2].

2.1 Lean manufacturing implementation

The lean manufacturing approach proved to be the most suitable process improvement method for most companies to resolve encountered problems. Lean manufacturing seeks to increase profitability, customer satisfaction, employee motivation, quality, and low manufacturing costs by identifying and eliminating waste by reducing the waiting time between customer requests and lead time. From the customer's perspective, waste implies activities with no added value [17]. Scholars have used single case study [18–20] and multiple case study [21] methodologies to examine lean manufacturing implementation. The selection between these methodologies depends on the research context.

Surveys are used for investigating lean implementation [22]. Dadashnejad and Valmohammadi [23] employed a set of questionnaires to gather and evaluate employees' perceptions of current processes and operational losses in one manufacturing firm. Lucato et al. [24] also examined lean practices in 51 companies of varying sizes and industrial sectors. The survey revealed key variations in the success of organizational lean initiatives. Belekoukias et al. [25] employed linear regression analysis to explore the relationship between essential lean tools and operational performance measures by modeling the correlation and impact of lean manufacturing practices on 140 manufacturers. Given the focus on subjective opinions rather than objective results, the survey method does not fully capture lean implementation.

Hence, lean implementation studies should emphasize empirical approaches to refine and validate existing theories [26]. Empirical works have delineated how lean implementation affects performance measures. A comparison of the various models

integrating the theory of constraints (TOC) with lean manufacturing revealed both elements to be complementary [27]. This theory aims at identifying and addressing production process bottlenecks to optimize throughput, while lean focuses on systematic waste reduction and elimination for improved efficiency.

Value stream mapping (VSM) is vital for facilitating lean implementation [28]. This instrument is used as the initial step in TOC to identify organizational waste while mapping value-adding activities and information flow in current production processes [27]. This robust lean tool was employed by Memari et al. [20] to perform activities analysis and identify the waste caused by inefficient layout and imbalanced production lines, leading to excessive WIP and unnecessary transportation. Meanwhile, Lacerda et al. [11] applied this tool to pinpoint the bottlenecks in generating plastic automotive components. These investigations, which solely focused on specific production processes without considering the overall product flow in the value stream, underscored discrepancies between the operation and available time for each operator.

Notwithstanding, static VSM fails to determine the complexity of actual processes [29], analyzes the component interactions in a production system, and provides the capability to verify or validate proposed system performance pre-implementation [30]. Irani and Zhou [31] claimed that using VSM in isolation may not generate meaningful results in certain scenarios. When applied to multiple products with different production flow patterns, this tool can prove ineffective. Moreover, VSM does not incorporate economic measures of value and adequately depict the impact of inefficient flows on WIP and product throughput, hence limiting its applicability in complex production settings.

Organizations have adopted and implemented lean manufacturing based on their operational settings [32]. Nevertheless, some researchers choose not to use VSM given lean implementation's absence of universality. Mulugeta's [10] time study conducted to identify waste and improve productivity in a garment manufacturing company highlighted excessive movement and transportation of workpieces between workstations as sources of waste. Khan et al. [19] similarly identified problems in an interior design company with Pareto charts and Ishikawa diagrams *via* Kaizen, 5S, and modification of organizational charts, leading to operational improvements.

Many companies struggle to align their approaches with the management control used to coordinate the process inputs, the process itself, and the process outputs and reduce the effectiveness of lean implementation [33]. This problem is exacerbated for SMEs, given their constrained resources [5]. Lugert et al. [32] also critiqued on how most lean implementation studies prioritize operational performance improvement over the key connection between strategic planning and production processes. Singh and Singh [2] recommended integrating distinctive approaches to address these weaknesses and generate optimal outcomes.

2.2 Computer modeling and simulation

Computer modeling and simulation methods are extensively employed to provide a risk-free environment for evaluating the impact of changes in procedures, processes, and information flow to support process improvement initiatives [34]. Based on Buer et al. [35], emergent technologies serve as a key competitive advantage that improves integrated production processes and operational performance. A robust computer model enables companies to address questions on system modeling, explore alternative scenarios testing, visualize processes with clarity, and alleviate financial risks [36].

The information derived from computer simulation facilitates decision-making in lean manufacturing implementation while also driving companies *via* the execution process to attain the desired outcomes [37]. Computer modeling and simulation provide decision-makers with optimal or near-optimal solutions. These operational tools facilitate the quantification of scenarios pre- and post-implementation [38] to prevent the potential failures resulting from adjustments or modifications and delineate system behavior *via* numerical assessment.

2.2.1 DES application

As hand-drawn maps frequently fail to capture intricate details, static VSM encounters limitations in addressing complex processes in the context of lean implementation. An enhanced VSM method incorporating DES was developed to improve operational performance. Combining process mapping and computer simulation is a key to evaluating multiple improvement scenarios and predicting their potential outcomes [39]. This instrument increases the level of detail for a more accurate representation of production processes. Managers who implement the enhanced VSM can identify time-related and other categories of waste to gauge effective management outputs [40].

Abdulmalek and Rajgopal [37] identified high production waiting times as a source of waste by examining the production processes of several grades of steel used in appliance manufacturing. A hybrid production system integrated with total productive maintenance was proposed to effectively reduce the total production lead time and the average inventory levels across all production stations. Likewise, Schmidtke et al.'s [41] case study on the production of exhaust gas purification catalysts revealed high inventory levels and excessive motion due to long production lead time and ambiguity in customer orders. Implementing process integration, controlling the production process at a single step designated as the pacemaker, and maintaining an optimal WIP level in the future state were proposed as three key improvement strategies.

Helleno et al. [29], who examined a manufacturing cell in the Brazilian metal industry, highlighted the need to increase production capacity in the wake of high demand fluctuations. Proportionally increasing current resources, which resulted in the lowest investment cost and greater flexibility, and adopting new process technologies, which required higher investment but achieved better productivity, were the strategies proposed. Omogbai and Salonitis [42] addressed material delays that increase processing times in their case study by re-routing production flow to minimize changeover time and WIP and improve machine utilization. Similarly, Mohd Yusoff et al.'s [43] study involving a Malaysian automotive manufacturing plant indicated an imbalanced workload across assembly workstations as a key challenge. The plant effectively improved production volume and overall productivity by rearranging the layout, adding a workstation, and balancing operator workloads.

Using a combination of lean, simulation, and optimization, Uriarte et al. [44] targeted increased production capacity in a highly variable production environment to improve an automotive component machining line's performance. Despite the lack of details on specific improvement strategies, their approach successfully enhanced material flow, optimized layouts, and integrated the new transport system with existing production to reduce waiting time, unnecessary transport, and inventory levels. Yang et al. [36] examined a fishing net production system with the same approach to determine the optimal combination of five key parameters with minimal performance

variance. The case study, which involved the same company as in their previous research, focused on strategic planning decisions. Notwithstanding, this study solely concentrated on the operational level.

2.2.2 SD application

The SD served as a simulation tool for improving process improvement and business performance *via* scenarios that evaluate potential strategic actions for future decision-making. Specifically, Georgiadis [45] examined the impact of capacity planning policies on long-term profitability by structuring an SD model to assess the decision-making process, which balances profit and capacity utilization. Mendoza et al. [46] used the SD model to explore different aggregate production planning strategies and analyze how demand variability and production time affect supply chain performance. Likewise, Deif and El-Maraghy [47] developed this model to explore the effects of implementing production leveling on key performance indicators of inventory levels, lead time, and customer satisfaction.

To simulate the capacity investment and formation patterns of self-interested production agents, Wang et al. [48] constructed an SD model to aid decision-makers in visualizing the dynamics of capacity formation and waste material exchanges, testing different capacity planning and incentivization strategies, and investigating the impact of price disruptions. An SD model was established by Suryani et al. [49] to address corn productivity and production issues resulting from land expansion by adding feedback loops, introducing new parameters, modifying the feedback loop structures, and altering model parameters. Moreover, Filho and Uzsoy [50] integrated an SD model with a factory physics approach to analyze the impact of simultaneous continuous improvement in setup and repair time on manufacturing cycle time in uncertain conditions.

The reviewed SD papers are independent studies that collectively enhance decision-making *via* scenario development. With each study addressing a novel problem, SD models serve to evaluate the impact of strategic actions on key performance indicators. These approaches indicate positive results in improving current performance, albeit with a sole focus on isolated improvement aspects. Potential synergies between strategic and operational levels were left unexamined.

2.2.3 Combination of DES and SD

Both DES and SD varied in their focus and methodology. The DES is stochastic in nature and emphasizes the finer details of a system that generates varying results with each run. Multiple executions and statistical methods are required for this variability, necessitating the analysis of the outcomes. Conversely, SD only requires a single execution to produce consistent results with every run. The inclusion of SD or DES in a process improvement project must be justified by their ability to reduce implementation risks, as computer simulation models incorporate time as a critical factor [51]. It is vital to understand how process changes impact key performance measures for organizational success [39].

The integration of DES and SD is a hybrid approach to harnessing the strengths of both techniques and addressing complex systems that prioritize detailed event-based interactions and dynamic system behaviors. Brailsford et al. [52] categorized types of integration into three categories: (i) automated integration contained within a commercial software package (CSP); (ii) manual integration, literally copying and

pasting data from one CSP into another; and (iii) integration using intermediate tools, such as Microsoft Excel. Regardless, the number of comprehensive frameworks outlining the full range of options available to modelers remains lacking. Technical considerations for integrating these methods and the significance of project-specific contexts are key aspects that remain relatively unaddressed [52, 53].

In process improvement, the combined use of DES and SD provides an innovative and comprehensive approach. Bowles and Gardiner's [39] study involving a manufacturer of pre-hung door machinery aimed to improve its design document control process by forming a cross-functional team for prioritization and approval and establishing standard operating procedures (SOP) for the engineering group. These measures effectively addressed 10 out of the 19 issues pertaining to the document control process. The SD was used to supplement the insights gained from process mapping and evaluate the impact of various process improvement scenarios on multiple performance measures during their redesign phase.

Bowles and Gardiner's [39] use of SD supported the recommendations developed *via* process mapping, with additional insights leading to further suggestions for improvement. Notwithstanding, the current SD model served to assess the predetermined strategies for adding production capacity following the optimal capacity value elicited from the process improvement strategy developed *via* DES. A sequential mixed-method approach comprising DES and SD was employed in the following case study, drawing on the methodology outlined by Morgan et al. [53]. This approach was used to evaluate different levels of production process improvement strategies and holistically facilitate the company's exploration of various scenarios.

3. Case study

The case study chose to examine a sample company manufacturing various aluminum casting products. This SME operates a job shop production system comprising three key stages: diecasting, secondary processing, and machining. Following a pre-defined process sequence, production is organized in batches and adheres to standard process cycle times. Products move sequentially through these stages and advance to the next stage only after the batch reaches the predetermined quantity at each stage. The machining processes were identified as bottleneck processes, limiting the overall system capacity, with each bottleneck process having a cycle time of 400 seconds per unit.

The monthly production time available was 28,380 minutes, based on two daily shifts of 10.75 hours each and over 22 working days per month, as per the production planner. The theoretical maximum production capacity was calculated at 4257 units per month with this value. Specifically, the total production time available was divided by the bottleneck process cycle time. The monthly production target was set at 4000 units, which accounted for rejection and downtime. The organizational challenges were evidenced by comparing planned and actual production outputs over 6 months. While the planned quantity remained a fixed quantity each month, the actual production output was found to fluctuate.

The planned targets were not attained despite the implementation of a fully automated high-pressure robotic diecasting process in the production plant. This failure can disrupt delivery schedules, lower customer satisfaction, compel customers to switch to competitors with more reliable alternatives, and undermine the company's long-term competitiveness and market reputation. Notably, companies with extended

production time are unable to swiftly adapt to order volume fluctuations, hence reducing operational flexibility. The organizational management should actively seek optimal solutions to improve production process efficiencies.

Companies also strive to increase production capacity and accommodate growing workloads, particularly when current production processes have reached their limits or cannot be scaled further, using relevant strategies. The need for transformative innovations becomes evident with the continuous rise in customer demand. Expanding production capacity potentially enhances the organizational ability to receive more orders and address customer demands. Nonetheless, the complexities underlying production capacity expansion necessitate serious consideration of the expansion time required, the risks related to investments in new facilities and technology upgrades, budget constraints, and current operational capabilities.

4. Methodology

The research flow (refer to **Figure 1**) starts by formulating the problem before developing the research objectives. This step requires a sound understanding of the existing production system and the challenges encountered by the sample company. This method involves determining the performance metrics to measure the system of interest and outlining the performance objectives to be achieved. The subsequent step entails collecting data in the form of input parameters and supplementary details necessary to represent the system.

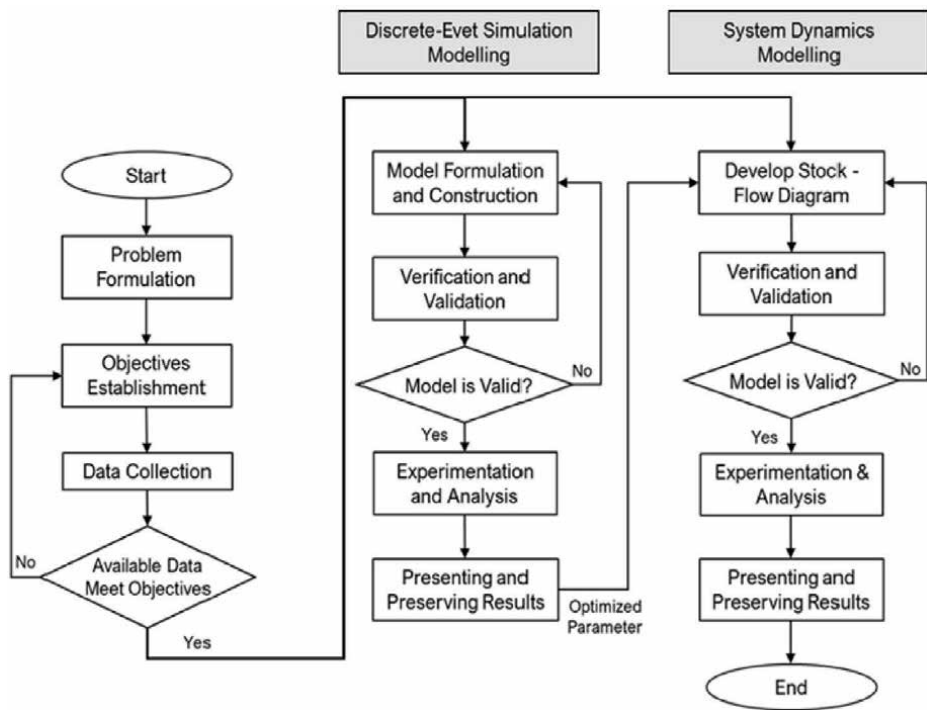


Figure 1.
Research flow framework.

Direct observations made during plant visits, focus group interviews, and the assessment of production reports and process flow charts served as empirical data. Subsequently, a detailed simulation specification and a computer model accurately representing the actual system were developed once the collected data was aligned with the established research objectives. Known as the “base model,” this representation defines the various components in the production processes, their interrelationship, and flow of inputs and outputs throughout the system to ensure that the simulation model encompasses all key aspects. The design phase begins by thoroughly analyzing the system components, which includes the machinery and manpower involved, production flow and sequence, as well as production planning schedules. In this vein, the built computer model reflects the complexities and interdependencies inherent in the actual production environment.

Experiments are then conducted by identifying potential scenarios to explore, adjusting input parameters, policies, and conditions, and estimating model outputs *via* statistical methods. This study provided a sound understanding of the system’s behavior, evaluated different improvement strategies, and measured the impact of changes by running multiple simulations and analyzing the elicited outcomes. With regard to DES, this iterative process also applies to the SD model development. The optimized parameters derived from DES (capacity and throughput time) served as key inputs for SD model construction in addition to using the collected data. These parameters provided key insights into production capacity by calculating the quantity that can be produced during normal production hours and overtime.

5. Results and discussion

The results of this study aimed at evaluating process improvement strategies in improving existing production processes. The study employs an integrated approach, combining DES and SD. This integration offers a comprehensive assessment of both short-term operational performance and long-term capacity planning. By integrating empirical data with simulation models, this approach evaluates the impact of production process improvement strategies and offers practical recommendations prior to implementation.

5.1 Scenario testing of DES model

The simulation results of the “base model” indicate that the system’s average throughput time is 1619.8 minutes, with 1599.1 minutes spent in queues. These findings highlight significant inefficiencies within the system, where transforming a single product from raw material to a finished good takes approximately 16.2 minutes. Consequently, for the sample company to produce 4000 units in a month, a total production time of 64,792 minutes is required. This underscores that the actual production processes are severely impacted by substantial delays caused by prolonged waiting times between production stages. To meet the desired production output, align with planning targets, and optimize capacity, substantial improvements to the existing production processes are imperative.

The base model was modified to assess improvement strategies through scenario testing. In the first adjustment (referred to as the improvement scenario one model), the machinery involving three machines was restructured to resolve bottlenecks at machines two and three. These two bottleneck processes were reorganized to operate

in parallel, allowing them to function simultaneously and improving the overall production flow. This modification was based on the similarity between the two processes, with the only difference being the type of cutting performed.

Consequently, the modifications from the model of improvement scenario one were retained, with additional adjustments made (referred to as the improvement scenario two model). The key adjustment involved dividing the created entity into smaller batches, a strategy known as production leveling. The second modification introduced a more flexible approach by subdividing the total entities created into smaller batches when transitioning between modules.

In the following scenario testing, the changes involve maintaining smaller batches for the total production quantity while reverting the arrangement of machines 2 and 3 from a parallel configuration back to the original series configuration (referred to as the improvement scenario three model). The aim of this change is to assess which modification yields the best results. Surprisingly, the simulation outcomes for this scenario testing are significantly better than those of the previous two improvement scenarios.

5.1.1 DES results

Table 1 presents a comparison of the simulation results for the base model and the three proposed improvement scenarios. This analysis offers valuable insights into the impact of each modification on production efficiency by reducing throughput time, waiting time, and the number of WIP while also exploring innovative solutions that can drive substantial productivity gains. Such a comprehensive comparison enables informed decision-making in process optimization. By examining these results, the sample company's management can determine which strategy delivers the most significant improvements before implementation. This analysis highlights the role of data-driven decision-making in enhancing operational performance. The decision to test the improvement strategies focuses on leveraging internal resources and capabilities while aligning them with the company's existing challenges.

The substantial improvements presented in **Table 1**, with improvement scenario three achieving an impressive 71% reduction in throughput time, highlight the effectiveness of the proposed strategies. These efficiency gains allow the sample company to meet its monthly production targets while adapting more effectively to market demands. By optimizing batch sizing through production scheduling, the company can now produce up to 6000 units per month without incurring additional operational costs as well as disrupting the delivery schedules.

By leveraging simulation-based experimentation, the sample company gains a powerful tool to thoroughly analyze its existing production processes. This approach

Performance measures	Simulation model			
	Base	Scenario 1	Scenario 2	Scenario 3
Average throughput time (minutes)	1619.8	1192.1	595.2	471.9
Average waiting time (minutes)	1599.1	1171.9	573.6	450.2
Production time required (minutes)	64,792	47,708	23,808	18,876

Table 1.
Comparison of simulation results.

enables a detailed examination of workflows and process bottlenecks, providing insights that would be difficult to achieve through VSM analysis. Using simulation analysis, the company can systematically identify waste and constraints, which often go unnoticed in complex production systems. Eliminating or minimizing these inefficiencies not only streamlines operations but also improves overall productivity.

5.2 Scenario testing of SD model

A stock-and-flow diagram is a quantitative model derived from the interconnections of variables forming a causal loop diagram. It integrates equations and relevant input parameters drawn from production records, management decisions, and optimized outputs generated by the developed DES model, such as throughput times and the maximum units producible within the available monthly production time. This SD model operates on the assumption that the current production processes have reached their capacity limits and cannot be further scaled. As a result, it underscores the need for improvement strategies aimed at increasing production capacity and capturing additional orders to support future growth.

Two actionable strategies were identified for scenario testing: implementing overtime work and outsourcing, as decided by the sample company's management. These strategies aim to expand production capacity through quick wins and cost-effective solutions that avoid significant investments and technical complexities. While conventional methods can provide estimates of the potential outcomes of these strategies, SD techniques offer a more detailed analysis of the entire system and extensive system feedback.

Based on the results of the improved DES model, the current production capacity is approximately 6000 units per month. Outsourcing adds an extra capacity of up to 2000 units per month. Additional units can alternatively be produced during overtime, depending on the number of overtime days in a month. The overtime duration is divided by the optimized throughput time generated by the DES model to determine how many units can be produced within this period. Implementing both improvement strategies at maximum capacity may lead to operational constraints, including storage issues, overproduction, and waste.

5.2.1 SD results

The first scenario for increasing production capacity focuses on testing a single strategy. By utilizing the outsourcing strategy alone, the sample company can achieve the desired production increase, as the outsourcing partner can produce up to 2000 additional units per month. Nonetheless, this approach leaves no allowance for rejected units, as the production output is already at its maximum capacity. Moreover, this strategy proves less profitable because each outsourced unit costs 16% more than the internal operating cost.

With an estimated operating cost of RM180.00 per unit, meeting the additional production demand would require outsourcing 2000 units at a cost of RM208.80 per unit. This results in a total monthly expense of RM417,600, which is RM57,600 higher than the production cost of RM360,000 for producing the same quantity internally. This increased expense would ultimately reduce the company's profit margin.

While using the overtime strategy only, the sample company could produce up to 2198 additional units per month by operating continuously, with two daily

shifts of 10.75 hours each over 30 working days, totaling 38,700 minutes of production time. Dividing this total production time by the optimized throughput time of 4.72 minutes per unit, as determined by the DES model, yields a total output of 8198 units per month. After accounting for rejections and downtime, subtracting the 6000 units produced during regular working hours results in a generation of 2000 units' net.

However, operating continuously, including weekends, is impractical for the production department. Sustained strain on resources and personnel could result in diminishing returns, increased fatigue, and a higher likelihood of errors, ultimately making this strategy unsustainable. Additionally, operating costs increase by 7% per unit with this strategy, raising the cost per unit to RM192.60. Multiplying this by 2000 units results in a monthly overtime cost of RM385,200.

In meeting customer demand effectively, the sample company must integrate both strategies. By utilizing overtime and outsourcing, the sample company can balance the production load, preventing overburdening of both the internal workforce and external facilities. The goal is to determine the optimal combination of these strategies to achieve the desired increase in production capacity in a cost-effective and efficient way. To enhance the outcomes, the initial SD model was modified by adding a proportionality variable.

To increase production from 6000 to 7000 units per month, the sample company utilizes 20% of the maximum output from the outsourcing partner and 40% from overtime. For the next increment, reaching 8000 units per month, the sample company relies on 45% outsourcing and 55% overtime. By refining the simulation model, the company determined that producing an additional 2000 units per month would increase operating costs by RM399,780. This approach saves RM17,820 compared to relying solely on the outsourcing strategy.

5.3 Discussion

VSM, a widely used lean manufacturing tool, is effective in identifying non-value-added activities within processes and resolving bottleneck issues [54]. Al-Rifai [55] emphasized that a detailed analysis of manufacturing processes using VSM can yield substantial benefits by overcoming operational challenges through streamlining operations. Chao et al. [56] suggest that the effectiveness of VSM analysis can be further enhanced by integrating computer simulation, as the transformation of existing production processes requires the incorporation of information systems.

This study adopts an approach that combines process flow mapping with DES modeling to diagnose problems within the production process. While many studies rely solely on VSM to identify bottlenecks as the primary source of inefficiencies [57, 58], this study reveals that the bottleneck processes are not the main factor hindering the sample company from achieving its planned production targets. Instead, the simulation analysis uncovers significant delays caused by extended waiting times between production stages, which slow down operations and prolong production processing durations.

Most studies combining VSM with simulation modeling follow an approach that includes developing a current-state map, analyzing the outcomes, and optimizing the process by designing a future state map. Addressing various challenges often requires improvement strategies tailored to specific production environments, considering unique needs, available resources, and minimal investments. The main goal of such

studies is to improve the operational performance of existing production processes by minimizing or eliminating waste. This improvement is evaluated by analyzing simulation results and calculating the percentage of achievement, as highlighted by Reda and Dvivedi [59], Mishra et al. [60], and many others.

In this study, parallel production, production leveling, and a combination of both were implemented as improvement strategies to optimize the current production process. Analysis from the scenario testing indicated that production leveling produced the most notable improvements compared to the other approaches. It effectively reduced throughput time and waiting time between production stages. A reduction in delays significantly improved productivity and efficiency, creating the capacity to produce an additional 2000 units. The company also can fully achieve its planned monthly production target of 4000 units, well within the available monthly production time.

Furthermore, the approach used in this study goes beyond a single approach in the process improvement study. By combining DES and SD, this hybrid approach not only focuses on waste reduction and process optimization but also strategically plans for future production capacity increases to meet additional demand. This combination is referred to as a sequential approach, where two or more distinct models are executed in sequence, with the output of one serving as the input for the next model [53]. Real-world problems and manufacturing operations are inherently complex, featuring many variables and characteristics, making it uncommon for a single method to effectively address all of them [52].

This study used optimized parameters from the DES simulation results of the designed future state map as input for the SD model. Scenario testing of the SD model was then analyzed to identify practical strategies for expanding production capacity cost-effectively. While the hybrid simulation approach among scholars remains relatively underrepresented, and the technique of combined simulation methods was unclear [52], this study presents a novel approach. It allows decision-makers to assess different improvement strategies before implementation to tackle modern, complex business challenges.

6. Conclusion

Manufacturing companies are undergoing significant transformations driven by various factors, including increasingly volatile markets, shifting customer demands, shorter product life cycles, and rising complexity. In such a dynamic environment, static production systems are becoming less effective as they struggle to keep up with evolving needs. Moreover, the ongoing digitalization of production plays a crucial role in reshaping operations. These trends highlight the growing need for flexible production systems, which require both short-term adjustments to the value stream and cost-effective long-term strategies.

In conclusion, this study makes a significant contribution to the field of operations management, particularly in enhancing production processes. By combining DES and SD, it introduces an innovative approach for evaluating the effectiveness of various improvement strategies. Academically, the study advances knowledge by demonstrating the practical application of these advanced methods in real-world contexts, bridging the gap between theoretical research and industrial practice. These contributions are invaluable for researchers and practitioners aiming to develop data-driven, scalable solutions for production process improvement.

Moreover, the use of computer simulation techniques in this study allowed the company to assess the potential impacts of proposed strategies in a controlled, risk-free environment. This approach facilitated detailed scenario analysis, enabling comparisons of different strategies under varying conditions. As a result, the sample company identified and implemented methods specifically suited to its operational needs and business priorities. The insights derived from these simulations supported informed decision-making, reducing reliance on costly trial-and-error methods in real-world operations.

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Staff Rostering: Tackling Understaffing and Deviation of Working Time from a Research, Business, and Well-Being Perspective

Kimmo Nurmi and Jari Kyngäs

Abstract

Workforce scheduling is a process where the available resources are matched to the volumes of work to be completed. Optimal matching is extremely important for companies and institutions that have employees working on shifts or on irregular working days. Most companies in the European Union are struggling to find qualified employees. Labor shortage is considered a major factor limiting production. When it comes to workforce scheduling, we are faced with the problem of understaffing. The chapter brings together the most important components of successful staff rostering: research on algorithms, human aspects, and business issues. The paper provides the best practices on how to effectively tackle understaffing and deviation of working time when considering these three components. The study uses two real-world examples from a bus transit company and from a hospital emergency department. The results are validated using the PEASTP metaheuristic, which is integrated into Finland's market-leading workforce management software.

Keywords: workforce scheduling, staff rostering, shift work, health issues, work-life balance, metaheuristics, PEASTP

1. Introduction

Workforce scheduling is a process where the available resources are matched to the volumes of work to be completed. Optimal matching is extremely important for companies and institutions that have employees working on shifts or on irregular working days. Such examples include hospitals, public transport, retail stores, call centers, industrial plants, cleaning, home care, guarding, manufacturing, and delivery of goods.

To ensure the best possible outcome for the employer and the best possible working conditions for the employees, shift work should be streamlined with an efficient

workforce scheduling process (see **Figure 1**). The process must consider service level agreements, labor regulations, and employees' competences, skills, and preferences, while simultaneously minimizing cost to the business. Other variables include seasonal changes in business, fluctuations in workload, and different company practices.

The workforce scheduling process includes three main optimization components: shift generation, staff rostering, and daily rescheduling. Shift generation transforms demand into shifts. The target is to create shifts that match the known and determined workload as accurately as possible. The generation of shifts is based on either a fluctuating demand on the number and type of employees (see e.g., [1, 2]), or the specific tasks that the shifts need to cover (see e.g., [3, 4]).

The shifts generated form an input for staff rostering, where employees are assigned to the shifts. The rostering includes the scheduling of working days, days off, and other vacations that must be carefully considered in resource and holiday planning. The interest of the academic community has mainly focused on staff rostering. The same holds for company practitioners. However, a new research study [5] showed that the quality of the shift generation phase has a significant impact on the number of required employees for the staff rostering phase.

The staff rosters generated are the outcome of the current situation at the time they were produced. Daily rescheduling deals with ad hoc changes in supply and demand, as well as in the workforce due to sick leaves and other no-shows, as well as changes in supply and demand. The organization should have an appropriate mechanism to choose suitable substitutes considering the employment contracts, labor regulations, required competences, salaries, and possible overtime payments.

At the turn of the 1980s, Garey and Johnson [6] and Bartholdi [7] showed that the staff rostering problem was NP-hard. Furthermore, different variations of shift generation and staff rostering, and even their subproblems, are known to be NP-hard and NP-complete [8–11]. Three good reviews and surveys of workforce scheduling are provided by Ernst et al. [12], Van Den Bergh et al. [13], and Ceschia et al. [14].

One more important observation of the importance of effective workforce scheduling should be noted. According to Eurostat, more than 75% of EU companies are already struggling to find employees. Labor shortage is considered a factor limiting production for 26% of companies on average in 2023. A smooth and streamlined

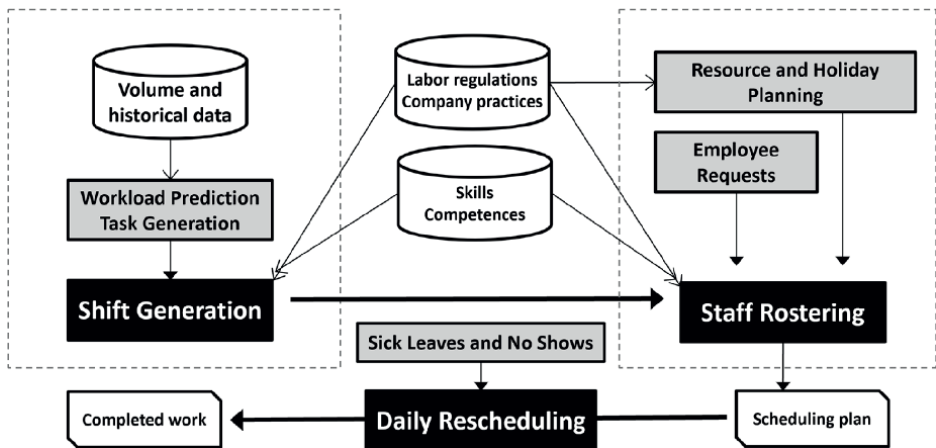


Figure 1.
The workforce scheduling process.

scheduling process and high-quality rosters for the employer and for the employees are vital for a successful business.

The two main contributions of the paper are the following:

1. The paper brings together the most important components of successful staff rostering: research on algorithms, human aspects, and business issues.
2. The paper provides the best practices on how to effectively tackle understaffing and deviation of working time when considering these three components.

To the best of our knowledge, this is the first research to examine staff rostering from three important perspectives: selecting the work that will be left unscheduled, the accepted deviation of working time, and the weight set to the accepted deviation. The study was motivated by our 20 years of experience in the staff rostering research as well as in the workforce scheduling business. As a result of the study, the best practices have been integrated into Finland's market-leading workforce management software.

The chapter is organized as follows. Section 2 reviews the staff rostering research. Section 3 examines how research has met the business issues. In Section 4, the human aspects, such as health issues and work-life balance, are addressed. Finally, in Section 5, we study three different methods to maximize the use of the available working time, considering business and health issues addressed in previous sections. The conclusion section summarizes our findings.

2. Staff rostering research

Mathematical workforce scheduling has 70-year history. In 1954, Edie's study [15] on traffic delays at toll booths was published. In the same year, Dantzig [16] proposed the first mathematical formulation of a personnel rostering problem based on a generalized set covering model. In the middle of 1960s, Wolfe and Young [17] and Howell [18] described the nurse rostering problem, and Arabeyre et al. [19] described the airline crew scheduling problem.

In the mid-1970s, Baker [20] distinguished three main groups of staff rostering: shift scheduling, days off scheduling, and tour scheduling, which combines the first two types. At the turn of the 1980s, Garey and Johnson [6] and Bartholdi [7] showed that the staff rostering problem was NP-hard. Another notable paper at that time was the review paper by Tien and Kamiyama [8], in which they considered five subproblems: temporal staff requirements, total staff requirements, recreation and leave, work schedules, and shift schedules.

The following two decades introduced several new application areas, models, and algorithms for various staff rostering problems. Most successful application areas included airline crew scheduling [21–25], railway crew scheduling [26, 27], bus driver scheduling [28–30], and call centers [31]. Undoubtedly, the most studied application area is nurse rostering. The first notable study in the 2000s introduced a range of new memetic approaches for the problem [32].

For the first 50 years, research focused mainly on developing models and ever better and faster algorithms. Until 2015, the models had become more complex as more constraints and goals were added, and more challenging instances were solved. However, the research was still mostly from a mathematical problem-solving

perspective. As numerous papers were published during that time, we only refer to some notable ones.

Meisels and Schaefer [33] modeled and solved some employee scheduling problems. Stark and Zimmermann [34] presented an exact branch-and-price algorithm for workforce scheduling. Maenhout and Vanhoucke [35] introduced a concept for personalized rostering. Chapados et al. [36] added an expected operating income maximization to their model. Brunner et al. [37] minimized the total assignment cost subject to individual contracts and prevailing labor regulations. De Causmaecker and Vanden Berghe [38] presented a reference model for timetabling and rostering.

Some of the notable heuristics developed for the workforce scheduling problem during the first decade include iterated local search [39], hyper-heuristics [40], memetic algorithms [41], hill-climbing [42], ant colony optimization [43], variable neighborhood search [44], and particle swarm optimization [45].

The theoretical framework of this study is based on the early work by Ernst et al. [12]. They reviewed rostering problems in specific application areas and the models and algorithms commonly used for solving rostering problems. The framework has been extended in several papers since then. For example, Van den Bergh et al. [13] evaluated many fields that are related to either the problem setting or the technical features. Furthermore, the two nurse rostering competitions have strongly affected the framework.

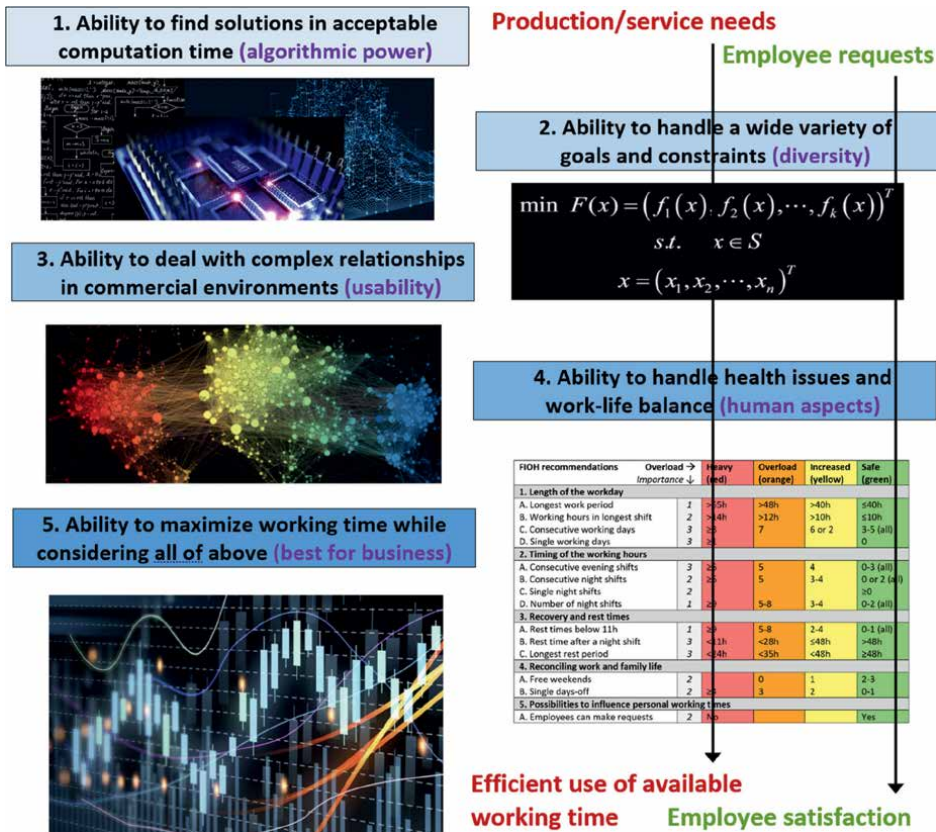


Figure 2.
The evolution of staff rostering research.

The First International Nurse Rostering Competition [46] was run in 2010. The problem was the assignment of nurses to shifts in a fixed planning horizon, subject to a large number of hard and soft constraint types. The Second International Nurse Rostering Competition [14] was run in 2015. The second competition proposed a smaller set of constraint types, but introduced a sequence of cases, referring to consecutive weeks of a longer planning horizon (4 or 8 weeks). Both formulations and instances have been taken as a challenge by many researchers and research groups. Optimal solutions as well as new best solutions have been found and reported during the last 10 years.

We end this section with **Figure 2** showing the evolution of staff rostering research. We describe the first 40 years as the ability to find solutions in acceptable computation time, and as the era of algorithmic power. The next 20 years are described as the ability to handle a wide variety of goals and constraints, and as the era of diversity.

In the last 15 years, some researchers have become active in collaborating with businesses. As a result, some workforce scheduling packages include academic-based staff rostering optimization. We call this an era of usability. It is only in the last few years that scheduling researchers have started to pay significant attention to the health aspects of scheduling. We call this an era of human aspects. Issues from both these eras are discussed in the next Sections 3 and 4.

3. Research meets business

There are hundreds of workforce scheduling solutions commercially available and in widespread use. However, only a few commercial products include mathematical staff rostering optimization. Most of these are based on the cooperation with staff rostering research teams in universities. Furthermore, most of the published cooperation concerns nurse rostering since public hospitals tend to be more open about their operational details than private companies.

Here we look at the work of 11 research teams. Burke et al. [47] presented and evaluated an efficient and effective tabu search procedure to solve real-world nurse rostering problems. The approach described was incorporated in a scheduling system, which was implemented in over 40 Belgian hospitals. A more generic problem model and an adaptive large neighborhood search algorithm were later introduced by Bilgin et al. [48]. The authors stated that the new model was able to solve several problem instances from different wards in different hospitals.

Burke and Curtois [49] adapted a variable depth search algorithm and a column generation algorithm for rostering problems. The method was used by a spin-out company formed by the University of Nottingham. The company is still actively operating.

Gärtner et al. [50] raised practitioners' expectations for shift scheduling. The background of the paper is roughly 20 years of experience in consulting in the field of working time and rostering. The authors reported that they also use optimization algorithms, such as the one presented in [51]. Kingston [52] has presented KHE18, a polynomial-time solver for nurse rostering. An improved version, KHE20, and additional experiments are reported in [53].

Böðvarsdóttir et al. [54] report a close collaboration with healthcare practitioners at Danish hospitals. Their model has been iteratively built up to include all aspects that are needed to match the real-world problem that practitioners face. Becker

et al. [55] proposed a novel exact algorithmic framework for the rotating workforce scheduling problem. They reported that for the first time, all 6000 instances of the status quo benchmark for rotating workforce scheduling were solved to optimality. The authors stated that the presented framework can be embedded into personnel scheduling software.

Ceschia et al. [56] introduced a new real-world formulation for the nurse rostering problem, arising in many Italian healthcare institutions, which has been developed in collaboration with a primary software company in the field. They proposed a MIP model and a local search method, driven by a Simulated Annealing metaheuristic, based on a combination of two neighborhoods. Nurmi et al. [57] published the five most important practical recommendations for shift work based on their 15 years of commercial experience. They showed the gap between the ideal recommendations, theoretical expectations, and everyday reality.

The work described above shows that research has undoubtedly met business. The models and methods developed have the ability to deal with complex relationships in commercial environments (see **Figure 2**). There is still some work to be done. Petrovic [58] stated that it requires a lot of effort to implement the results of research in practice. Hundreds of workforce scheduling models and optimization methods have been published, but only dozens of them have been implemented in practice (see e.g., Section 2).

Probably due to the theoretical background and interest of the researchers, there has been a bit of competition in the academic scheduling community to see who can find the best solutions to the published benchmark instances using their own solution method. If the proposed method shows good performance on some new instances, or among the best performances on some existing instances, it will most likely be published in a scientific conference or journal. It should be clear that even though a method can be powerful for several instances, it is not guaranteed to work as well for other instances. The No Free Lunch Theorem [59] implies that there cannot exist a superior optimization method. Nevertheless, each new model and method demonstrates advances in the workforce scheduling community.

Even the best methods still have a long way to go before the model and method can be integrated into a commercial product. At least the following requirements exist (see also **Figure 2**):

- The model should have the ability to represent a wide variety of goals and constraints that are present in real-world scheduling.
- The method should have the ability to adapt to different real-world scenarios, i.e., the parameter tuning of the method should not be too complex.
- The computation time of the method should be acceptable considering the release time of the rosters.

Note that in our opinion, we should not seek the fastest possible solution method. In real-world use, it is advantageous to use more computation time to achieve top-quality rosters. To support optimization, we need a quick tool to check whether it is even possible to match the work to the available employees and their competence, and, for example, whether the employee requests can be fulfilled even in theory.

A successful implementation of an optimization model and methodology requires a company or public institution to be willing to renew the current workforce

scheduling process and to question the current policies and hidden practices. An essential part of successful commercial integration is the dialog with the various parties. First, we must discuss with top management, human relations department, and IT department from a business perspective, and then with supervisors, shift planners, and shop stewards from an operational perspective.

It is also obvious that the possible business partner has existing software with such manual workforce scheduling that at least some of the current users are most likely satisfied with. All of this requires a lot of convincing negotiation and business skills, which are not necessarily the assets of the researchers. Unfortunately, even having the best optimization method has no practical relevance or impact on the outcome of whether the method will be commercially adopted.

We end this section with one important note. When the goal is to generate the best possible academic solutions as well as the best possible commercial solutions, it is essential to understand the complexity of the workforce scheduling process (see **Figure 1**). Based on our 15 years of experience in cooperating with companies and working closely with customers and end-users, we claim that the usefulness and utility of the optimized rosters depend more on the good-quality outcome of all the preceding decisions and phases than the actual staff rostering optimization phase.

4. Health issues and work-life balance

In Section 2, we stated that the first three eras of staff rostering research concentrated on algorithms, goals, constraints, and collaborating with businesses. It is only in the last few years that some scheduling researchers have started to pay significant attention to the health issues of scheduling. However, the human aspects of shift work have been studied for decades, but separately from research on scheduling optimization.

It is still the case that

- health professionals publish articles on which health considerations are important in shift work planning and how best to reconcile them in theory, and
- optimization professionals publish articles on the best models to represent and the best methods to solve a wide variety of goals and constraints.

As we noted in Section 1, more than 75% of EU companies are already struggling to find employees. Due to the labor shortage, working conditions and employee satisfaction have become competitive factors between companies. Employee well-being and engagement are crucial to retain employees and keep the business going. Companies with engaged employees are more profitable compared to those without them. This is another reason why companies must pay attention to employees' health and well-being.

We first discuss some of the most important findings from the health research community. From an employee perspective, shift work is associated with pressure on health issues and social and family life. As a result, workforce schedulers should address the health, safety, and well-being of the employees together with the financial objectives from the employer's point of view.

In 1729, French scientist Jean-Jacques d'Ortous de Mairan carried out the first experiment to separate the internal clock from its response to daily stimuli. The world

became interested in sleep rhythms in 2017 at the latest, when US scientists were awarded the Nobel Prize for Medicine after discovering the intracellular mechanism of circadian rhythms [60]. A recent Finnish study has found that up to a third of Finns live at the wrong pace for their own sleep rhythm. They feel that their personal ability to sleep at certain times does not match the times they need to wake up to get to school and work (see e.g., [61]).

Some people can be characterized as early risers (early birds) and some as late sleepers (night owls). As a result, some people are more exposed to evening and night work than others, and vice versa. Early risers rule our society's clock. Unfortunately, late sleepers cannot easily control their behavior. Some individuals are more influenced by these effects than others are. Thus, employers can increase productivity, as well as job satisfaction, by respecting the employees' body clocks with better-targeted shifts. When employees have sufficient control over their working hours, the negative effects of shift work on their health and work-life balance are buffered. Good work time control in shift work can be possible without compromising shift ergonomics, as shown in [62].

High levels of work time control have also been shown to positively influence mental health outcomes such as affective well-being and perceived stress [62]. The extensive research by Virtanen et al. [63] showed that good mental health in combination with the opportunity to control working time seems to be key factors in extended employment into older age. One of the most intriguing results was that personal control over scheduling interprets career continuation beyond the legal age of retirement even better than one's health issues.

Night work disrupts the normal sleep-wake cycle, giving rise to circadian misalignment, interfering with both sleep duration and quality [64]. The fourth consecutive night shift shows a risk increase of 36% compared to the first night shift [65]. Working hours in the evenings and at night also impair social well-being and work-life balance [66]. Furthermore, a week or more of unsocial working hours increases accident risk [65].

Short rest time between shifts (≤ 11 hours), described as quick returns, should be avoided, as ruled by the EU Working Time Directive. They have detrimental effects on acute health problems [67]. Nielsen et al. [68] showed that the shorter the time between shifts, the higher the risk of injury within the first two days following a quick return. Furthermore, the quick returns described earlier could also potentially influence lifestyle factors adversely through their association with stress, fatigue, and insomnia [69].

However, not all studies present only negative challenges. Karhula et al. [70] reported that the permanent night workers were more often satisfied with their colleagues and autonomy at work than the day workers and shift workers. The study by Buchvold et al. [64] did not find a significant impact on lifestyle factors in relation to different exposures to night work.

The effects of the length of the working day have also been a subject of research. The study by Ropponen et al. [71] showed that less than 12-hour shifts were not associated with an increased likelihood of occupational injuries. In the shift work study considering industry workers in large Finnish companies [72], the employees were found to sleep and feel better when the length of the working day was 12 hours instead of 8 hours. Furthermore, the 4-year registry study by Vedaa et al. [73] showed that long working hours were found to be associated with fewer sick leave days. The explanatory factor for all these findings is the extra days off that come into the planning period because of longer working days, which in turn imply restorative effects.

Finally, according to Nurmi et al. [5], the stress and risk factors are better considered with longer shifts. Moreover, the study revealed that the staff demand is significantly easier to cover with longer than 8-hour shifts, and fewer employees are needed when the average shift length increases to 10 hours.

4.1 Well-being measures

As stated earlier, the staff rostering optimization has been more time-related. It is only in the last few years that some scheduling researchers have started to pay significant attention to the health issues of scheduling. To the best of our knowledge, Gärtner et al. [50] were the first ones to propose additional constraints to the optimization models to address employees' well-being. They did not, however, present concrete constraint models of how their ideas could be implemented.

Petrovic et al. [74] proposed well-being measures to be included in the objective function while generating a roster. The work included work-life balance measures, fatigue, and risk indices introduced in 2006 by the Health and Safety Executive (HSE) in the United Kingdom [75]. The goal was to investigate to employee well-being can be improved while maintaining high performance of rosters. They did not, however, provide concrete optimization models against the corresponding HSE model.

The Finnish Institute of Occupational Health has published its recommendations for shift work based on 22 risk and stress factors, 14 of which are shown in **Figure 3**. The institute introduced traffic lights for these factors to indicate the degree of overload. Nurmi et al. [76] used an optimization framework to show that problems arise when all these recommendations should be satisfied together in real-world staff rostering. The findings were based on the two real-world instances from a university hospital in Finland: an operating theater unit and an intensive-care unit. The authors

Recommendations	Overload → Importance ↓	Heavy (red)	Overload (orange)	Increased (yellow)	Safe (green)
1. Length of the workday					
A. Longest work period ¹	1	>55h	>48h	>40h	≤40h
B. Working hours in longest shift ²	2	>14h	>12h	>10h	≤10h
C. Consecutive working days ³	3	≥8	7	6 or 2	3-5 (all)
D. Single working days ³	3	≥1			0
2. Timing of the working hours					
A. Consecutive evening shifts ³	3	≥6	5	4	0-3 (all)
B. Consecutive night shifts	2	≥6	5	3-4	0 or 2 (all)
C. Single night shifts	2				≥0
D. Number of night shifts	1	≥9	5-8	3-4	0-2 (all)
3. Recovery and rest times					
A. Rest times below 11h ³	1	≥9	5-8	2-4	0-1 (all)
B. Rest time after a night shift	3	<11h	<28h	≤48h	>48h
C. Longest rest period ⁴	3	<24h	<35h	<48h	≥48h
4. Reconciling work and family life					
A. Free weekends ⁵	2		0	1	2-3
B. Single days-off	2	≥4	3	2	0-1
5. Possibilities to influence personal working times					
A. Employees can make requests	2	No			Yes

Figure 3.
Fourteen stress and risk factors and the recommendations for shift work published by the Finnish Institute of Occupational Health for a planning horizon of 3 weeks [76].

stated that the ideal recommendations by the institution should act as solid guidance for general staff rostering rules and practices, and the notable differences to recommendations should be deployed only when both the employer and employees accept them.

Ceschia et al. [56] introduced a new real-world formulation for the nurse rostering problem. Their model considered nurses with different skills, special shifts depending on the skills, time work-load limits, and different types of days off. In addition, preferences and incompatibilities between nurses were taken into account. Basically, they were able to design high-quality nurse rostering plans to guarantee efficiency, safety, and quality-of-care balanced with staff well-being. Their model was not based on national official guidance as in [74, 76].

Nurmi et al. [57] have recently published their practical recommendations for shift work based on the traffic light model of the Finnish Institute of Occupational Health (see **Figure 3**). The recommendations are based on their 15 years of commercial experience in optimizing workforce schedules. Some of the most important results include the following:

- Minimizing single working days cannot be a hard target.
- Minimizing single days off cannot be a hard target.
- Single night shifts should not be allowed.
- Forcing at least two free weekends instead of one cannot be a target.
- The upper limit of consecutive working days should be six instead of five.
- The night shift factors should be soft targets instead of hard targets.

We end this section with a fairness discussion, which the optimization community has approached very little in its studies. The research by Leineweber et al. [77] suggested that employees who feel unfairly treated are more likely to develop health problems. Also, individuals with health problems are more likely to view their employer's treatment of them as unfair. The first question is how to define fairness, especially in the presence of employees' varying internal clocks and different preferences for working times and days off. Hoang et al. [78] introduced a new measure of social fairness based on the unfair feelings of the players involved in an allocation problem. They say that an allocation is envy-free if every involved player prefers its allocation to any other player's allocation.

Self-rostering and preference scheduling have been proposed as a solution to fairness. Self-rostering works only if employees consider not only their own preferences, but also the needs of their colleagues and the employer. The process often leads to overstaffing and/or understaffing of certain shifts. Self-rostering is far from easy because in manual staff rostering, seniority and interpersonal relationships play a notable role. Using an optimization method, they should not affect the outcome.

The authors have approached the fairness issue mainly in two ways. First, the shift scheduler does not belong to the unit she is optimizing. Instead, shift schedulers are centralized in the administration unit, from where they plan several units at a time. This eliminates personal identities. This also removes the challenges posed by the turnover of shift schedulers.

Secondly, the employee requests are given as a three-level process supporting autonomous shift planning. Everyone can request, e.g., 10% of the shifts/days off that she necessarily wants (hard target). Everyone can also request, e.g., 40% of the shifts/days off that she would like to have. They will receive those that can be provided from the point of view of labor needs (employer's point of view) and that can be provided from the point of view of mutual interest and equality (employee's point of view).

5. The best ways to efficiently maximize the use of the available working time

Section 4 reviewed the main research findings on the human aspects of shift work. Based on the current scientific data on health and recovery issues [79], the three most important issues to consider are night shifts, rest times, and employees' influence over their personal working times. These issues, as well as other human aspects, have recently been considered in the optimization community.

Despite some good news, the most important thing from the employer's point of view is maximizing the use of the available working time, i.e., securing that the number of employees at work covers the expected workload as much as possible. The world has changed radically in Finland and in Europe over the last few years due to global labor shortages. Financial efficiency used to be optimized with the goal of getting the same work done with, e.g., 5% fewer employees. Now it is optimized with the goal of getting 5% more work done with the current workforce.

The need for a sophisticated optimization method has become increasingly necessary. The reason is the considerable number of indirect and hidden interactions between two major targets: maximizing the working time and considering the human aspects. The complex, multifactorial, and interdependent relations of the targets cause them to compete with each other. A small change in one target may lead to inconsistency in another target. On the other hand, a small relaxation in one target may lead to substantial improvement in another target. An important health issue or social perspective most likely competes with a staffing requirement or with an individual preference (see e.g., [76]).

As stated in Section 4, the staff rostering researchers have recently paid attention to the health issues of scheduling. However, there has been very few research on the effects of health issues together with maximizing the use of the available working time. We are only aware of [57, 76]. To the best of our knowledge, no research paper has examined the effect of three important issues:

1. The method of selecting the work that will be left unscheduled.
2. The accepted deviation of the employee's total working time from the target.
3. The weight set to the accepted deviation (issue 2).

We examine the three issues using the PEASTP metaheuristic (see e.g., [76]) and a computational intelligence framework integrated into a market-leading workforce management software in Finland. The real-world cases include and consider the issues shown in **Figure 2**: algorithmic power, diversity, human aspects, and what is best for business.

5.1 The method of selecting the work that will be left unscheduled

We are not dealing here with a case where employees have more available working time than there is work available, i.e., overstaffing. The use of part-time and casual workers, or employees from another unit of the company, will solve this problem. However, we would like to note that Purnomo and Bard (see e.g., [80]) defined the workload demand as a lower and upper limit on the number of nurses needed per shift. They justified this because of nationwide nursing staff shortages. They assumed it would be unusual to be able to cover all the demand. In the case of understaffing (issue 1), an equivalent workforce as in overstaffing can be used to carry out the work that will be left unscheduled. Another solution is to use overtime for full-time employees. This would most likely cost more. Ceschia et al. [56] stated that the understaffing issue can be solved only if managers integrate strategic decisions about workforce planning related to the optimal size of personnel and mix of their skills to meet coverage requirements.

We are interested in finding the best method to minimize the work that will be left unscheduled. In the 10-year-old review, Van den Bergh et al. [13] stated that back then, in almost 75% of the studies, researchers classified coverage constraint as a hard constraint, i.e., understaffing is not allowed. This should be obvious, because leaving work undone, for example, in a hospital intensive-care unit, cannot be less important than other optimization targets. Even in the latest nurse rostering competition [14], there is a contradiction in the rules that leaving one shift undone is equivalent to, for example, organizing a complete weekend for one employee. Ultimately, the former has operational and financial implications, as you must use an extra employee to do work that will be left unscheduled.

As an example, we consider a real-world case from the biggest bus transit company in Finland. The number of bus drivers in one of their units is 115, of which 89 work full-time and 26 part-time with variable hours. The planning period is 2 weeks, so the total number of working days or days off for employees is $14 \times 115 = 1610$. They must have a total of 557 days off in this 2-week period, giving a total of $1610 - 557 = 1053$ working days. However, there are 1093 bus routes to be completed. Thus, theoretically, the best number of work that could be left unscheduled is $1093 - 1053 = 40$.

The shift structure includes four shift types: 400 morning, 404 days, 248 evening, and 41 night, totaling 1093 shifts. The timeframe is 2 weeks. The requirements for staff rostering are stated as follows:

Necessary requirement:

No. The staff demand for each day and each shift must be respected.

Hard requirements:

H1. Five shift sequences are forbidden: ME, MN, DE, DN, and ND.

H2. The rest time between two shifts must be at least 9 hours.

H3. Some employees cannot start working early in the morning and/or end working late in the evening.

H4. The maximum length of a work stretch is 5.

H5. At least one free weekend within 4 weeks.

H6. At least 4 days off (full-time employee).

H7. Exactly one shift per day (a bus driver has two or more routes assigned to one shift).

Soft requirements:

- S1. One shift sequence should be avoided: ED.
- S2. The rest time between two shifts should be at least 11 hours.
- S3. The total working time should not exceed 80 hours.
- S4. The total working time added with the so-called waiting time should be at least 80 hours.
- S5. The working time in three consecutive days should not exceed 1890 minutes.
- S6. The longest rest period must be at least 35 hours.
- S7. Single working days should be minimized.
- S8. Single days off should be minimized.
- S9. The percentage of evening and night shifts (30–50%) should be evenly distributed among employees. Four employees should get only morning shifts, and five employees only late or night shifts.
- S10. There should be 2 days off at least on the other end of a work stretch.
- S11. There should be at most eight working days around a single day off ($2 + D + 6$, $3 + D + 5$, or $4 + D + 4$).

We compare the effect of three methods of selecting the work that will be left unscheduled when the total need for work exceeds the total resources available to the employees:

Normal: Normal optimization with no shifts removed during optimization.

Pseudo: Optimization, which assigns some work to so-called pseudo employees.

Remover: Optimization, which removes some work during the optimization run.

Pseudo employees act like shift depositories. Usually, no constraints are applied to them. Sometimes competences are applied to get the most crucial shifts to the actual employees. A pseudo employee can also be defined with the characteristics of an average employee, allowing easier transfer of work to an actual employee.

A pseudo employee can work every day, i.e., 14 days in 2 weeks. Because the best number of work that could be left unscheduled is 40, we might think we need at least $40/14 = 2.86 = 3$ pseudo employees. However, the total duration of shifts (i.e., bus routes) is 517,709 minutes, and the employees can cover only 502,272 minutes. This is 15,437 minutes short. A pseudo employee working like an actual employee works 4800 minutes in 2 weeks. This would mean $15,437/4800 = 3.2$ pseudo employees. We ended up using four pseudo employees.

The Remover approach removes shifts from the optimization at certain intervals. The removed shift never returns to the optimization. Let us denote the number of optimization rounds by n and the number of current violations of selected hard constraints by h . The Remover is activated when the number of hard constraint violations has not decreased during the last n/k rounds. The $h/2$ shifts whose removal would decrease the number of hard violations the most are removed from the optimization. The last removal removes all the rest shifts that cause violations. This must be carried out when no less than n/k rounds are left, because the optimization requires time to recover from a situation where some shifts have been removed from the current best solution. In our real-world cases, we use the value $k = 10$. This has meant three to six Remover activations.

	Normal	Pseudo	Remover
Necessary requirement			
N0. Staff demand	0	0	0
Hard requirements			
Violation sum	46	53.5	43.5
Soft requirements			
Violation sum	249	148	204

The blue color indicates clear superiority.

Table 1.
The optimization results for comparing the effect of three methods of selecting the work that will be left unscheduled. The results are average values of six runs.

Table 1 shows the optimization results for comparing the effect of the three methods of selecting the work that will be left unscheduled. The experiments were run with an AMD Ryzen 9 5950X 16-core processor with 32 GB of memory. We ran the PEASTP metaheuristic six times for each setup. A single run was given 15 minutes. The same setup will be applied to the other two comparisons later.

The results could be interpreted so that the Normal method outperforms the Pseudo method because of the lower number of hard violations. However, if these 46 shifts (or less) causing the violations were removed from the final solution, the working hours of the employees assigned to these shifts would no longer be within the accepted working time deviation. Furthermore, the number of soft violations is highest for the Normal method. **Table 2** shows the detailed comparison of the Pseudo and Remover methods.

The results show that the Remover method outperforms the Pseudo method because of the lower number of hard violations, but the Pseudo method handles soft constraints better. The difference in soft violations is not significant. As an example, consider the number of single days off, which means that on average, one of eight employees has one extra single day off. The same holds for not having two days off at least on the other end of a work stretch. The higher number of total soft constraint violations is the price we have to pay for the fact to get 10 more shifts completed. An additional advantage for Remover is that it removes work evenly from all shift types: 5.4%, 3.8%, 2.3% and 2.0%, while Pseudo removes accordingly: 3.3%, 4.5%, 7.2% and 10.6%. Also, note the high number of night shifts removed.

5.2 The accepted deviation of the employee's total working time from the target

The second issue to examine is the effect of the accepted deviation of the employee's total working time from the target. In a surprising number of staff rostering publications, the accepted deviation is one working day. For example, in the recent nurse rostering study by Ceschia et al. [56], the deviation is 8 hours (480 minutes). As stated earlier, we have been puzzled as to why work can be left undone. If you need to have n employees working in a shift, you need to have n employees, not $n - 1$, for example, surgeries in the emergency department, or bus drivers driving the bus routes.

We are not aware of any organization in Finland where the deviation could be one working day. Therefore, such optimization constraint does not exist, but instead an accepted deviation is defined for the whole planning period, for example, -4 hours to $+4$ hours in hospitals, and -3 hours to 0 hours in public transport. As a result, if

	Pseudo	Remover
Necessary requirement		
N0. Staff demand	0	0
Hard requirements		
Violation sum	53.5	43.5
Soft requirements		
S1. Avoided shift sequences	1.5	1.8
S2. Daily rest time	0.0	4.5
S3. Working times 1	0.0	1.8
S4. Working times 2	0.0	1.3
S5. Workloads of three shifts	0.0	0.3
S6. Longest rest periods	0.2	2.0
S7. Single working days	2.7	2.5
S8. Single days off	92.2	107.2
S9. Even distributions	28.3	43.0
S10. Work stretches and days off	21.5	31.0
S11. Workloads around single day-offs	2.2	8.2

The blue color indicates clear superiority.

Table 2.
The detailed optimization results for comparing the effect of the Pseudo and Remover methods. The results are average values of six runs.

an employee's working time for the planning period is short or exceeded, the working time on some working days must be increased or decreased to achieve the total working time under the collective agreement.

As an example, we consider a real-world case from a hospital emergency department, where the working week is 38 hours and 15 minutes. The number of employees is 85. The planning period is 3 weeks. The total duration of shifts is 446,355 minutes, and the employees can cover 464,969 minutes. Thus, employees could, at least in theory, do all the work. Therefore, we will use the Normal optimization (see Section 5.1).

The shift structure includes four shift types: 249 morning, 135 days, 243 evening, and 189 night, totaling 816 shifts. The number of different competences required in the shifts is 23. There are 107 employee requests for days off that need to be fulfilled, and 23 requests for shifts that should preferably be fulfilled.

We study the effect of accepting 8-hour (1 working day) deviation instead of 4 hours. The requirements for staff rostering are stated below. The optimization considers all the human aspects, stress and risk factors, and the recommendations for shift work as given in **Figure 3** and in [76]. The corresponding factors are given in parentheses.

Necessary requirement:

No. The staff demand for each day and each shift must be respected.

Hard requirements:

H1. Six shift sequences are forbidden: NM, ND, NE, NRM, NRD, NRE, where R is a so-called rest day (see the explanation below).

- H2. The rest time between two shifts must be at least 11 hours (3A).
- H3. Competences required in the shift.
- H4. The maximum length of a work stretch is 6 (1C).
- H5. At least one free weekend (4A).
- H6. Employees' days off requests (5A).
- H7. Exactly one shift per day.
- H8. Longest rest period in 1 week (3C).
- H9. Consecutive and number of night shifts (2B, 2D, 3B).
- H10. Single night shifts (2C).
- H11. Zero-night shifts—some employees cannot have night shifts (2D).

Soft requirements:

- S1. One shift sequence should be avoided: EM.
- S2. Employees' shift requests (5A).
- S3. The accepted deviation of the employee's total working time ± 4 hours or ± 8 hours.
- S4. The maximum number of consecutive evening shifts is 3 (2A).
- S5. The working time in five consecutive days should not exceed 2820 minutes (1A).
- S6. Single working days should be minimized (1D).
- S7. Single days off should be minimized (4B).
- S8. The percentage of evening shifts (20–40%) should be evenly distributed between employees.

In Finnish hospitals, after a sequence of night shifts, a so-called rest day or sleeping day must follow a sequence of night shifts. This is not counted as a day off. Furthermore, at least 2 days off must follow a rest day. This has straightforward implications. For the employer, single night shifts or even only two-night shifts in a row are not rational, since more employees are then needed to cover the night shifts. Ceschia et al. [56] reported that the notion of rest day is also used in Italy, where at least 1 day off must follow a rest day.

Table 3 shows the optimization results for comparing the effect of doubling the accepted deviation of the employee's total working time from ± 4 hours to ± 8 hours, i.e., to one working day. The results show that the number of hard constraint violations, as well as the number of soft constraint violations, would clearly decrease if we could increase the accepted deviation to one working day. Unfortunately, this is not possible in Finnish hospitals, making the problem-solving much harder.

5.3 The weight set to the accepted deviation

The third issue to examine is the effect of the weight set on the accepted deviation. In the weighted sum approach, a set of constraints is scaled into a weighted sum single-objective by multiplying the violations of each constraint by a given weight.

	±4 hours deviation	±8 hours deviation	±4 hours with 10× weight
Necessary requirement			
N0. Staff demand	0	0	0
Hard requirements	8.5	2.5	10.7
H1. Forbidden shifts	0.5	0.0	1.0
H2. Daily rest times (3A)	0.0	0.0	0.0
H3. Required competences	2.8	0.3	2.3
H4. Work stretches (1C)	0.0	0.2	0.7
H5. Free weekends (4A)	0.5	0.0	1.0
H6. Days off requests (5A)	1.7	0.5	2.0
H7. One shift per day	0.8	0.5	1.5
H8. Longest rest periods (3C)	0.0	0.0	0.0
H9. Night shifts (2B, 2D, 3B)	1.7	1.0	1.3
H10. Single night shifts (2C)	0.5	0.0	0.8
H11. Zero night shifts (2D)	0.0	0.0	0.0
Soft requirements	36.7	19.2	43.0
S1. Avoided shift sequences	0.0	0.0	0.0
S2. Shift requests (5A)	8.8	7.5	9.0
S3. Working times	0.9	0.6	0.2
S4. Evening work stretches (2A)	0.0	0.0	0.0
S5. Workloads of five shifts (1A)	2.7	1.3	3.8
S6. Single working days (1D)	5.0	2.0	6.0
S7. Single days off (4B)	17.5	7.3	20.0
S8. Even distributions	1.8	0.5	4.0

The blue color indicates clear superiority and the red color indicates inferiority.

Table 3.
The optimization results for comparing the effect of the accepted deviation of the employee's total working time, and the weight set to the accepted deviation.

Soft constraints are given small weights, and hard constraints are given significantly higher weights, but nevertheless, setting appropriate weights is a non-trivial task. However, there has been insufficient attention to which solutions result from a particular set of weights.

Böðvarsdóttir et al. [54] created the Behind-the-Scenes Weight Tuning method to automatically generate objective weights to remove the need for manual interventions. The authors state that the methodology requires a change in mindset and moves away from old procedures. They stated that prior to their work, the Automatic Weight Extraction method by Mihaylov et al. [81] was the only such method. However, this is not the case. The PEASTP metaheuristic includes an adaptive penalty method (ADAGEN), which was created more than 25 years ago [82]. First, the soft constraints are assigned fixed weights according to their priority and significance. Then, the ADAGEN method assigns dynamic weights to each of the hard constraints based on

the weights assigned to the soft constraints. Each weight is updated iteratively based on the current number of violations of each hard constraint.

One striking feature in staff rostering publications is the very high values used for the hard constraint weights. This is understandable for those hard constraints that are essential or mandatory in the sense that the final solution cannot be accepted. However, we should bear in mind that the optimization setting is just an approximation of practice. Some hard constraint violations can turn out to be accepted. For example, if the maximum number of consecutive night shifts is three, it may temporarily be four for some employees by agreement with them.

Using significantly high values for hard constraints most likely enforces the number of hard violations to be zero, if such a solution can be found theoretically. However, the optimization method most likely converges toward a local optimum with quite many soft violations and cannot escape from the solution neighborhood to find new promising search areas. Next, we demonstrate the effect of the weight set to the accepted deviation using the earlier hospital emergency department case.

Table 3 shows the optimization results for comparing the effect of increasing the weight for the accepted deviation tenfold. The results show that the number of violations increases practically for every hard and soft constraint. This is the price we must pay for trying to force the working time deviation within ± 4 hours. The results also show that the PEASTP metaheuristic produces usable solutions without using higher weight values, since the ADAGEN method dynamically handles the weights. This has been confirmed by our commercial customers.

6. Conclusions

We described the evolution of staff rostering research on algorithms, human aspects, and business issues. The workforce scheduling model should have the ability to represent a wide variety of goals and constraints that are present in real-world scheduling. We discussed some of the most important findings on pressure on health issues, and social and family life, which all must be considered when optimizing staff rosters. The method should have the ability to adapt to different real-world scenarios. Furthermore, the computation time of the method should be acceptable considering the release time of the rosters.

One of the biggest challenges in staff rostering is tackling the challenges posed by understaffing by considering business and well-being issues. The most important thing from the employer's point of view is maximizing the use of the available working time, i.e., securing that the number of employees at work covers the expected workload as much as possible. The paper provided best practices from three important perspectives: selecting the work that will be left unscheduled, the accepted deviation of working time, and the weight set to the accepted deviation.

The first study found the best method of selecting the work that will be left unscheduled when the total need for work exceeds the total resources available to the employees. The Remover method outperformed the Pseudo method because of the lower number of hard violations, but the Pseudo method handles soft constraints better. The difference in soft violations is not significant.

The second study examined the effect of the accepted deviation of the employee's total working time from the target. The results showed that the number of hard constraint violations, as well as the number of soft constraint violations, would clearly

decrease in case we could increase the accepted deviation. We noted that, unfortunately, this is not possible in Finnish hospitals.

The third study examined the effect of weight set to the accepted deviation. The results showed that increasing the weight increases the number of violations practically for every hard and soft constraint. The three studies were motivated by our 20 years of experience in staff rostering research as well as in the workforce scheduling business. As a result of the studies, the best practices have been integrated into Finland's market-leading workforce management software.

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Section 4

Artificial Intelligence and Digital Transformation in Operations

AI-Assisted Emission Reporting for Small and Medium-Sized Enterprises (SMEs)

Yining Hu

Abstract

Many Small and Medium-Sized Enterprises (SMEs) from various sectors in Australia are looking for smart, affordable, and user-friendly ways to support their emission reporting. Despite not currently being required by the government due to their small size and limited revenue, many hold the view that emission reporting will eventually become mandatory. Unlike large enterprises, however, SMEs often lack the resources and knowledge to integrate sustainability monitoring and reporting systems into their existing businesses, and are often reluctant to embrace digital transformation as it is complicated and time-consuming to implement changes. However, as forward-thinking SMEs begin to take actions and potentially use sustainability to establish their brand image, SMEs that do not adapt to the changes will quickly fall behind. The advancement of Artificial Intelligence (AI) and Generative AI (Gen-AI) is shifting the way companies solve problems. Advanced sensors and smart algorithms are being used to identify people and objects, while Gen-AI-powered chatbots are replacing human experts in answering questions. Gathering information on the web and synthesizing information has become easier with AI tools. This opens up the possibility of leveraging AI capabilities for more accessible emission reporting and sustainability recommendations. In this chapter, we will discuss the common drivers for emission reporting of SMEs and the difficulties they face, and explore how AI can assist. We will also examine three case studies in detail, which are derived from real-life SMEs.

Keywords: sustainability, emission reporting, small and medium-sized enterprises (SMEs), artificial intelligence (AI), sustainability strategy recommendations

1. Introduction

Australia has officially started mandatory emission reporting in 2025 [1], making it one of the first few nations to make emission reporting compulsory among others such as the EU, the US, New Zealand, and Singapore. Large entities in Australia are now required to publish annual climate statements to disclose their scope one, two and three greenhouse gas emissions and make assumption on how a global

temperature increase of one or two degrees may affect their businesses. Despite not included in this current legislation change, SMEs have also been reminded by the Australian Securities and Investments Commission (ASIC) that the large entities they engage with may need to obtain emissions-related information from them to fulfill their scope three emission reporting obligations [2]. This means that SMEs who cannot provide emission information may become less competitive when collaborating with large enterprises. In the future, carbon footprint accounting and emission reporting are likely to become compulsory for all SMEs.

Large enterprises can afford to have dedicated personnel to work on emission monitoring and reporting, and implement systems and engage consultants when needed. However, this can be hard to achieve in SMEs due to lack of knowledge and awareness, lack of dedicated personnel, lack of data and data collection tools, limited financial resources and time to implement the required systems, etc. [3, 4]. A few commercial tools exist for carbon accounting for households and businesses, such as the CoolClimate calculator [5] developed at the University of California, the Carbon Trust SME Calculator [6] which helps UK-based SMEs to measure emissions from fuel and electricity consumption, and several greenhouse gas calculators published by the Australian Clean Energy Regulator (CER) [7]. Several recent studies have also proposed methods to help SMEs with carbon accounting. Eleftheriadis and Anagnostopoulou developed a carbon footprint calculator for a small Greek Cheese Factory using the Life Cycle Assessment (LCA) method. Hu et al. [8] proposed and implemented a blockchain based software—the CarbonApp—for tracking cows' emissions and feeds in a dairy supply chain. These tools rely on a great amount of detailed data, real-time tracking and continuous monitoring to accurately calculate emissions.

The reality, however, is that many SMEs do not have sufficient knowledge in what data to collect, or enough time to ensure all required data is captured properly into the carbon accounting system, and as a result lose track of their emissions [9, 10]. Integrating advanced carbon metering systems can streamline the process by eliminating manual data entry [11]. However, there are often barriers SMEs face when adopting digital technologies due to lack of knowledge and personnel, and high initial implementation cost.

With the advance in Artificial Intelligence (AI), and how seamlessly it has been integrated in day-to-day life through technologies such as face scanning for identification and Large Language Models (LLMs)-powered chatbots that can answer any questions like a knowledgeable friend, more and more SMEs are seeking ways to leverage AI in their existing business operations to help them understand their carbon footprint and recommend actions they can take to stay sustainable. AI can extract information from various media such as text, audio, images and videos, and has capabilities to think and create. This highlights the potential of using AI in emission reporting and customizing recommendations.

In this chapter, we examine how AI can possibly assist SMEs with emission reporting by streamlining the process, reducing costs compared to existing technologies or engaging with human experts, and enabling simple interactions with minimal user input. We analyze sustainability reporting in SMEs using the Technology-Organization-Environment (TOE) framework [12] and find that the drivers are mainly environmental and organizational, such as regulatory requirements, the voluntary carbon market, demands from the SMEs' large enterprise partners, customers, cost-saving opportunities, establishing brand identity and attracting employees. While the barriers are mainly technological and organizational, including challenges with data collection, storage and analysis and high initial capital cost, lack of

expertise in sustainability reporting and technology, and complex reporting format with unforeseen changes. We also conclude that AI can be used to extract and synthesize information to create emission profiles of SMEs, Gen-AI can be used to input missing data, and intelligent recommender systems can be built to suggest sustainability strategies. To apply these AI capabilities in real-life settings, we focus on three case studies based on SMEs in Australia by explaining the specific sustainability issues they face and proposing potential AI-enabled solutions.

The rest of this chapter is organized as follow. Section 2 discusses the drivers and difficulties SMEs face in emission reporting. Section 3 discusses common AI capabilities that can potentially be used in emission reporting and sustainability strategy recommendation. Section 4 takes a deeper look into three real-life scenarios I encountered during the author's teaching and interacting with SME clients, and what AI solutions can be designed to help them. Section 5 outlines other factors to consider when designing and implementing such solutions. Finally, Section 6 concludes the chapter.

2. Drivers and barriers in emission reporting

Emission reporting requires SMEs to understand their carbon footprint, develop the reporting compliant with the required formats, and develop sustainability strategies and monitor the progress. There are companies that provide such services, but they are often expensive to subscribe to, and are limited in their own capabilities as they rely on human expertise and manual accounting. Without leveraging external consultancies, SMEs can also implement and integrate their own sustainability monitoring and reporting systems. However, this is not straightforward as many SMEs lack the expertise in sustainability reporting and face challenges in digital adoption.

Understanding the drivers and barriers SMEs have will guide us on how to effectively design AI-assisted systems for emission reporting. To assess these drivers and barriers, we adhere to the TOE Framework, which is commonly applied to understand how organizations, including SMEs, adopt new technologies. TOE has also been adapted for analyzing sustainability reporting in SMEs [13, 14]. Technology refers to the functionality, complexity, compatibility, and usability of the technology itself. Organization refers to factors such as the size, structure, culture, and resources of the organization. Environmental factors include market conditions, regulatory requirements, and social and cultural conventions.

2.1 Emission reporting frameworks

The International Financial Reporting Standards (IFRS) Sustainability Disclosure Standards by the IFRS Foundation set the global baseline for sustainability related financial disclosures, requiring companies to disclose sustainability-related risks and opportunities that could reasonably affect their financial position, performance, and future cash flows. Different geopolitical regions have their own implementations of the IFRS Sustainability Disclosure Standards. The Australian Sustainability Reporting Standards (ASRS), for example, introduces additional details such as a phased implementation timeline (grouping companies based on their size and financials), and a compliance requirement with the Australian Accounting Standards Board (AASB) S2 Climate-related Disclosures.

Based on the Greenhouse Gas Protocol [15], emissions are classified into–scope one: direct emissions, scope two: indirect emissions from purchased electricity or heating, and scope three: all other indirect emissions from suppliers, product use and employee commuting. Each scope is further divided into multiple categories, with scope three containing 15 categories itself. This imposes challenges in data collection. Moreover, companies are expected to be forward-looking by disclosing their transition plans and climate targets.

2.2 Drivers

2.2.1 Environment

Governments & regulatory bodies: Governments around the world are setting up more stringent, mandatory Environmental, Social, and Governance (ESG) reporting requirements.

Voluntary carbon market: The voluntary carbon market is growing with standardization bodies such as Verra [16] and Gold Standard [17] publishing methodologies for businesses and individuals across various sectors to measure their carbon footprint reduction and claim carbon credits. Many SMEs are seeking ways to reduce carbon footprint and generate a new stream of income by trading carbon credits.

Large enterprise partners: The pressure may come from the large-enterprise business partners of SMEs, as they need emission information from the SMEs to satisfy their own reporting requirements.

Customers: In some cases, the pressure also comes from customers, as a large portion of consumers are willing to pay a premium for sustainable products and change their purchasing habits to reduce negative environmental impact–this is especially true for Gen Z [18].

Competitors: When an SME's competitors are capable of emission reporting and are taking actions to reduce emissions, the SME is automatically impacted.

Investors: There is also an increasing emphasis on sustainability in the financial sector, with investors such as venture capitals and banks encouraging voluntary reporting [19].

2.2.2 Organization

Discovering cost-saving opportunities: Tracking emissions often reveals energy or material inefficiencies, and allows businesses to identify cost-saving opportunities.

Establishing brand identity: Some SMEs may adopt a sustainability-focused approach and use carbon neutrality as a brand principle, such as KeepCup [20]–a company that sells reusable coffee cups and water bottles, and Allbirds [21]–a brand for sustainable shoes and clothing.

Attracting employees: To some extent, employees, especially the younger ones also increasingly value working for environmentally responsible companies [22].

2.3 Barriers

The transformation, however, is not easy, as there are difficulties SMEs face when integrating emission reporting processes and systems into their usual business practices [23]. Several studies have reported on the barriers SMEs face in emission

reporting in a systematic manner [3, 23], with the most frequently mentioned barriers being lack of resources, high initial capital cost of implementing sustainability measures, and lack of expertise [3].

2.3.1 Technology

Advanced and dedicated sustainability tracking and reporting systems are seldom part of SMEs' core businesses. Sometimes, the only digital system an SME has is an accounting system. Comprehensive carbon accounting requires a large amount of data collected from all significant sources of Greenhouse Gas (GHG) emissions across energy usage, water usage and transport. The *data collection, storage and analysis* all impose major difficulties to SMEs.

Collection: Sensors are needed to collect various data. In a dairy supply chain, simple temperature sensors can measure and track the temperature of fridges during the transport of fresh milk. This is an essential part of the supply chain as milk should be kept cold for freshness. The temperature data can also be used to calculate energy usage of the fridges. However, other emissions produced in the supply chain, such as the methane emissions from livestock, and emissions from fossil fuel usage require much more specialized sensor systems to measure and record. These systems are often absent as they are not required for the business to sustain.

Storage and access: For SMEs with advanced sensor systems and corresponding IT systems for data collection, they may still lack the ability to make use of the data and may not have been properly storing historical data. Continuing with the dairy supply chain example, some farmers may have installed commercially-available, advanced dairy management systems that are capable of measuring animal health, breeding activities, milk production, and inventory. Despite the fact that much of this data can be used to (indirectly) calculate emissions, it is often overlooked by farmers, as their main focus is on milk test results, i.e., protein levels and milk volume—the factors that determine the milk price. Additionally, as the dairy management software is proprietary, data access for the farmer is only limited to importing and exporting data manually at a limited frequency. This makes it difficult to enable API integration with other software that could use the same data for emission calculations.

Analysis: Even when SMEs have full access to their data and have been storing historical records, they may still lack the expertise to calculate carbon footprint using that data. The options are to work with carbon accountants or use specialized carbon accounting software—both of which can be expensive and inefficient.

2.3.2 Organization

High initial capital cost: Many SMEs are used to manual work [24], and depend heavily on tacit knowledge—unwritten, experience-based knowledge held by individuals—which includes memorization of product details and processes [25]. Setting up new IT systems and adopting technologies can be complicated and costly. As a real-world example, a small manufacturing business may store hundreds types of products in their warehouse, and still rely on manual counting to keep track of their stock levels. Implementing a new product management system requires placing bar-codes on all products and entering each one of them into the system, which can take up to six months of manual work. This will interrupt the normal business operations, and hence the business owner is reluctant to adopt such changes due to the time and financial costs.

Lack of expertise: SME owners and staff are specialized in their business domains and often find the need to outsource digital transformation projects or to license and white-label other products. However, many SMEs struggle to find people with the right skill set or the right technology due to a lack of knowledge in sustainability and technology themselves and limited financial resources. For instance, having a customer-facing website is the choice of many businesses. SMEs outside of the technology industry tend to develop their initial website through another company, and sometimes they do not own it. This may work as a short-term solution, but after a few years, their hosting services may become unavailable due to changes within that company. Just to update their websites and to modernize the User Interface (UI), they have to find other software houses or freelancers, and may even consider using overseas developers to reduce costs. Some collaborate with universities and engage students to develop the software; however, without professional supervision, students may only produce prototypes that are not ready for use. Moreover, SMEs have unique features and needs and are often looking for bespoke solutions, which are not easily accessible or can only be accessed at a high cost.

2.3.3 Environment

Emission reporting is often required in *complex formats*, which evolve as policies change. For example, with the adoption of the Corporate Sustainability Reporting Directive (CSRD) in 2022, the European Union (EU) mandated that companies meeting certain criteria must use the European Sustainability Reporting Standards (ESRS) starting in 2024 instead of the previously-used Global Reporting Initiative (GRI) Standards. Many businesses faced significant difficulties as ESRS imposes an increased reporting complexity, and the businesses lacked the suitable IT systems and internal expertise to interpret and apply ESRS. A 2024 PwC survey showed that more than 60% of EU-listed companies expected moderate to significant increases in compliance costs and needed major overhauls to meet the updated requirements [26].

3. AI capabilities

AI makes many aspects of life easier through automation, the reduction of manual work, and the ability to analyze large volumes of data. It is used in systems such as smartphone assistants like Siri and Google Assistant, which leverage Natural Language Processing (NLP) to understand voice commands, send texts, and set reminders. Maps also use AI to suggest optimal routes and assist with navigation. Modern chatbots like ChatGPT understand questions in various formats and generate responses based on information extracted from multiple sources. Many of these capabilities can potentially help SMEs with emission reporting and developing sustainability strategies.

3.1 Information extraction and synthesis

When multiple sources of data exist and can be directly used for emission calculation, smart algorithms and streamlined systems can be designed to automatically calculate emissions and aggregate results across these sources to develop a holistic view of the SME;s emissions, creating an emission profile.

If the data cannot be directly used to calculate emissions or if there are no advanced and dedicated sensor systems in place to capture all required data, AI can also estimate and predict emissions based on the context [27] through various types of inputs such as text, images, videos, etc. Saez et al. proposed to use transformers for CO₂ emission prediction in self-driving vehicles using various vehicle telemetry data collected by the self-driving system, such as speed, acceleration, throttle position, engine load, etc. [28]. Hua et al. proposed to use AI to infer emissions in construction industry based on factors such as material choices, energy consumption patterns, and operational behaviors [27].

3.2 Creativity

A complete dataset can be difficult to obtain, and when it is unavailable, AI can enable smart data collection from messy inputs and impute missing data [29, 30]. Chen et al. [31] showed that machine learning models perform better than traditional linear models in computationally estimating missing data of industrial consumption and pollution based on information collected from 701 Chinese cities between 2006 and 2018. Mekki et al. [32] demonstrated that simple linear regression models can predict missing values using the 2020 Carbon Disclosure Project (CDP) dataset, which contains environmental data from various organizations.

In cases where business owners are not tracking the emissions from their operations, a Gen-AI-powered chatbot can be used to have conversations with the business owners around their operations to infer the emissions, leveraging information on the business sector, the number and usage of appliances, utility costs, purchases of raw materials, waste management, etc.

3.3 Recommendation

The purpose of emission reporting is likely to go beyond reporting itself. Very often through emission calculation, businesses may recognize the need to reduce emissions and seek guidance on what actions they could take. There are commercial services that provide such advice, but they also require continuous monitoring of progress and charge a high premium for bespoke advice, as they rely on human expertise. The consultants themselves may have limited understanding in specific business domains, and interacting with consultants can result in delays. When engaging with these services, SMEs may become over-reliant on external advisors and fail to build internal capacity (just like outsourcing website development to software houses). This can hinder long-term sustainability if the service is discontinued.

Given the unique emission profile of an SME, AI can recommend realistic sustainability strategies based on insights from other SMEs with similar profiles. Unlike human expertise, which is often limited to specific fields, AI can efficiently process information from a wide range of sources. AI models can also be updated with new data and adapt to recent changes, making them suitable for supporting long-term sustainability goals. Furthermore, when regulatory reporting formats change, AI can be used to customize reports to meet different formatting requirements. In contrast, human experts are typically limited by their existing knowledge and require more time to learn and adapt to changes.

4. Case studies

In this section we discuss three SMEs in Australia that are either seeking sustainability solutions or are sustainability service providers themselves looking to enhance their offerings through AI. We discuss the problems they want to solve and the difficulties they face, and explore how the above-mentioned AI capabilities can be leveraged.

4.1 SME A: Emission reduction through feed additives in agriculture

SME A is a dairy manufacturer that contracts dairy farmers and collects milk from them daily to make dairy products. The company is looking to reduce emissions in its dairy supply chain, and claim carbon credits with the emission reduced. One aspect they have considered is reducing methane emissions from dairy cows, as cows produce a significant amount of methane during digestion, and methane is a powerful greenhouse gas that traps 25 times more heat than CO₂ [33]. The solution they are experimenting with involves introducing a feed additive for the cows, which interferes with their digestion process and reduces methane emissions.

A blockchain-based data collection software was proposed in [8], allowing farmers to register feed types and amount for each cow at milking times twice a day and accepting real-time methane measurement data from a methane sensor system. These data can be used to calculate the cows' methane emissions, and be further converted into carbon reduction and hence carbon credits. The application currently requires manual data entry of feed types and amount.

Without redesigning the application, AI can be used to streamline data entry. For example, we can design the user interface to accept file uploads—such as receipts for feed additive purchases—and use AI to extract relevant information like feed quantity and purchase date, and apply the calculation over the entire herd instead of individual cows. This approach improves the reliability of data registration by reducing human error and increases efficiency.

4.2 SME B: Energy usage reduction in electric appliances

SME 2 is a busy coffee shop that serves local customers. They have typical coffee shop appliances such as a commercial coffee machine, two customer-facing fridges, two internal fridges, several toasters, a dish washer, some lights, etc.

They noticed several thousand dollars in monthly energy spending and decided to reduce that cost. However, when speaking with an energy assessor, the only information they could provide was their total energy bill, which gave no insight into the actual usage of each appliance, which is not sufficient to identify the cause of the high electricity consumption.

When energy assessors visited the facility in person, they found that the fridges were placed in direct sunlight. As a result, the fridges consumed more energy than necessary to maintain the cool temperature—especially during the summer months when daylight is strong. This example shows that details such as the fridge's power rating, location, and usage are important for identifying energy-saving opportunities, but these details are often overlooked by business owners and typically only discovered through in-person assessments.

Rather than explicitly asking business owners to keep track of and disclose every aspect of their energy usage, we could potentially incorporate AI-based

image analysis to identify and count appliances, determine their placement, and assess whether they are being used appropriately. This would only require business owners to provide photos or videos of their shops.

4.3 SME C: Gen-AI to infer carbon footprint, generate sustainability reporting, and recommendations on sustainability strategies

SME C helps other businesses with emission reporting and recommends ways to reduce emissions. Currently, business information is collected through a series of questions on a web form to understand the motivation for emission reduction, size of the business, sourcing of materials, etc. Generic recommendations are provided for free based on these basic information, while customized recommendations are only accessible to clients with subscriptions. However, solutions recommended to the paying clients are often around installing solar panels and using batteries to store unused electricity, which does not meet the needs of SMEs that demand more specialized emission reduction solutions.

On the one hand, SME C wants their system to be smarter in understanding the large number of continuously evolving tender requirements, so they can easily produce reports that meet specific formatting standards. By using LLMs, we can efficiently extract requirements from these tender documents and build report-generating engines that produce reports aligned with them. On the other hand, SME C considers leveraging AI to improve their sustainability recommendations.

AI can be used to understand a business emission profile and suggest a range of concrete actions to take, utilizing existing data for similar businesses. Since the completeness and quality of data are the keys to accurate emission reporting and sustainability strategy recommendations, in cases where an owner cannot provide detailed receipts, spending records, or all the required information, they can instead provide their usual business operations in terms of hours of operation and number of staff, energy, water and transport usages—and use chatbots trained on relevant datasets to synthesize the available information and generate customized reports and recommendations.

5. Other factors

Accuracy: Despite several prior studies showing promising results of using AI in imputing missing data and predicting emissions, due to the lack of complete datasets, the prediction accuracy remains low for certain scope three categories [34], such as Category 9: Downstream Transportation and Distribution, and Category 11: Use of Sold Products. Moreover, without quality datasets, it is also hard to develop reliable AI models. Future research should aim to collect more relevant data and determine the minimum percentage of data required for AI models to achieve an acceptable accuracy in data imputation, and emission calculation or prediction.

User-friendliness and integration with existing systems: For wider adoption, the AI-assisted emission reporting solutions need to be user-friendly, especially for non-technical users. The solutions should also be low-cost and easy to integrate into SMEs' regular business operations. This means that any AI-powered systems should seamlessly interoperate with existing systems for data collection and other relevant processes.

Data storage, access, usage, privacy and security: The AI solutions will require an increased amount of data to be collected and shared by SMEs, naturally triggering concerns around data collection, storage, access permissions, and how the data is shared, analyzed and protected. For instance, images of a shop's interior setup may accidentally capture biometrics of customers or staff members. Therefore, how we ensure data privacy and guard the data from malicious access need to be considered when developing and deploying such solutions.

Government support and policy implication: Governments around the world are increasingly recognizing the importance of sustainability and are taking steps to support businesses in meeting emission reporting requirements. The Australian Government offers several grants and funding opportunities, such as the grants administered by the Department of Climate Change, Energy, the Environment and Water (DCCEE) and the Australian Carbon Credit Unit (ACCU) Scheme which is managed by the CER, to assist SMEs in monitoring their carbon footprint, reporting emissions, and transitioning to sustainable practices. The Artificial Intelligence (AI) Adopt Program [35] was also developed to establish AI Adopt Centres to support SMEs in adopting responsible AI-enabled services, particularly in sectors such as renewables and low-emissions technologies.

With targeted grant schemes or funding opportunities, as well as tax incentives dedicated to applying AI in sustainability related processes, the development and adoption of the technology can be accelerated. To ensure proper use of AI, regulatory bodies also need to set clear rules around ethics and privacy of data collection, security of data storage and transparency and auditability of AI-generated data.

6. Conclusion

This chapter highlights the drivers and barriers in emission reporting for SMEs with respect to the TOE framework, and explored how AI capabilities such as information extraction and synthesis, creativity, and recommendation can be used to help SMEs with emission reporting. In general, these AI capabilities can be leveraged to better understand the operations of a SME and generate a holistic emission profile for it. Leveraging AI's capability of collecting and analyzing a large amount of information, AI can be used to customize sustainability strategy recommendations based on the unique emission profile of the SME. This chapter also discusses three case studies based on Australian SMEs to demonstrate how these AI capabilities can be used to address real-life challenges. Finally this chapter points out other aspects to consider when developing such solutions and before rolling them out. As the performance of AI models largely relies on the size and quality of the training datasets, we can expect more data to be collected from SMEs, which naturally raises concerns about data privacy and security. User-friendliness and ease of integration are also important to consider when deploying such solutions in real-life settings. Governments play an important role in supporting these initiatives, regulating AI usage and accelerating technology development and adoption.

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Abbreviations

AASB	Australian accounting standards board
ACCU	Australian carbon credit unit
AI	artificial intelligence
ASIC	Australian securities and investments commission
ASRS	Australian sustainability reporting standards
CDP	carbon disclosure project
CER	clean energy regulator
CSRD	corporate sustainability reporting directive
DCCEEW	climate change, energy, the environment and water
ESG	environmental, social, and governance
ESRS	European sustainability reporting standards
EU	European union
Gen-AI	generative AI
GHG	greenhouse gas
GRI	global reporting initiative
IFRS	international financial reporting standards
LCA	life cycle assessment
LLMs	large language models
NLP	natural language processing
SME	small and medium-sized enterprise
TOE	technology-organization-environment
UI	user interface

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*Edited by Muddassar Sarfraz
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Future Frontiers in Operations Management – Navigating the 21st Century is a unique and forward-looking exploration of how today's organizations have adapted to the evolving challenges of technological transformation, customer demand, and social disruption. This book is a timely and essential resource in the field of operations management. It drives the meaningful change within the organization. In an era where volatility has become the norm, this book positions operations management as central to business success. It traces the evolution of operations management to identify the potential challenges and opportunities across industries. The book is a valuable guide, and we hope it will attract scholarly attention for its impressive body of knowledge. The book follows an easily readable format that is expressed efficiently. The book consists of 9 chapters. These chapters help readers understand the real-world application of operations management principles. This book is beneficial for every individual as it provides a practical understanding of operations management across diverse industries. These examples provide valuable lessons to organizations and equip readers to apply these concepts in the real world.

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