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# EXPLORING THE POTENTIAL OF BLOCKCHAIN FOR TRACEABILITY IN SUPPLY CHAIN: A HYBRID SIMULATION APPROACH

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# EXPLORING THE POTENTIAL OF BLOCKCHAIN FOR TRACEABILITY IN SUPPLY CHAIN: A HYBRID SIMULATION APPROACH

Thesis presented to the Graduate Program in Industrial Engineering at the Federal University of São Carlos, as part of the requirements for obtaining the PhD degree in Industrial Engineering.

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O Relatório de Defesa assinado pelos membros da Comissão Julgadora encontra-se arquivado junto ao Programa de Pós-Graduação em Engenharia de Produção.

*To my mom Maria Lúcia and my dad Júlio César*
*for the unconditional dedication and support.*

*To my brother Luis Guilherme*
*who has always been a reference in my journey.*

*To my niece Antonella*
*for all the joy and shine brought to our days and thoughts.*

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# ABSTRACT

While the scientific literature on blockchain applications in supply chain management is vast, it is short of empirical evidence due to the novelty of the technology and the inherent complexity of implementing such systems. In situations where empirical evidence is lacking or difficult to gather, modeling and simulation serve as effective tools for capturing the complexities of supply chain networks. This allows for a thorough examination and understanding of these systems, facilitating informed and consistent decision-making. Consequently, potential advantages and risks can be identified prior to their implementation in the real world. However, guidelines to assist scholars and practitioners in creating realistic hybrid simulation models in this context are missing in the literature, which brings great complexity to the modeling process. Thus, the main objective of this work is to propose and test a framework to support the modeling and simulation of supply chain traceability considering blockchain technology. The framework comprises a step-by-step guide that embraces the phases of model design, model development, and output evaluation. In addition, to enhance understanding and adoption, this research incorporates concepts and terminologies from existing and well-established frameworks for both practitioners and scholars, namely SCOR, GTS, and ADACOR. Furthermore, it employs a hybrid modeling approach that combines principles and methods from agent-based modeling and discrete-event simulation paradigms. To accomplish this objective, this work is deployed in three parts. First, to deal with a large publication rate of works related to blockchain in supply chain management, a review of reviews is developed, which is a tertiary study that gathers evidence from literature reviews. Secondly, following the Design Science Research approach, a novel methodological framework is proposed to help build hybrid simulation models of different levels of granularity. Finally, to demonstrate its potential, the proposed methodological framework is applied to a real-scale industrial case in Canada, comprising a live lobster supply chain to identify the potential impacts of a blockchain-based traceability system on the physical supply chain network structure through the lens of network theory, considering single and multi-level supplier evaluation.



**Keywords:** Methodological framework. Supply chain traceability. Distributed ledger technology. SCOR. GTS. Agent-based modeling and simulation. Systematic literature review. Supply chain network structure.

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| | |
|---|---|
| Aa | Asset agent |
| ABMS | Agent-based modeling and simulation |
| ADACOR | ADAptive holonic COntrol aRchitecture |
| AHP | Analytic Hierarchy Process |
| BCa | Blockchain agent |
| BCT | Blockchain technology |
| BPa | Business Processes agent |
| CTE | Critical Tracking Events |
| Da | Deliver agent |
| DES | Discrete event simulation |
| DRa | Deliver Return agents |
| DSR | Design Science Research |
| FAO | Food and Agriculture Organization |
| GIS | Geographic Information System |
| GTS | Global Traceability Standard |
| HS | Hybrid simulation |
| Ia | Instance agent |
| IoT | Internet of Things |
| ICT | Information and communication technologies |
| KDE | Key Data Elements |
| KPI | Key Performance Indicator |
| LUa | Logistic unit agent |
| Ma | Make agent |
| NFC | Near Field Communication |
| ODD | Overview, Design Concepts, and Details |
| OFAT | One-factor-at-a-time |
| OTIF | On-time in-full |
| Pa | Plan agent |
| P2P | Peer-to-peer |
| QR | Quick response |
| RFID | Radio Frequency Identification |
| RQ | Research question |

| | |
|---|---|
| Sa | Source agent |
| SCa | Smart contract agents |
| SCM | Supply chain management |
| SCPa | Supply Chain Party agent |
| SCOR | Supply Chain Operations Reference |
| SD | System dynamics |
| SDG | Sustainable Development Goals |
| SRa | Source Return agents |
| SSC | Seafood supply chain |
| TOa | Traceable Objects agents |
| TOPSIS | Technique for Order of Preference by Similarity to Ideal Solution |
| TRU | Traceable resource unit |
| UML | Unified Modeling Language |

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# 1 INTRODUCTION

This chapter is divided into four parts. First, it presents the context of the thesis and its motivation. In the second part, the objectives are specified. In the sequence, a summary of the research design is provided. At last, the structure of the following chapters is briefly described.

## 1.1 Contextualization and motivation

From what was learned a few decades ago, a company does not compete as an individual entity but as part of a network of interconnected parties (CHRISTOPHER, 2000). The concept of supply chain management (SCM) emerged as the field related to the integration of business processes across the entire flow of products, services, and information (LAMBERT; COOPER; PAGH, 1998). Over the years, SCM has extended its scope, embracing other topics, such as supply chain sustainability (MARTINS; PATO, 2019), supply chain resilience (RAZAK; HENDRY; STEVENSON, 2023), supply chain disruptions (MANUPATI *et al.*, 2022), and digital transformation of supply chains (TAN *et al.*, 2023).

With the establishment of multiple and nested flows at the global level, the concept of traceability started to be seen as an element to increase coordination in supply chains (BANTERLE; STRANIERI, 2010) and as a competitive advantage driver (CANAVARI *et al.*, 2010). Aspects leveraged by traceability practices encompass different perspectives, including quality assurance, regulatory compliance, sustainable initiatives, product counterfeiting, and customer awareness (AHMED; MACCARTHY; 2023). Recent works regarding traceability applications reveal different objectives, such as food supply chain performance (KAFETZOPOULOS *et al.*, 2023), detection of COVID-19 vaccine counterfeiting (MUNASINGHE; HALGAMUGE, 2023), sustainable development in the fashion sector (RIEMENS *et al.*, 2023), and the reverse flow of power batteries (ZHANG *et al.*, 2023).

However, the adoption of traceability practices faces challenges, due to information flows established between companies using different internal systems, leading to a lack of standardization and an increase in errors since multiple records are needed (STORØY; THAKUR; OLSEN, 2013). According to Kafetzopoulos *et al.* (2023), traceability challenges include data acquisition, technology availability, privacy issues, consumer perception, and levels of granularity. Ahmed and Maccarthy (2023) mention challenges related to the regulation of traceability solutions, investments required to enable and scale solutions, different perceptions among supply chain partners, and issues of security and commitment with sensible data stored in the traceability system.

In the context of digital transformation, emerging technologies from Industry 4.0, especially blockchain, offer the potential to overcome traceability issues. After emerging as the technology behind Bitcoin and other cryptocurrencies, and the involvement in financial applications anchored in smart contracts, blockchain transcended and started to be considered as a disruptive alternative to leverage SCM (SABERI *et al.*, 2018). Additionally, the possibility of integrating smart contracts provides prominent alternatives to verify agreements and trigger different types of actions (CHRISTIDIS; DEVETSIKIOTIS, 2016).

Among other possibilities, blockchain can provide data about the origins of materials, purchase orders, and inventory levels, as well as shipping documentation can be shared with other parties in real-time, bringing fluidness to information flows (COLE; STEVENSON; AITKEN, 2019). In terms of the potential to support traceability practices, a blockchain can keep digital footprints throughout the entire supply chain (WANG *et al.*, 2019), as it allows to register the executor of each action, the instant, and the location (KSHETRI, 2018), besides other types of information.

However, despite all the hype involved, the possible contributions of blockchain to supply chains are still found in the preliminary stage of comprehension and are clearly in their course of development (SABERI *et al.,* 2019). For example, a report from FAO provides the state of blockchain development in the seafood industry. This report identified several limitations, including the fact that most projects have been considering relatively short and not clearly defined or vertically integrated supply chains; and that the solutions have not been tested in real contexts, under complex supply chain scenarios (BLAHA; KATAFONO, 2020). On the other hand, the traditional supply chain systems are complex, making traceability very time-consuming, restraining the efficiency of processes, and making the number of parties involved a relevant challenge for blockchain adoption and implementation (GURTU; JOHNY, 2019).

To face these challenges and the lack of empirical studies to assist the adoption of blockchain, simulation is recommended as a powerful and low-risk tool to analyze supply chain complexity and assist in selecting support technologies. Simulation can be taken as a promising and affordable alternative for large-scale tests, since it is an appropriate alternative to model and evaluate scenarios that contain information flows associated with the flows of materials (PERSSON; ARALDI, 2009). Tests may be employed, for example, to perform feasibility and risk analysis, to advance the maturity level of perception and knowledge.

In operations and supply chain management, three main simulation paradigms are adopted or combined. Discrete-event simulation (DES) is a process-oriented approach in which the events that alter the state variables occur at discrete points in time. System dynamics (SD) follows a continuous approach to analyzing stocks and flows over time, based on feedback loop diagrams and differential equations (SCHEIDEGGER *et al.*, 2018). Lastly, agent-based modeling and simulation (ABMS) allow for capturing behaviors and studying interactions following decision rules previously defined upon agents' levels of individuality and autonomy (UTOMO *et al.*, 2018).

Based on both scientific and grey literature, ABMS is seen as the best approach to deal with the complexity of highly distributed systems (GALLAND *et al.*, 2003; LABARTHE *et al.*, 2007), such as supply chains and blockchain, and the intrinsic characteristics of this interplay. However, guidelines to assist scholars and practitioners in how to create realistic hybrid simulation models are missing in the literature, making the modeling process more complex and time-consuming.

Beyond the particularities of the high number of elements to be represented, conceiving a hybrid simulation also carries technical issues. First, establishing the problem boundaries is essential to guide the paradigm selection. The next definitions comprise the role of each method to see the enhancement obtained through a hybrid approach (MORGAN; HOWICK; BELTON, 2017), also considering the modeling and computational efforts required.

Among the frameworks related to blockchain in SCM, works are reporting discrete-event simulation, focused on information sharing (WANG *et al.*, 2020), and on the customer order management process (MARTINEZ *et al.*, 2019). As for the system dynamics modeling, a framework to address information asymmetry exists (XUE; DOU; SHANG, 2020). In contrast, some frameworks do not embrace simulation but do offer relevant insights for simulation modeling, e.g., related to smart contract design (DOLGUI *et al.*, 2020), structuring a traceability system (FENG *et al.*, 2020), multiple blockchains usage (LIU; LI, 2020), and provenance issues (CUI *et al.*, 2019).

None of these works focuses on describing a structured process to develop hybrid simulation models to provide quantitatively evaluate blockchain benefits to SCM. A toolkit is essential to guide the modeler in making consistent and compatible decisions concerning how the involved components are going to be deployed as it affects the strategy for combining the simulation paradigms selected.

In this context, the main objective of this work is to propose and test a framework to model and simulate supply chain traceability considering blockchain through hybrid simulation.

Hybrid simulation is conceptualized as the mixing of multiple paradigms, aiming to enhance the representation of the complexity and particularities of a problem or situation (MORGAN; HOWICK; BELTON, 2017; BRAILSFORD *et al.*, 2019). Herein, a framework is comprehended as a systematic and reusable set of steps designated to support developing models and simulating situation-driven conditions (DORIGATTI *et al.*, 2016).

This work is deployed in three parts, which are described as follows, alongside their respective research questions.

**Part I:** First, to deal with a large rate of publication of works related to blockchain in supply chain management, three initial research questions allow us to get a consolidated picture of the current literature, as outlined below:

RQ1.1: What are the main supply chain topics approached in reviews about blockchain in supply chain management?

RQ1.2: What are the main blockchain features studied in reviews about blockchain in supply chain management?

RQ1.3: Which directions for future research have been reported in reviews about blockchain in supply chain management?

To answer these questions, a review of reviews is performed, which is presented in Chapter 3. This study indicated that a low number of works in this field have been adopting simulation approaches (QUEIROZ; TELLES; BONILLA, 2019; VARRIALE *et al.*, 2020; ESMAEILIAN *et al.*, 2020; DUTTA *et al.*, 2020) and that there is a claim for studies about the impacts of traceability, revealing several opportunities to be explored (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018).

**Part II:** Chapter 3 provides a multidisciplinary set of definitions and mechanisms to build hybrid simulation models, thus a methodological framework is proposed in Chapter 4 to answer the following research questions:

RQ2.1: Which are the entities needed to model supply chain traceability considering blockchain?

RQ2.2: Which are the main steps to model blockchain-based supply chain traceability?

To answer these questions, a methodological framework for hybrid simulation is developed together with a proof-of-concept. The framework is then tested in a real-scale industrial case in the next part of this thesis.

**Part III:** The methodological framework is employed to develop a simulation study to provide a quantitative exploration of supply chain network structure, to answer the following research questions:

RQ3.1: How the proposed framework is used to address supply chain phenomena?

RQ3.2: How the proposed framework is used to involve a theoretical lens to address supply chain phenomena?

The existing studies in this field are currently focused on the potential and feasibility of blockchain in terms of efficiency and information sharing (WANG *et al.*, 2020; MARTINEZ *et al.*, 2019; TOZANLI *et al.*, 2020; VARRIALE *et al.*, 2021). Taking a complementary direction, the last part of this PhD thesis adopts the lens of network theory to assess how blockchain-based supply chain traceability impacts the supplier evaluation process, and consequently, the supply chain network structure by providing higher transparency in dyadic relationships.

These research questions organized into three parts are the foundations for stating the PhD thesis objectives, as explained in the next sub-section.

## 1.2 Objective

The main objective of this work is to propose and test a novel framework to model and simulate supply chain traceability supported by blockchain technology. This objective was deployed into specific objectives, as shown in Table 1, which also presents the research method adopted for each part.

Table 1 - Objectives' outline

| Objectives | Chapter | Research method |
|---|---|---|
| Specific Objective 1 | | |
| Examine the present and future perspectives of blockchain in SCM and identify how simulation has been considered | 3. Present and future of blockchain in supply chain management: a review of reviews and research agenda | Systematic literature review |
| Specific Objective 2 | | |
| Develop a framework to model and simulate blockchain-based supply chain traceability systems | 4. A framework for modeling and simulating blockchain-based supply chain traceability systems | Design science research/Hybrid simulation |
| Specific Objective 3 | | |
| Assess the framework potential to explore particular supply chain phenomena through theoretical lens | 5. Extending supplier evaluation horizons through blockchain-based traceability | Design science research/Hybrid simulation |

## 1.3 Summary of the research design

In this work, three research methods are employed: systematic literature review, design science research, and hybrid simulation.

A literature review helps to deal with the multiple viewpoints that compose the body of knowledge related to a specific field. It is indicated as an initial step to map previous works and to posit relevant research questions after identifying a gap (TRANFIELD; DENYER; SMART, 2003). By condensing the information of interest objectively and without bias, a literature review establishes the empirical basis for research and determines directions in both conceptual and theoretical aspects. Additionally, analyzing previous works contributes to finding trade-offs and checking if relevant constructs and concepts were properly considered, mitigating future problems (TROCHIM; DONNELLY; ARORA, 2016).

Due to the release of an ever-growing number of primary and even secondary research papers, a large number of papers about blockchain in supply chain management have been published in the scientific literature in recent years, which may be a barrier for those desiring to understand what has been done so far. Therefore, we perform a tertiary review, which is an approach that considers reviews as its ‘unit of analysis’.

The guidelines indicated to develop secondary systematic literature reviews, such as the ones provided by Moher *et al.* (2009), Denyer and Tranfield (2009), and Tranfield, Denyer, and Smart (2003), are the same used to perform a tertiary review (GAROUSI; MÄNTYLÄ, 2016). Works that consider literature reviews as units of analysis are also referred to by other terms, such as overview of reviews, umbrella review, meta-review, synthesis of reviews, and summary of reviews (HUNT *et al.*, 2018). This approach is ideal to be applied to explore themes that are having large publication rates, such as blockchain in SCM, and has recently been gaining momentum in the supply chain domain (MARTINS; PATO, 2019; BARATA, 2021; CENTOBELLI *et al.*, 2021; CORMACK; THOMÉ; SILVESTRE; 2021).

During the tertiary review development, a small set of studies involving simulation in the blockchain-SCM interplay was found, leading to the identification of the need to develop a framework to guide the process of building simulation models to analyze the impacts of blockchain platforms on supply chain traceability.

A conceptual framework determines “interlinked concepts that together provide a comprehensive understanding of a phenomenon or phenomena”, complemented by the notion that it represents “a construct in which each concept plays an integral role” (JABAREEN, 2009).

According to Guba and Lincoln (1994), there are three types of conceptual frameworks:

- Ontological, which addresses the “way things are”;
- Epistemological, which focuses on “how things really work”;
- Methodological, which considers the process of building and “understanding the real world”.

The framework provided by this PhD thesis is classified as a methodological one since it presents guidelines and procedures to conduct the development of hybrid simulation models for the comprehension of supply chain traceability impact under the usage of blockchain technology. Besides the assumptions and roles posited, the concepts related to each component of the framework have characteristics and attributes that allow the establishment of robust connections between the main building blocks of the hybrid simulation model under consideration.

The development of the framework is based on the Design Science Research (DSR) research strategy, which is focused on creating and testing new artifacts and solutions, such as the proposed framework, after identifying practical opportunities (SIMON, 1996). In other words, DSR is an approach aimed at bringing practice to theory (HOLMSTRÖM; KETOKIVI; HAMERI, 2009).

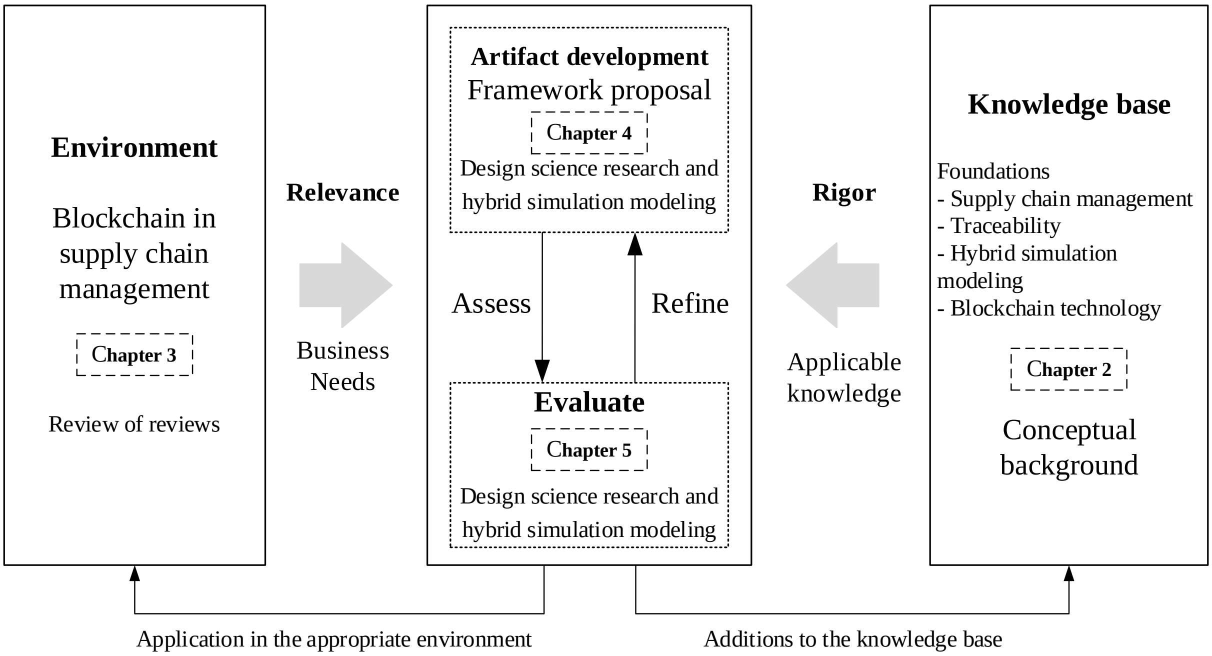
DSR approach consists of analyzing a problem in its context and then performing cycles of testing and refinement until obtaining a design solution, referred to as an artifact. Besides utility, evaluated in terms of practical relevance, the contribution of the artifact proposed is also assessed considering pragmatic validity, which encompasses the effectiveness and potential to achieve the desired results when dealing with a situation properly contextualized. These two elements do not incur a trade-off between them (VAN AKEN; CHANDRASEKARAN; HALMAN, 2016).

Combining insights from different areas is essential to trigger new ideas, and this work proposes a novel way to use existing tools – modeling and simulation – for an emerging and relevant problem – blockchain technology usage in supply chain management (HOLMSTRÖM; KETOKIVI; HAMERI, 2009).

Particularly, the agent-based paradigm is well-suited to represent complex distributed systems, since it allows for linking both micro and macro-level behaviors, by exploring agents' ability to interpret information, make decisions, establish communications, initiate social relations, and sense conditions (MACAL, 2016). The discrete-event simulation is indicated to represent process-based contexts (FERREIRA; ARMELLINI; SANTA-EULALIA, 2020). These characteristics will both be explored for modeling a supply chain with real field data. Simulation modeling of different scenarios is performed to investigate the impacts on supply chain network structure in terms of traceability data found on a blockchain to address supplier and subsupplier evaluation. A multicriteria method is employed through an updatable approach to enrich the agents' decision-making ability and provide a refined use for stored traceability data.

Figure 1 exhibits an overview of the thesis research design. The structure is based on the linkages stated by Hevner *et al.* (2004) for conducting Design Science Research, and associations with corresponding chapters are given.

Figure 1 - Research design based on DSR




**Source:** based on Hevner *et al.* (2004).

Additional details about each method are provided in specific sections, namely Chapter 3 (Paper 1: Systematic Literature Review), Chapter 4 (Paper 2: Design Science Research and hybrid simulation), and Chapter 5 (Paper 3: Design Science Research and hybrid simulation), respectively.

## 1.4 Thesis structure

This thesis is composed of six chapters. Chapters 3, 4, and 5 are presented in the format of papers. Some repeated parts will appear in different sections due to the adoption of this type of structure. The author anticipates his apologies about that.

Chapter 1 contains the introduction, including the contextualization and motivation, the definition of the objectives established for each following part, and an outline of the respective research methods adopted. Chapter 2 brings a synthesized conceptual background to this thesis. Chapter 3 exhibits a review of reviews about blockchain in supply chain management, which is performed according to a protocol similar to a standard systematic literature review. Chapter 4 presents the development and preliminary validation through a proof-of-concept of a methodological framework to build hybrid simulation models to represent supply chain traceability considering blockchain. In Chapter 5, following the procedures described in the framework proposed, a hybrid simulation model is built to test the framework in a real-scale application. Chapter 6 comes up with a general overview of the thesis, as well as a summary of the contributions, limitations, and recommendations for future works.

# 2 CONCEPTUAL BACKGROUND

This chapter contains a brief conceptual background about supply chain management and the Supply Chain Operations Reference (SCOR) model, blockchain in supply chain management, supply chain traceability, and agent-based simulation modeling. Those are the main topics of this thesis.

## 2.1 Supply chain management and SCOR model

A supply chain is a group of organizations that perform transactions, establishing both downstream and upstream flows of materials, services, information, and finances related to the transformation of materials to deliver products. Parts involved include raw material and component producers, product assemblers, wholesalers, retailer merchants, and transportation companies, among others, and the customers that are the final part considered. As a phenomenon of business, a supply chain emerges naturally, despite the implementation of efforts to manage the relations. Among the facts to illustrate the inherent complexity, an organization can be part of multiple supply chains and have different types of relations with the same organization according to specific network configurations (MENTZER *et al.*, 2001).

In this context, the concept of supply chain management (SCM) embraces the efforts to orchestrate the relations with other parties, focused on achieving alignment to leverage and maintain competitiveness regarding costs and service levels, which are measures of efficiency and effectiveness, respectively. From two complementary perspectives, SCM is seen as a management philosophy as well as a set of management processes. Moreover, the meaning of any individual effort must be addressed in terms of both strategic and systemic orientation to be able to be extended over dyadic interactions. In other words, the scope of SCM has a functional component as it relies on business functions, and an organizational one, as it deals with inter-firms' relationships to coordinate flows and sustain long-term performance (MENTZER *et al.*, 2001).

A remarkable observation is that any company sees the supply chain structure from a different point of view, as it takes itself as the focal point. Thus, the links that establish the configuration and inherent frictions between members must be handled through processes of customer/service relationship management, demand management, order fulfillment, manufacturing flow management, procurement, and product development and commercialization. Additionally, SCM should encompass the reverse flow, and thus manage returns of materials after consumption (LAMBERT; COOPER; PAGH, 1998).

In this context, the SCOR model is a widely adopted approach for supply chain modeling (NTABE *et al.*, 2015), which can represent and connect all the relevant elements. It comprises a generic and hierarchical structure that makes it suitable to support the representation of many business scenarios related to nearly any kind of supply chain. The whole idea relies on practices of business process reengineering, benchmarking, and process measurement, providing a standard cross-functional representation (APICS, 2017).

As a reference model, SCOR contains descriptions of processes, specifications of relationships among processes, standard metrics, recommended practices, and overall alignments to obtain performance improvements (APICS, 2017).

Based on a hierarchical structure, for each organization belonging to a network, SCOR addresses the integration of six primary management processes, which are briefly described as follows (APICS, 2017):

- Plan (sP) – designates the development of operational plans and corrective adjustments, embracing the balancing of resources and requirements to achieve the network objectives, which includes matching supply with demand levels for different products and channels. Besides an overall supply chain plan, this process is decomposed into specific plan processes to support source, make, deliver, and return management.
- Source (sS) – deals with the actions related to the receipt and transfer of any kind of material and service. Besides handling invoices from suppliers, it covers the emission of purchase orders, scheduling deliveries, and storage of units, as well as inspections and payment authorizations.
- Make (sM) – reports the processes responsible for converting material and creating content aiming to add value to generate both product and service deliverables. This term encompasses different categories, from assembly and maintenance to end-of-use processes, such as recycling and remanufacturing, among other segment-driven possibilities. In other words, this process implies modifying inputs to generate outputs.
- Deliver (sD) – handles order management and order fulfillment activities, which include receiving, validating, maintaining, and creating customer orders, as well as warehouse activities such as scheduling order deliveries, picking goods, and even packaging and labeling logistics units. Additionally, this process deals with

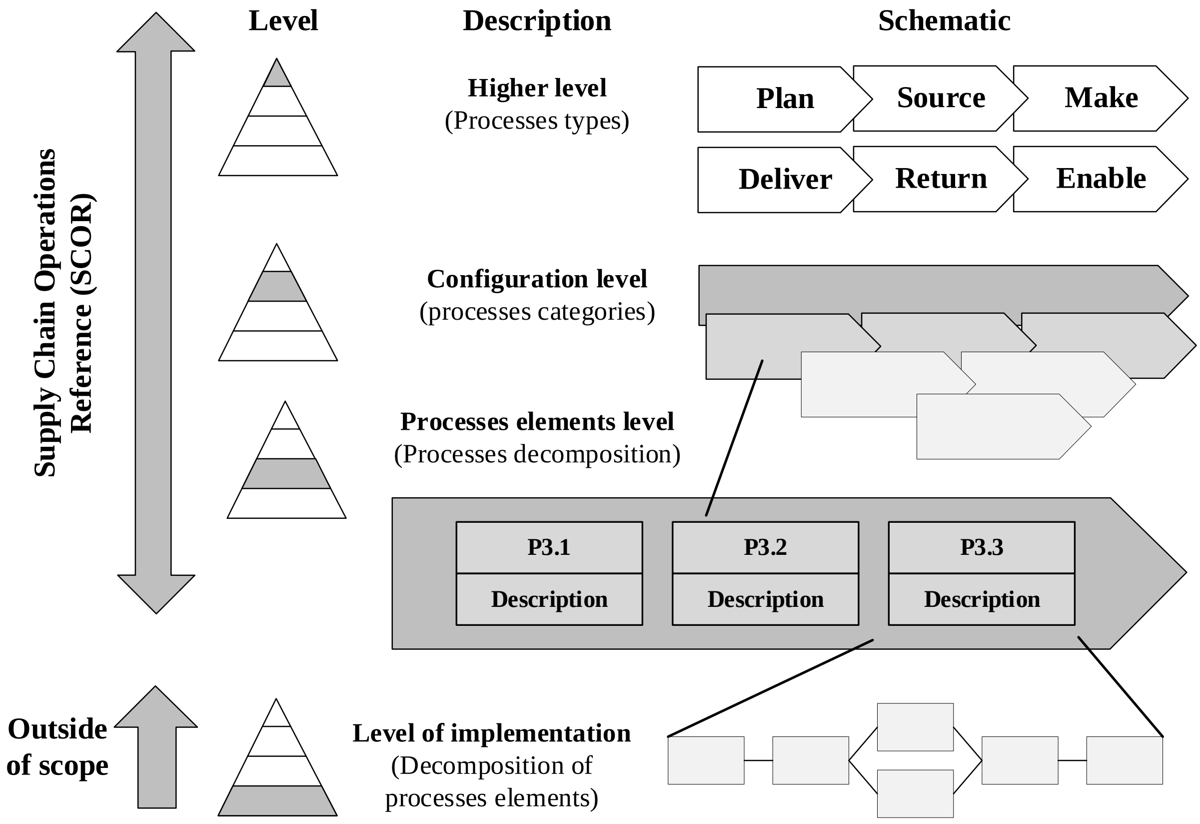
transportation decisions and import/export processes, including generating invoices and other documents needed to release materials for shipment.

- Return (sR) – describes processes regarding the reverse flow of materials, which moves from a customer to its supplier, for replacement, maintenance, or disposition, due to wrong deliveries, warranty, or environmental issues. This process also includes identifying the reason to return and scheduling the corresponding actions, as well as providing the documents needed. At level 2, return processes are divided to distinguish materials that a company itself is sending (source return) from those that are being received from a customer (deliver return).
- Enable (sE) – focuses on monitoring and managing the overall performance of the supply chain through processes regarding information, relationship, resources, assets, business rules, compliance, and contracts. It provides essential inputs and guidelines to assist planning and execution processes. Enable processes provide the orchestration with other domains, as it connects for instance financial procedures, human resources, information and communication technologies, sales forces, and portfolio management.

As the name implies, plan is devoted to planning processes, source, make, deliver, and return are classified as execution processes, while enable processes support both categories.

SCOR has three hierarchical levels, which are decomposed in a top-down approach to bring details. The top-level establishes the scope and directions for the supply chain operation. At the second level, the company delineates its business model according to the guidelines of a typical process category, choosing among make-to-stock, make-to-order, or engineer-to-order. After the interface between types and categories of processes, in level 3, processes are decomposed in their respective flows. SCOR describes each process, containing a standard definition, performance metrics, and inputs/outputs. In some cases, SCOR lists best practices, while also recognizing standard and emerging practices, which vary according to geography and industry. Level 4 is out of the scope of SCOR and refers to the implementation of the context-specific process elements depending on the industry, product, location, and/or technology involved in the processes (APICS, 2017). Figure 2 shows the levels considered in the SCOR model.

Figure 2 - SCOR hierarchical decomposition




**Source:** based on APICS (2017).

After an overview of supply chain management and the SCOR model, the next section presents the description of blockchain features and their applicability in the supply chain context.

## 2.2 Blockchain in supply chain management

A blockchain is a distributed ledger that registers data related to transactions or any other type of information, regulated by a consensus mechanism and secured by cryptography techniques (LONGO *et al.*, 2019). The concept was released by Satoshi Nakamoto, in 2008, and, as the name suggests, it consists of linking blocks in a chain (NAKAMOTO, 2008).

Among several of its particularities, a blockchain operates without relying on a central entity. In other words, disintermediation is promoted, offering distinguished possibilities to solve dispute resolutions and provide validations (WANG; HAN; BEYNON-DAVIES, 2019).

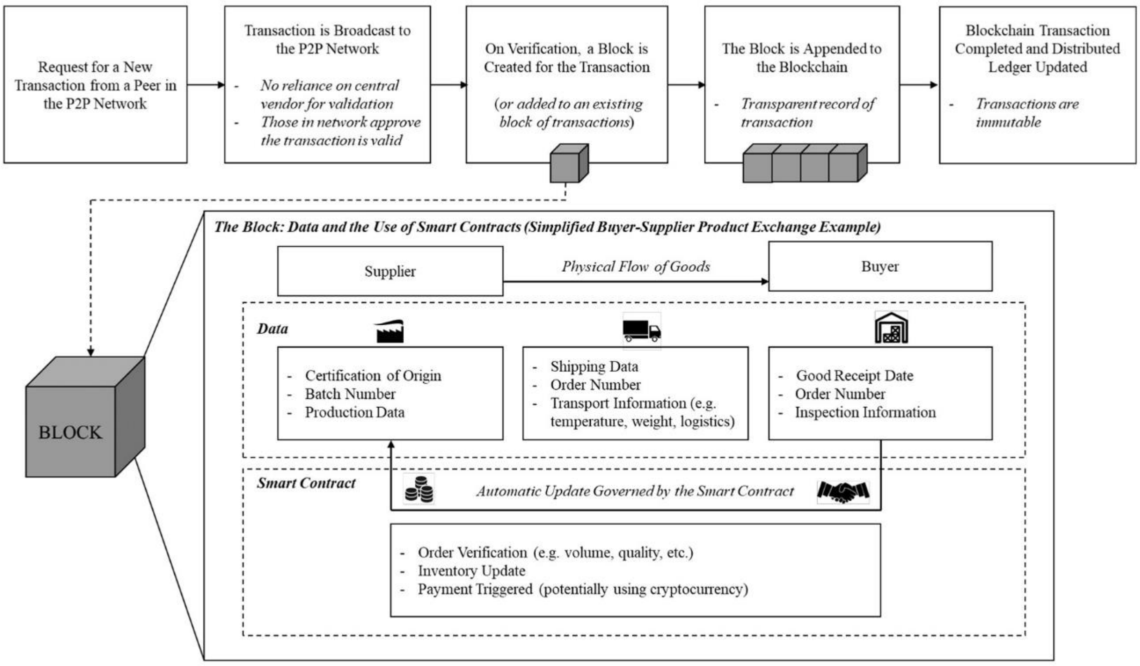
Besides promoting supply chain transparency and assuring trust in the information shared, blockchain leads to a multi-organizational and synchronized network that also allows real-time updates. Another potential feature is that a blockchain can store smart contracts, which are computer protocols that trigger algorithms to force or check the fulfilment of agreed conditions in an automated way (CHRISTIDIS; DEVETSIKIOTIS, 2016), assuring that the rules implemented are being attended to by the involved parties.

Based on a peer-to-peer (P2P) configuration, each node of a blockchain keeps a copy of the information stored, facilitating the identification of attempts to submit tampered information. Additionally, since the data is registered, the immutability principle prevents any part of making any change, implying that if a mistake is made, a new block must be later inserted with accurate information to correct mistakes (SABERI *et al.*, 2019).

However, blockchain is not supposed to replace conventional databases, because it is not intended to deal with large volumes of data, and the use of aggregated or pre-processed data is recommended (LONGO *et al.*, 2019). From another perspective, governance is a two-sided theme. While a blockchain network requires its governance statements, it also impacts the governance of transportation, logistics, and supply chains, and this interface determines which information is going to be shared and the level of openness accepted (KOH *et al.*, 2020).

Figure 3 illustrates in its upper part the flow of events that represents a transaction registered in a blockchain, including having a consensus among members before appending a new block. The bottom part displays examples of information that can be recorded alongside the physical flow of a supply chain and the optional use of a smart contract linking and automating the interface between a buyer and a supplier.

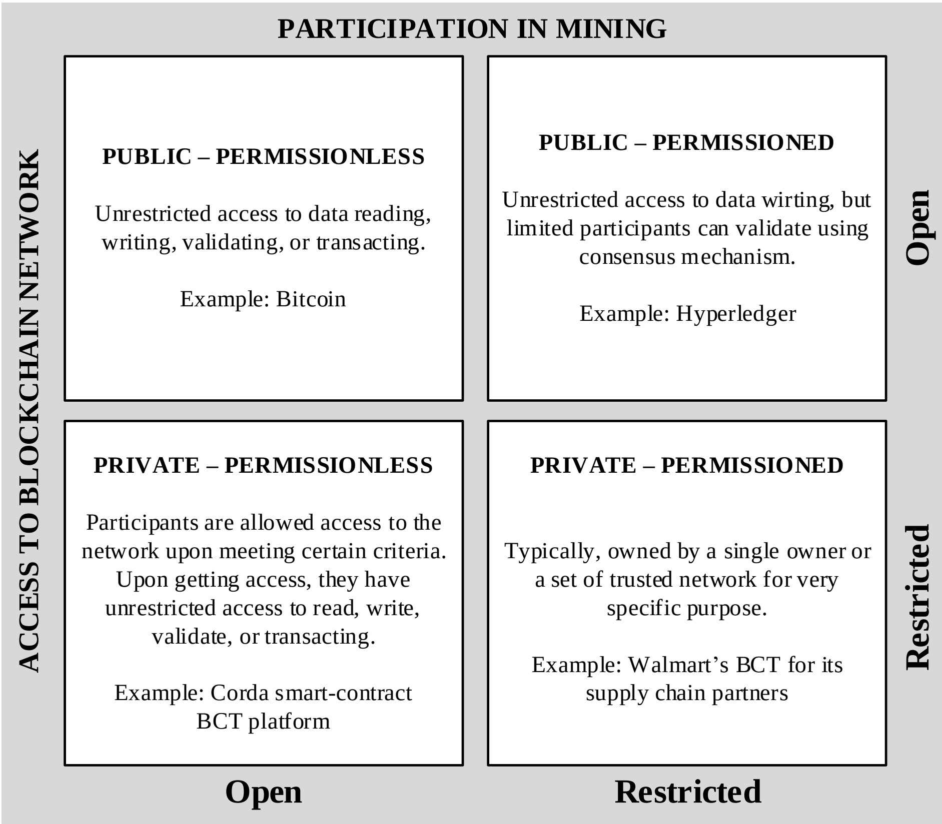
Figure 3 - Working logic of blockchain technology




**Source:** Cole, Stevenson, and Aitken (2019, p. 472).

A blockchain is classified into two perspectives. In terms of membership access, in a public one, any party can make its registration and start its participation, while in a private one, entrance is authorized only if the candidate matches specific criteria. Alternatively, regarding participation in mining, in a permissionless blockchain, all the participants are assigned to perform any type of action; in contrast, in a permissioned platform, validation procedures are restricted to certain parties (NANDI *et al.*, 2020). A hybrid combination is referred to as a consortium blockchain (ZHENG *et al.*, 2017). Figure 4 synthesizes and combines the classifications of a blockchain according to access for membership and participation in mining.

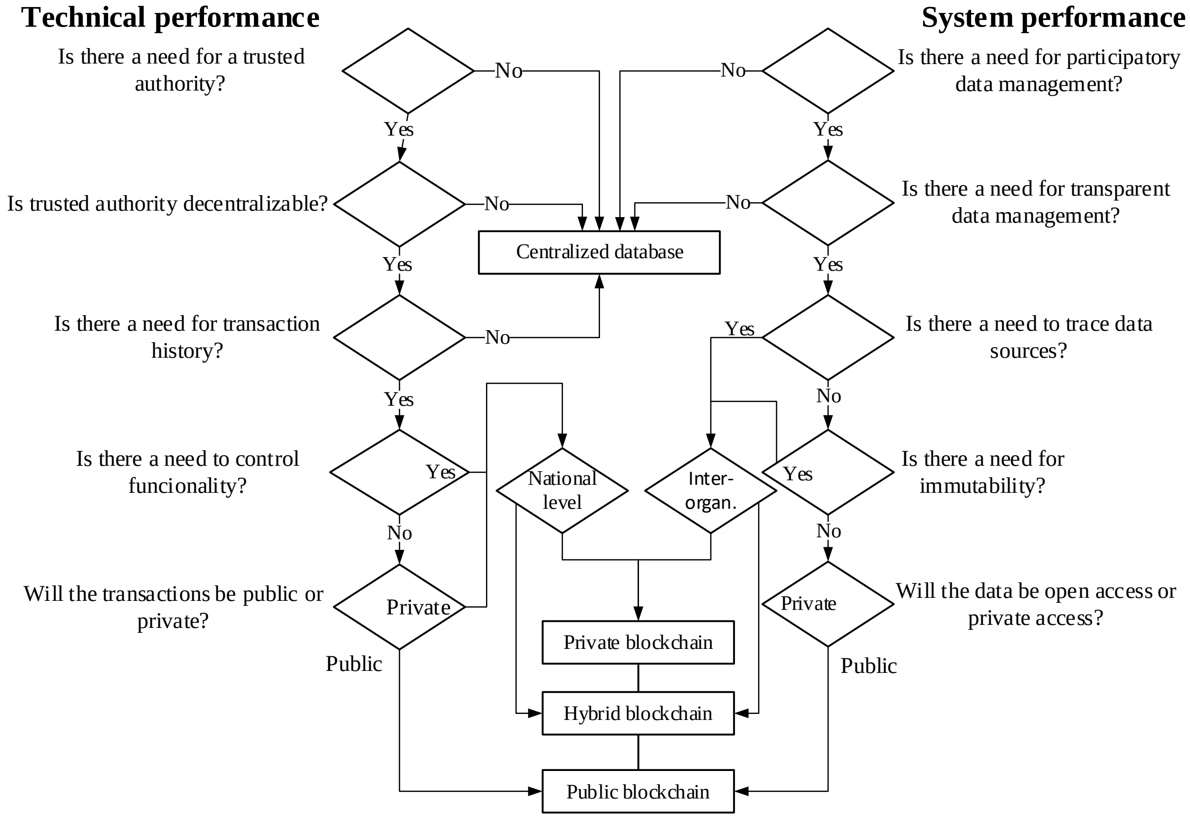
Figure 4 - Types of blockchain




**Source:** Nandi *et al.* (2020, p. 16).

Figure 5 shows a suitability flowchart proposed by Feng *et al.* (2020). The proposal considers both technical and system performance and is focused on supporting strategic supply chain objectives of traceability management. It includes private, public, and hybrid blockchain types, and indicates that a centralized database is still an option for some cases. Blockchain is not a universal answer and taking it as "a solution looking for a problem" is a wrong assumption (HUGHES *et al.*, 2019). In addition, blockchain is emphasized as a technology mostly suitable for inter-organizational issues (WANG; HAN; BEYNON-DAVIES, 2019).

Figure 5 - Flowchart of suitability analysis for a blockchain-based traceability system




**Source:** Feng *et al.* (2020, p. 9).

After taking a brief overview of the potential applications of blockchain in supply management, the next section provides fundamental definitions of supply chain traceability, including formal definitions, types of information needed, and the levels of granularity following the GTS standard (GS1, 2017).

## 2.3 Supply chain traceability

Traceability comprehends the possibility of following the corresponding flow of both material and information within a single organization or in movements between different supply chain parties when either physical or virtual movements occur (KARLSEN *et al.*, 2013). For Thakur *et al.* (2011), collecting information about the flow of products, as well as their quality and process parameters, should consider transition states, whether the progress is triggered internally or externally to the object.

According to the International Organization for Standardization (ISO, 2015), the ISO 9001: 2015 defines traceability as "(…) the ability to trace the history, application or location of an object". In practical terms, tracing a product or service means gathering information about the origin of materials and parts, the processing history, the distribution, and the location after delivery (GS1, 2017).

The terms ‘‘tracking’’ and ‘‘tracing’’ are employed interchangeably to refer to traceability, but some particularities must be addressed. Tracking is a forward-driven approach that encompasses the downstream path of a unit by recording identifications from a top-down perspective. In contrast, tracing adopts a backward-driven approach to distinguish the origin of the components that a product is made up of, following a bottom-up perspective. An efficient combination of both functions attests to a streamlined traceability system (SCHWÄGELE, 2005; STORØY; THAKUR; OLSEN, 2013). Alternatively, Dupuy *et al.* (2005) associate tracing with getting the origin and characteristics of a product and tracking with getting the localization.

According to Moe (1998), internal traceability focuses on tracking a product or a batch and the sequence of events it is submitted to inside the boundaries of a single supply chain party, while external traceability covers the interactions involving at least two parties of a supply chain. Processes of transport, storage, processing, distribution, and sales are monitorable in internal and external dimensions. Lindwall and Sandahl (1996) classify traceability as horizontal and vertical. The former comprises item differentiation between different product models, and the latter encompasses dependent items within a model. However, despite the perspective considered, more than recorded, product, process, and transport, information must be linked to enable traceability throughout the chain of events and later to the proper retrieval of information to rebuild the previous history (KARLSEN *et al.*, 2013).

The elements needed to perform traceability include unique identification of traceable units and registers of processes' data. An identifier can be associated with an individual production facility, a parent company, or even with the supply chain, either nationally or globally (OLSEN; BORIT, 2018).

According to the GTS (GS1, 2017), a well-adopted standard in the literature and practice (BEHNKE; JANSSEN, 2020; STORØY; THAKUR; OLSEN, 2013; DASAKLIS *et al.*, 2022; OLSEN; BORIT, 2018; AHMED; MACCARTHY, 2023), any entity that can be traced is referred to as a Traceable Resource Unit (TRU), which represents a traceable object. In this context, a batch is a group of entities that has similar characteristics after having the same processes (STORØY; THAKUR; OLSEN, 2013). TRUs also imply a hierarchical structure, since an item is inside a pallet that is part of a container and can also represent a TRU itself at different levels of granularity (OLSEN; BORIT, 2018).

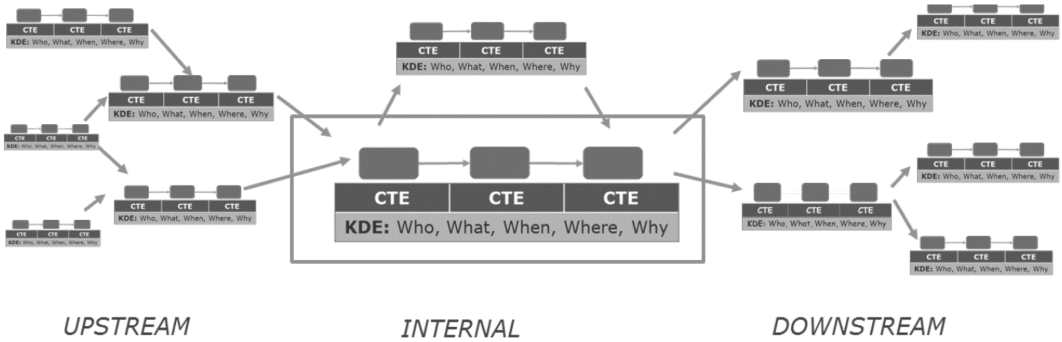
Following the guidelines found in GTS, traceability is accomplished by first identifying and capturing information about Critical Tracking Events (CTE) that happen with TRUs, including steps of receiving, transforming, packing, shipping, and transporting (GS1, 2017). The data that together represent a CTE are referred to as Key Data Elements (KDE), and embrace five dimensions:

- Who - supply chain party or stakeholder;
- What - traceable resource unit or traceable object;
- Where - location, externally, or resource, internally;
- When - trace event;
- Why - business process;

In a nutshell, traceability relies on the combination of static and dynamic data, throwing a multi-party and multi-chain challenge (GS1, 2017). Static data, also referred to as master data, offers information needed to understand the context of the product, and thus the event is inserted (THAKUR *et al.*, 2011), including the description of products, parties, locations, and assets. Dynamic data includes transaction data and visibility data. The former category assigns modifications such as a transfer of ownership (e.g. orders and invoices) or a transfer of custody (e.g. transport instruction and proof-of-delivery), while the latter represents the accomplishment of a relevant business process, and these data are usually captured for traceability purposes. All these categories possess data that will be kept internal and data that can be freely shared with partners. As an illustrative example, shipping and receiving are events that denote milestones on a chain of custody or ownership (GS1, 2017).

Figure 6 exhibits where CTEs are posited alongside the flow of a supply chain, and each company must define which events are assumed as critical to have their KDEs captured to contribute to achieving end-to-end supply chain traceability.

Figure 6 - Traceability data across supply chains




**Source:** GS1 (2017, p. 17).

The quality of any type of data is evaluated according to four aspects. Besides completeness and accuracy, it is essential to confirm the consistency of data across different systems, as well as the validity assured by time-stamping signals (GS1, 2017).

Traceability is addressed from different perspectives. Palletized items are part of a logistic unit, as well as an asset such as a truck or a vessel can equally be a traceable object. Finally, any product can be assumed as a traceable object. In this context, three main levels of identification are adopted to discriminate traceable objects (GS1, 2017):

- Class-level – allows the identification of different types of products or parts;
- Batch/lot-level– refers to a small number of items produced in the same machine or period of work receives the same ID;
- Instance-level – represents a specific ID attached to each single item;

The level of identification required will influence the time and cost to implement a traceability system, which must be aligned with supply chain parties, as it is possible to establish different combinations. This coordination is essential since end-to-end traceability depends on all the parties involved with the regular custody, trade, and transformation processes, and even with maintenance and end-of-use actions (GS1, 2017).

Moreover, end-to-end traceability demands accessing and combining data maintained by other supply chain members. In this scenario, blockchain emerges as an interesting alternative due to its decentralized configuration. Despite having methods, procedures, and routines currently indicated for traceability management, each company has its practices, which makes systems' interoperability a worthy feature (GS1, 2017).

A well-established traceability system comprehends components to identify and mark traceable objects, to provide automatic captures of events, and to record and share data both inter- and externally (GS1, 2017).

As a final remark, among the drivers for traceability, Karlsen *et al.* (2013) highlight the following: legislation, safety, quality, sustainability, welfare, certification, competitive advantages, chain communication, threats, and production optimization. Storøy, Thakur, and Olsen (2013) mention aspects such as documenting the chain of custody and production practices, attending to regulatory demands, and measuring costs with production and logistics. In addition, risk management, supply chain efficiency, customer trust, and brand integrity are also important drivers for organizations that decide to perform traceability, and other aspects considered during traceability implementation decisions include supply chain role, cost-benefit analyses, and technologies affordable (GS1, 2017).

After getting into the definition of the main concepts regarding traceability, the next section presents the main aspects concerning agent-based simulation modeling, including details that are useful to represent supply chain traceability.

### 2.4 Agent-based simulation modeling

Agent-based modeling and simulation (ABMS) is a powerful alternative to explore the behavior of complex and distributed business systems. Based on a bottom-up approach, the components and their characteristics are represented and submitted to analysis, revealing the occurrence of possible nonlinear events that a decision-maker could not suppose without the assistance of a virtual environment (MACAL, 2016).

One distinctive feature of agent modeling is the potential to link micro- and macro-level behaviors, allowing the observation of different scales and viewpoints. Agents are modular entities that have their own set of attributes, rules, and behaviors, which can interpret information, take decisions, and establish communication, as well as absorb conditions of the context they are inserted in. Attributes are used to identify agents and can be either static or dynamic, i.e., being prone to changes, during a simulation run. Alternatively, ABMS is usable to study the formation of structures. In other words, it corresponds to evaluating the configurations determined by the rules considered (MACAL; NORTH, 2010).

According to Macal (2016), in ABMS, an agent is denoted by four main key features:

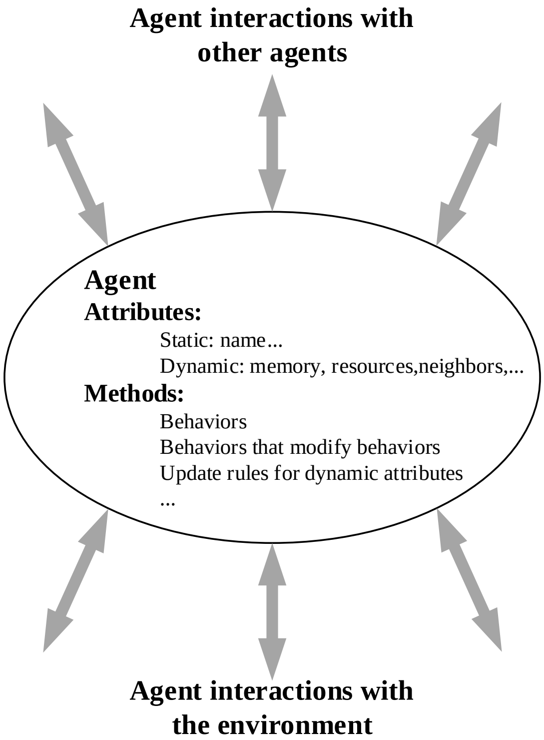
- Individuality: agents are specified individually, based on aspects included in their scope.
- Autonomy: agents are equipped to sense conditions and act regarding their perceptions.
- Interactivity: agents can establish relations with other agents and with their environments.
- Adaptivity: agents are embedded with the ability to update their behaviors as they learn with new experiences.

By representing processes and mechanisms, theories can be studied, and causal relations can be identified regarding the phenomena under consideration (MACAL, 2016). Figure 7 exhibits agents' internal characteristics and their interactions with both the environment and other agents.

The use of ABMS supports the finer levels of granularity found in databases. However, the agent rules determine the networks' structure and the flow of information for different types of relationships. Moreover, these interactions do not need to follow a timeline. Time-stepped configurations, activity-based input triggers, and discrete-event interfaces can be taken as alternatives to time control. Although, large models require a scheduler to provide synchronization among events (NORTH; MACAL, 2007).

Agents' behaviors are activated in three steps. Initially, an agent evaluates their state and decides an action to take. In the sequence, this action is performed. At last, the impact of the action is measured. Additionally, an agent can take decisions based on its own predefined goals (MACAL; NORTH, 2010).

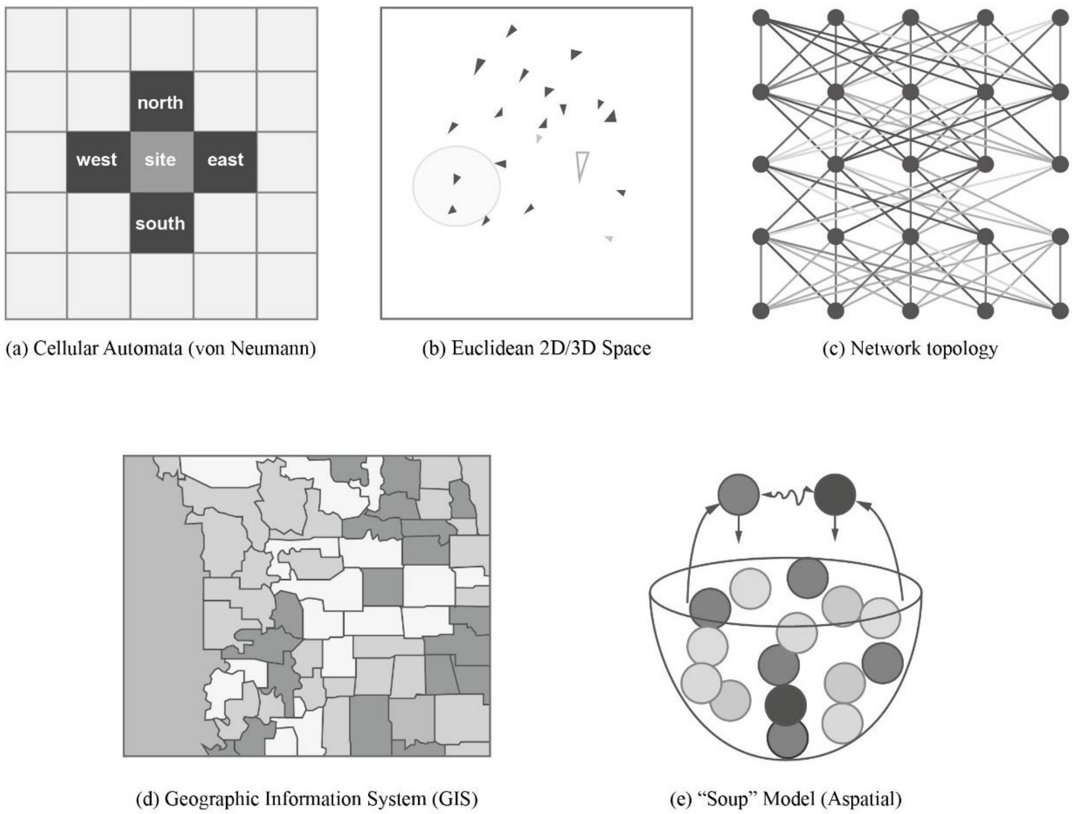
Figure 7 - Agent characterization




**Source:** Macal and North (2010, p. 154).

The types of connections established between agents are determined by the model topology or connectedness and represent the mechanism of information exchange. Figure 8 shows five common interaction topologies. A cellular automata model is structured upon a grid that addresses the agent movements, considering that each cell is the position of a single agent. In a Euclidean 2D/3D approach, agents move in multiple directions. In a network-based model, if the links are pre-determined and fixed, a static network is set up; in contrast, a dynamic network is observed if the links vary according to the model's endogenous behavior. When a Geographic Information System (GIS) is used, real distances are imported to the virtual environment using a length scale. In a soup or aspatial model, the position is considered irrelevant, since the interactions are randomly assigned, and the focus is on the information exchanged. Combinations of multiple topologies are commonly employed in agent-based modeling (MACAL; NORTH, 2010).

Figure 8 - Topologies for agent relationships and social interaction




**Source:** Macal and North (2010, p. 155).

Hierarchies between different classes of agents can be assigned through inheriting properties and behaviors. Parent classes also referred to as superclasses, are the inheritance sources, while child classes or subclasses are those that receive the properties. This is an alternative to refine information and provide specialization to agents. Access to both behaviors and properties may be controlled, being assigned as "public" or "private" (NORTH; MACAL, 2007). Considering the individuality of heterogeneous agents, Table 2 presents a classification of agent-based simulation models according to aspects associated with its properties and describes examples of blockchain usage in different contexts.

Describing an agent-based model is important to support analysis and understanding, but it encompasses a challenging and broad task due to overall complexity and the level and amount of detail involved. Aiming to make this communication process more efficient, Grimm *et al.* (2006) proposed the ODD protocol, which was later updated (GRIMM *et al.*, 2010; GRIMM *et al.*, 2020). The idea is to provide a list with a sequence to describe the elements that are part of an agent-based model. The acronym ODD refers to the three main blocks: Overview, Design concepts, and Details.

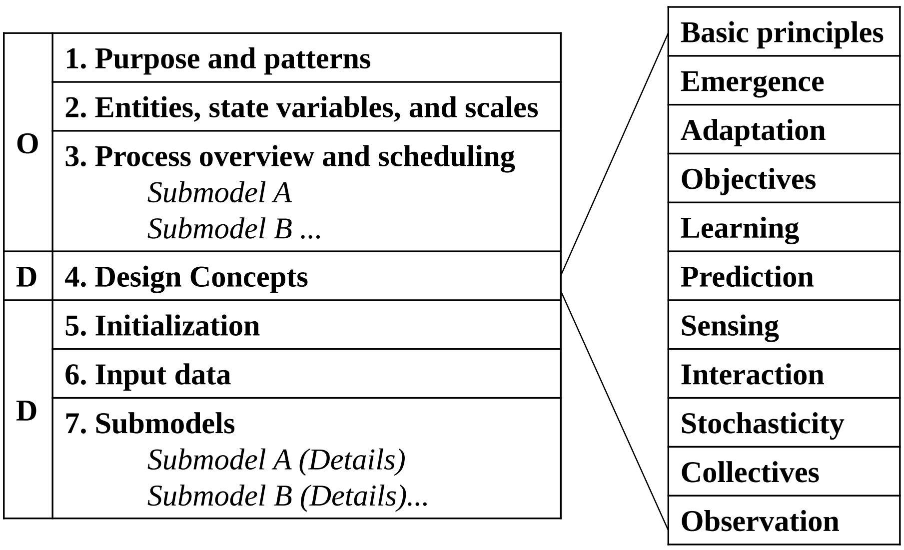
Figure 9 exhibits the components of each block, based on the last version, found in Grimm *et al.* (2020).

Table 2 - Definitions for blockchain-based traceability models according to agents' properties

| Definition/agent properties | Behaviors | Interactions | Adaptability | Example |
|---|---|---|---|---|
| Individual ABMS | Prescribed, scripted | Limited | None | The number of existing blockchains is fixed and the agents perform predefined transactions |
| Autonomous ABMS | Autonomous, dynamic | Limited | None | Agents select their suppliers and set Smart contracts conditions on existing blockchains |
| Interactive ABMS | Autonomous, dynamic | Between other agents and the environment | None | Agents influence others to collaborate on a blockchain, based on demands |
| Adaptive ABMS | Autonomous, dynamic | Between other agents and the environment | Agents change behavior during the simulation | Multiple blockchains are considered, and the access to write and read information is determined by performance evaluation |

**Source:** based on Macal (2016).

Figure 9 - Structure of ODD protocol




**Source:** Grimm *et al.* (2020, p. 2).

Each block is briefly presented as follows, starting with the “Overview”. The “Purpose and patterns” of a model refers, respectively, to the scope considered, and to possible patterns involved in the model development. In “Entities, state variables, and scales”, the low-level entities should be listed alongside the existing hierarchical level, and their characteristics, besides the temporal and spatial resolutions adopted. In “Process overview and scheduling”, both individual and environmental processes are specified, as well as the sequence of processes’ execution, considering state variables update and the synchronism among events.

The second block, named “Design concepts”, comprehends a checklist of how essential concepts are implemented according to the model design. Notice that some of the concepts, such as learning, and collectives are optional.

- Basic principles: expresses the theories, hypotheses, and modeling approaches employed in the model design both at system and agent levels.
- Emergence: differs phenomena that emerge from agents’ interactions from those that are straightly imposed.
- Adaptation: refers to the decisions that an agent makes after receiving stimuli.
- Objectives: addresses the criteria of success taken into consideration to evaluate alternatives in decision-making processes.
- Learning: stresses changes in how agents define their adaptive behavior after their experiences.
- Prediction: represents the agents’ ability to estimate the consequences of their decisions in future scenarios.
- Sensing: identifies the state variables that agents can detect and involve in their decisions.
- Interaction: outlines the types of direct or indirect interactions that occur, including the way that communication processes are performed.
- Stochasticity: informs the premises, assumptions, and purposes for the inclusion of random variables.
- Collectives: points out agents that are accounted as a group based on a characteristic or condition, which can be even temporary.
- Observation: specifies how data is collected for tests and analyses.

At last, “Details” focuses on aspects related to model execution and reproducibility. In “Initialization”, information about agents’ creation should be provided, including quantities and the initial values of their state variables and intermediate structures. In “Input data”, values inserted to start a model and how those were obtained should be listed, which also includes conditions that will be triggered in a later instant. “Submodels” brings the complete representation of processes previously listed in “Process overview and scheduling”, embracing equations, algorithms, and parameters specifications (GRIMM *et al.*, 2006).

As an additional remark, the authors strongly recommend the use of tables and flowcharts to present relevant information. Moreover, to maintain the standard sequence, in case one or more design concepts are not utilized, this condition should be mentioned in the model documentation (GRIMM *et al.*, 2006).

Although ODD protocol originated from ecological modeling, it became an interdisciplinary alternative, as applications in multiple fields are found. Examples in the supply chain domain are limited and include the assessment of the resilience and efficiency of food supply chains (VAN VOORN *et al.*, 2020) and the study of supplier networks’ formation and evolution as complex adaptive systems (EARNEST; WILKINSON, 2018).

# 3 PRESENT AND FUTURE PERSPECTIVES OF BLOCKCHAIN IN SUPPLY CHAIN MANAGEMENT: A REVIEW OF REVIEWS AND RESEARCH AGENDA

In this chapter, a systematic review of reviews is performed to identify the main benefits of blockchain application to supply chain management and the main blockchain features associated with supply chain management. The approach adopted assisted in dealing with the large rate of publications related to blockchain in supply chain management and finding works that have applied simulation modeling.

The content presented in this chapter was submitted to the journal **"Computers & Industrial Engineering"** on September 27th, 2021, for a double-blind peer-review evaluation, and accepted on March 21st, 2023. It was published online on March 24th, 2023. The corresponding citation is given below:

RISSO, L. A.; GANGA, G. M. D.; GODINHO FILHO, M.; DE SANTA-EULALIA, L. A.; CHIKHI, T.; MOSCONI, E. Present and future perspectives of blockchain in supply chain management: a review of reviews and research agenda. **Computers & Industrial Engineering**, v. 179, 109195, 2023.

**Abstract:** A growing number of papers addressing blockchain to supply chain management has been found, extending the range for scholars and practitioners aiming to comprehend the state of the art in this emerging field. Thus, we depict the current state of the art of blockchain in supply chain management and identify the main gaps to be explored in order to advance knowledge in this interplay. We employ the systematic literature review approach in a review of reviews to look into 103 review papers found in peer-reviewed scientific journals currently assigned to Scopus or Web of Science databases. Our results extend the discussion through an integrative approach that embraces blockchain technology in the context of supply chain management from multiple perspectives, encompassing the interface between physical and virtual flows beyond one-step-back and one-step- forward scope. We also consider disruptive aspects of blockchain technology as an alternative to integrate different supply chain stakeholders and provide information sharing to support both process-monitoring and decision-making in different industries and segments.

**Keywords:** Meta-review. Umbrella review. Blockchain. Supply chain management.

### 3.1 Introduction

A supply chain comprises a group of organizations that perform transactions, establishing both downstream and upstream flows of materials, services, information, and finances related to the transformation of materials to deliver products. Supply chain management (SCM) embraces the efforts to orchestrate the relations with other parties, focused on maintaining competitiveness regarding costs and service levels (MENTZER *et al.*, 2001), as well as on promoting the synergy between intra- and inter-company efforts (LAMBERT; COOPER; PAGH, 1998).

In the context of SCM, besides promoting transparency and assuring trust in the information shared, blockchain leads to a multi-organizational and synchronized network that also allows real-time updates (COLE; STEVENSON; AITKEN, 2019). Due to these distinctive features, blockchain technology is seen as a promising alternative to offer unique capabilities to leverage the performance of supply chain operations. It refers to an information and communication platform that promotes new processes and governance structures (SCHMIDT; WAGNER, 2019), impacting how transactions and relations between parties occur (KSHETRI, 2018). According to Iansiti and Lakhani (2017), it acts as a foundational technology since it proposes a new basis for economic and social systems.

Blockchain's potential comes from its working logic, which relies on a sequential connection of data that indicates transactions previously performed. Based on an alphanumeric string called hash, all these data blocks are replicated and information is dispersed to be simultaneously stored in the nodes of different supply chain stakeholders in a distributed infrastructure. These data are also protected by cryptographic procedures. For new block insertion, a consensus mechanism is applied in a peer-to-peer network to obtain validation and update permission without intermediary participation (NAKAMOTO, 2008).

Besides the hash of its previous block, each block carries a timestamp, and every change requires the entire process, addressing an immutability condition (TÖNNISSEN; TEUTEBERG, 2020). Due to this tamper-proof scheme, information cannot be modified, thus raw data integrity is assured, and anticounterfeiting initiatives are supported (THAKKER *et al.*, 2021). Moreover, an agreement can be automatically determined by setting up a smart contract that triggers transactions only if conditions in an algorithm are matched (CHRISTIDIS; DEVETSIKIOTIS, 2016). According to its design, a smart contract can also encompass control capabilities regarding automated information feedback and disruption detection (DOLGUI *et al.*, 2020).

In the supply chain management context, these characteristics offer outstanding possibilities to allow information sharing and real-time synchronization since blockchain can be used to solve database and messaging problems (KSHETRI, 2018). In a well-defined configuration, off-chain repositories and on-chain records can interoperate to complement traditional databases. By doing so, relevant data are shared with the interested parties (CHANG; CHEN; LU, 2019; LAMBOURDIERE; CORBIN, 2020), avoiding the formation of 'data silos' (NANDI *et al.*, 2020) and storage problems of 'data explosion' (LIN *et al.*, 2019).

Blockchain is highlighted as a solution to achieve traceability and end-to-end transparency in supply chain processes, overcoming one-step-back and one-step-forward practices based on the availability of reliable and timely information (COLE; STEVENSON; AITKEN, 2019; ASTILL *et al.*, 2019). Information transmitted can support dynamic monitoring of cargo movements, recall interventions (KSHETRI, 2017), and product provenance in an auditable and permanent system. Suppliers' reputation can be evaluated based on blockchain registers (LI *et al.*, 2020; SUN *et al.*, 2021), and the combined application of blockchain with smart technologies such as the Internet of Things, big data, and cloud computing provides a secure, dynamic, responsive, and knowledge-based approach, collaborating with manufacturing, logistics, and even product recovery practices (TOZANLI; KONGAR; GUPTA, 2020).

In addition, short-term buyer-supplier interactions are taken in a virtual environment classified as a 'network of trust' (COLE; STEVENSON; AITKEN, 2019), built upon a single version of the truth that is gradually constructed by the interaction between possible unknown parties (WONG *et al.*, 2020), thus changing trust paradigms in supply chain management. A blockchain also supports the integration of heterogeneous traceability data recorded by the multiple involved parties (CASINO *et al.*, 2020).

Regarding access for participation, a blockchain is classified as 'public' or 'private', while the terms 'permissionless' and 'permissioned' refer to the actions each participant can execute (CHANG; IAKOVOU; SHI, 2019). Moreover, a hybrid combination is classified as a consortium blockchain (JUMA; SHAALAN; KAMEL, 2019).

Due to the potential to improve SCM, an ever-growing number of primary and even secondary research papers focused on blockchain has been released, extending the range beyond cryptocurrencies and smart contracts for financial transactions. The approaches have gradually been evolving from theory-building to practical application attempts (ZHAO *et al.*, 2019). As a result, a large number of papers have been published in the scientific literature in recent years, which may be a barrier for those desiring to understand what has been done so far.

Thus, this paper aims to depict the current state of the art of blockchain in supply chain management and identify the main gaps to be explored in order to advance knowledge in this interplay. The research questions defined for this study are the following:

RQ1.1: What are the main supply chain topics approached in reviews about blockchain in supply chain management?

RQ1.2: What are the blockchain features studied in reviews about blockchain in supply chain management?

RQ1.3: Which directions for future research have been reported in reviews about blockchain in supply chain management?

We perform a review of reviews, which is based on evidence from literature reviews. Alternative terminologies for this approach include overview of reviews, umbrella review, meta-review, synthesis of reviews, and summary of reviews (HUNT *et al.*, 2018). This type of literature review provides a ‘compact and comprehensive overview of the state of knowledge in a specific research area’ (ABEDINNIA *et al.*, 2017), and represents a useful alternative to deal with themes facing large publication rates, such as noticed about blockchain in supply chain management. We found reviews of reviews related to supply chain management (SEURING; GOLD, 2012; CARTER; WASHISPACK, 2018; MARTINS; PATO, 2019; CENTOBELLI *et al.*, 2021; CORMACK; THOMÉ; SILVESTRE, 2021), but none of them emphasized technological aspects, particularly the blockchain.

This chapter is structured as follows. Section 3.2 describes the method employed, including planning, conducting, and reporting steps. Section 3.3 exhibits a descriptive analysis of the sample. Section 3.4 contains the findings obtained through a content analysis considering supply chain topics and blockchain features. Section 3.5 comprises a synthesis of research directions indicated for primary works. Section 3.6 gives the discussion concerning the findings. Section 3.7 provides a research agenda with topics recommended for future literature reviews. Finally, Section 3.8 presents the conclusions and limitations of this study.

## 3.2 Method

A systematic literature review (SLR) approach is recommended to perform a review of reviews (GAROUSI; MÄNTYLÄ, 2016) to fulfill rigor and replicability principles, and thus obtain consistent results. This approach considers reviews as its ‘unit of analysis’. We adopted the stages of planning, conducting, and reporting/dissemination (TRANFIELD; DENYER; SMART, 2003; DENYER; TRANFIELD, 2009).

### *3.2.1 Planning the review*

We first aim to identify supply chain topics discussed in terms of general metrics and requirements associated with blockchain perspectives (RQ1.1). Then, we engaged in identifying which blockchain features have been highlighted in the supply chain management context (RQ1.2). Finally, we want to explore the research directions indicated for future works associating blockchain with supply chain management (RQ1.3).

First, we applied the search protocol presented in Table 3. Then, following the guidelines from the preferred reporting items for systematic reviews and meta-analyses (PRISMA) approach (MOHER *et al.*, 2009), we performed the steps indicated to identify, screen, and analyze papers that were assigned to be part of the sample.

### *3.2.2 Conducting the review*

#### 3.2.2.1 Material collection

Scopus and Web of Science were the databases consulted, which include prominent journals covering the themes of interest. Only papers written entirely in the English language were considered. No limitation as to scientific areas or journals was established. In terms of type, we focused on journal publications, thus conference papers, book chapters, and editorials were not included in our search process. The fields selected to address the search are specific for each database. Considering that the initiatives performed by IBM and Maersk happened in 2016 (KSHETRI, 2018), we have set the publication date from January 2016 to June 2022. The strings used were different spelling forms for the word 'blockchain', combined with a connector AND with the terms 'supply chain*'. The full syntax for the search query is specific to each database. All this information is synthesized in Table 3, which presents the search protocol, and supplies the search configuration for Scopus and Web of Science databases separately.

For complementary purposes, we performed a backward snowballing by examining each reference of elected papers. All titles identified were selected and submitted to the same criteria applied to the material found in the database searches.

Table 3 - Search protocol

| Information | Description | |
|---|---|---|
| Search criteria | | |
| Databases | Scopus | Web of Science |
| Language | English | English |
| Scientific areas | All | All |
| Journals | All | All |
| Article types | Article and Review | Article, review, and early cites |
| Search fields | Title, abstract, and keywords | Topic |
| Date of publication | From January 2016 to June 2022 | From January 2016 to June 2022 |
| Search terms | | |
| | "blockchain" OR "block chain" OR "block-chain" AND "supply chain*" | |
| Search query | | |
| Scopus | ( TITLE-ABS-KEY ( "blockchain" OR "block chain" OR "block-chain" ) AND TITLE-ABS-KEY ( "supply chain*" ) ) AND PUBYEAR > 2015 AND PUBYEAR < 2023 AND ( LIMIT-TO ( DOCTYPE , "ar" ) OR LIMIT TO ( DOCTYPE , "re" ) ) AND ( LIMIT-TO ( LANGUAGE , "English" ) ) | |
| Web of Science | ((((TS=("blockchain" OR "block chain" OR "block-chain" )) AND TS=(supply chain*)) AND PY=(2016-2022)) AND DT=(Article OR Early Access OR Review)) AND LA=(English) | |

3.2.2.2 Material selection and analysis

The initial pool of papers was established according to the inclusion criteria applied to the selection phase. Then, in the analysis sub-phase, the exclusion criteria were applied. Inclusion and exclusion criteria are listed in Table 4.

Only articles and reviews (I1), submitted to a peer-reviewed evaluation process (I2) were considered to be part of our sample. All the sections must be written in English language (I3) and the period considered was from January 2016 to June 2022 (I4). Papers that provide a review followed by a case study (DI VAIO; VARRIALE, 2020; FOSSO WAMBA *et al.*, 2020) or a survey (SHOAIB; LIM; WANG, 2020) were also considered eligible due to the content of their first part.

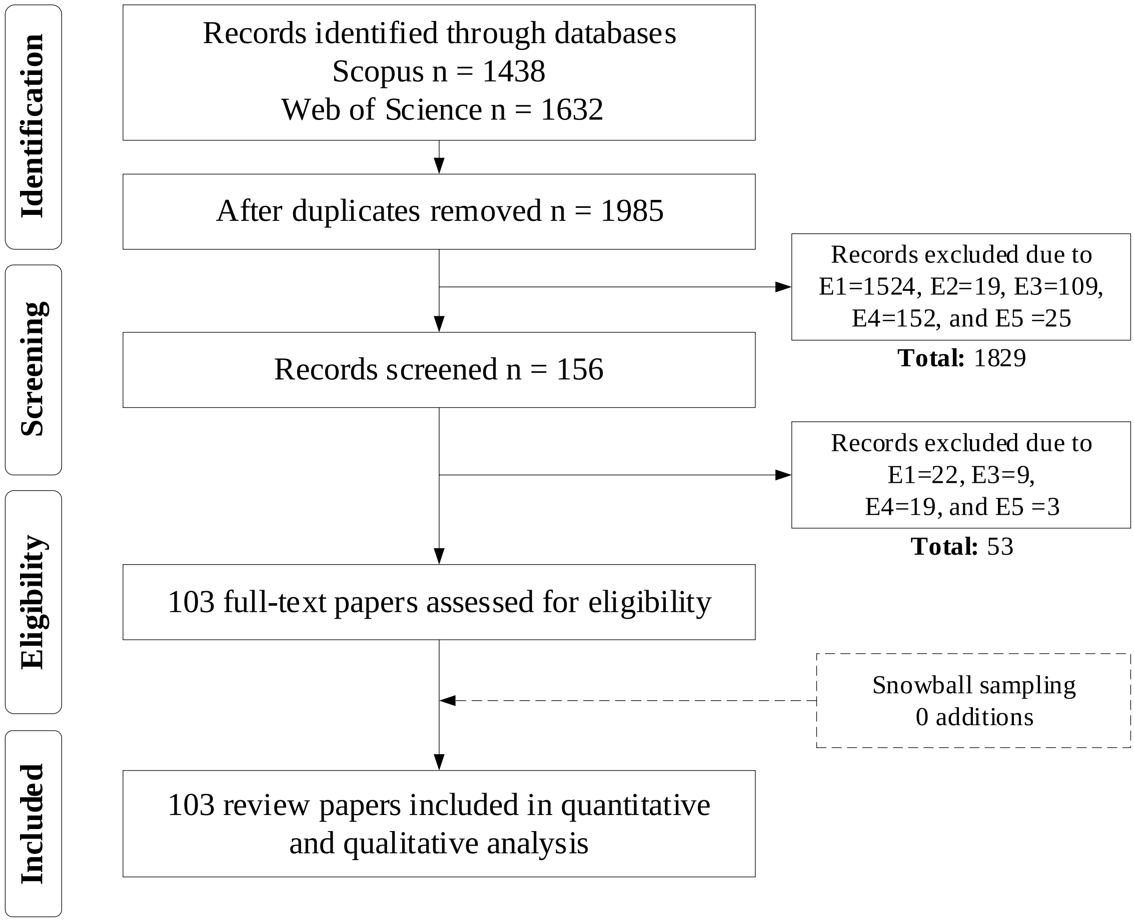
Among the exclusion criteria, E.1 eliminates those that are not literature reviews, while E.2 sets apart editorial and conference papers. The following criterion eliminates review papers that contain vague mentions of blockchain without exploring its features (E.3) or that only mention supply chain as a domain of application (E.4). Review papers centered on technical aspects, addressing algorithms, architectures, protocols, or hardware issues (E.5) were not considered since we are interested in managerial implications.

Table 4 - Criteria of inclusion and exclusion

| Criteria | Description |
|---|---|
| Inclusion (I) | I.1 - The paper is an article or a review |
| | I.2 - The paper is published in a peer-reviewed journal |
| | I.3 - The text is entirely written in English |
| | I.4 – The date of publication was between January 2016 and June 2022 |
| Exclusion (E) | E.1 - The article is not a literature review |
| | E.2 - Editorials or conference proceedings |
| | E.3 - Do not explore blockchain issues |
| | E.4 - Do not approach supply chain issues |
| | E.5 - Focuses only on technical considerations |

The analysis was performed in two rounds. A preliminary analysis for the screening step was based on titles and abstract reading. Then, the remaining papers were entirely read for assessing eligibility. The backward snowballing did not return any paper. A total of 103 literature reviews were selected to compose the sample. Quantitative results concerning each step are presented in Figure 10, following the steps of preferred reporting items for systematic reviews and meta-analyses (PRISMA) approach (MOHER *et al.*, 2009).

Figure 10 - Search and selection strategy




3.2.2.3 Systematic Map

A systematic map was established to support both gathering paper general information and answering our research questions, based on the approach adopted by Garousi and Mäntylä (2016). We first listed the year and the journal of each paper to get the temporal trend and the origin, respectively. We also classified the reviews as 'systematic' or 'narrative'. The last classification criterion refers to objectives established for each review paper, according to different combinations of six codes. Except for 'Factors listing', the other five codes were adopted from Martins and Pato (2019).

To assist in answering, we defined codes for each category assigned to our research questions (RQ). This process was based on attribute generalization combined with iterative refinement on an initial list made after the first reading of titles, abstracts, and even introductions if needed. Codes for categories 'supply chain requirements' and 'blockchain features' related to RQ1.1, and RQ1.2, respectively, were then converted by similarity to the ones with the highest occurrence, also considering the terms indicated by Tönnissen and Teuteberg (2020). Papers that highlight applications to specific industries or segments are also categorized. For RQ1.3, we applied an inductive approach to identify the main directions considered. Among the codes identified, 'costs', 'security', and 'sustainability' involve the same definitions given for RQ1.1, while 'traceability' takes the same approach previously assigned to RQ1.2.

The systematic map is presented in Table 5, including the list of categories and subcategories, as well as descriptions considered for each code. In addition, it is indicated whether single (S) or multiple (M) classifications are allowed for each subcategory.

Table 5 - Systematic map

| Categories | Subcategories | Description |
|---|---|---|
| Paper information | | |
| Review type (S) | | |
| | Narrative | Adopts a non-structured procedure, relying on the authors' background. |
| | Systematic | Involves following a protocol to collect and analyze the sample comprehensively |
| Review objectives (M) | | |
| | Factors listing | Comprises efforts to list sets of critical success factors, drivers, and/or barriers |
| | Framework | Indicates the proposal of either a conceptual or a categorical structure |
| | Gaps and directions | Stands for the identification of paths to be further explored |
| | New issues | Embraces innovative applications into specific operations or businesses |
| | Research consolidation | Corresponds to the integration of heterogeneous trends around a particular theme |
| | State of the art | Consists of getting the status in a scientific domain |
| Supply chain general metrics (RQ1.1.a) (M) | | |
| | Cost | Refers to financial aspects related to investments and expenditures |
| | Flexibility | Represents the system's ability to vary its outputs in terms of mix, volume, and other |
| | Quality | Stands for good properties of product and process elements |
| | Reliability | Corresponds to system robustness, including its availability and maintainability |
| | Safety | Comprises external and physical threats, such as product damage during transportation |
| | Security | Distinguishes internal and virtual issues, such as a hacker attack |
| | Speed | Includes the time needed to access, process, or transmit information and lead time reductions |
| | Sustainability | Attends to the use of resources without compromising environmental, social, and economic elements |

| Categories | Subcategories | Description |
|---|---|---|
| Supply chain requirements (RQ1.1.b) (M) | | |
| | Anticounterfeit | Means offering alternatives to inhibit the circulation of fake products |
| | Compliance | Implies a way of providing registers to assure that regulations and/or norms were met |
| | Decentralization | Corresponds to distributed schemes of information and power |
| | Disintermediation | Outlines the change in the procedures for doing business by eliminating a formal validator |
| | Dispute resolution | Is assigned to the discussions of agreements |
| | Provenance | Represents the possibility of assessing information of origin |
| | Property rigths | Refers to the digitalization of property |
| | Transparency | Embraces making data updates wholly and quickly available, avoiding decisions based on asymmetric data |
| | Trust | Includes elements such as reliable information and relationship issues |
| Blockchain features (RQ1.2) (M) | | |
| | Chronological chain | Reflects the sequential approach based on timestamped information |
| | Consensus mechanism | Is the case when the way of establishing agreements is emphasized |
| | Digital signature | Considers mathematical schemes employed to validate authenticity |
| | Immutability | Refers to relying on cryptographic functions to make data unchangeable |
| | Peer-to-peer network | Embraces the possibility of a disintermediated configuration |
| | Permanent availability | Exposes the database function, as registers are kept for future access |
| | Real-time processing | Is related to data capturing, allowing fast-tracking of background information |
| | Smart contracts | Concerns applications of decisions automatically triggered by algorithms under specific conditions |
| | Traceability | Comprehends taking any type of information about a product path during its production and/or distribution |
| | Verifiability | Displays the possibility of checking the authenticity of any information related to materials or transactions |
| Research directions (RQ1.3) (M) | | |
| | Adoption and contextual factors | Considers the factors addressed for deciding to implement a Blockchain |
| | Competitiveness | Is related to obtaining distinguished attributes of performance |
| | Governance | Encompasses structures and processes designed for a specific purpose |
| | Information/Data Management | Refers to the aspects and approaches to handling virtual processes |

| Categories | Subcategories | Description |
|---|---|---|
| | Relationships | Embraces the changes in the dynamics of business interactions and reputation building in the virtual environment |
| | Technology integration | Outlines the combination with other technologies and with legacy systems |
| | Theoretical development | Indicates the exploration through conceptual lenses |
| | Structural complexity | Comprises elements of a multi-party supply chain configuration |

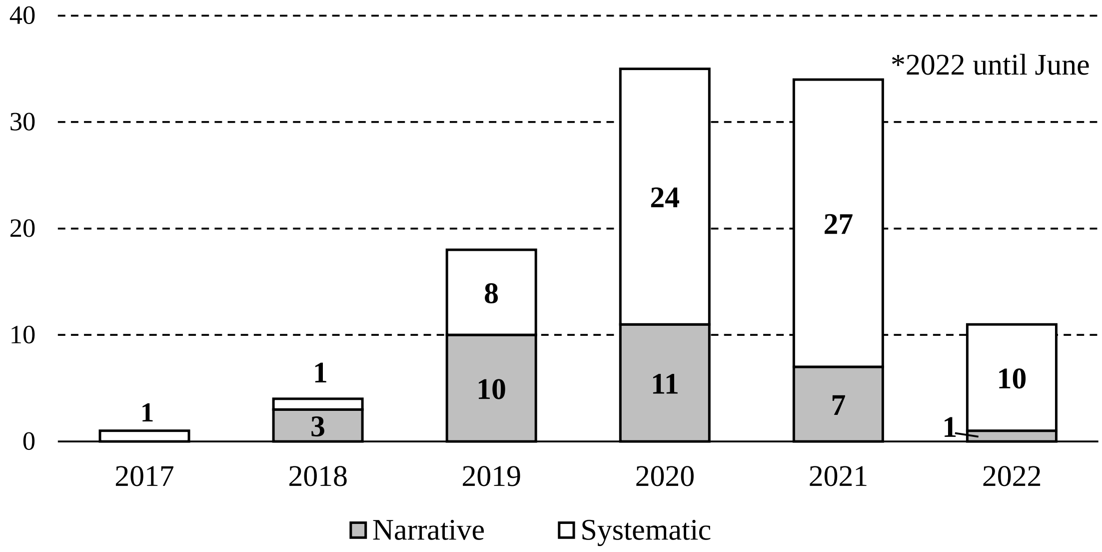
*3.2.3 Reporting and dissemination of results*

First, a descriptive analysis is given to present general information about the sample. Then, content analysis is performed focused on supply chain topics and blockchain features, following the stages indicated by Bengtsson (2016), namely: decontextualization, recontextualization, categorization, and compilation. We also synthesize the directions indicated by the analyzed papers for future primary works. After answering our three RQs, we propose a research agenda with 15 topics for future literature reviews according to our findings.

## 3.3 Descriptive analysis

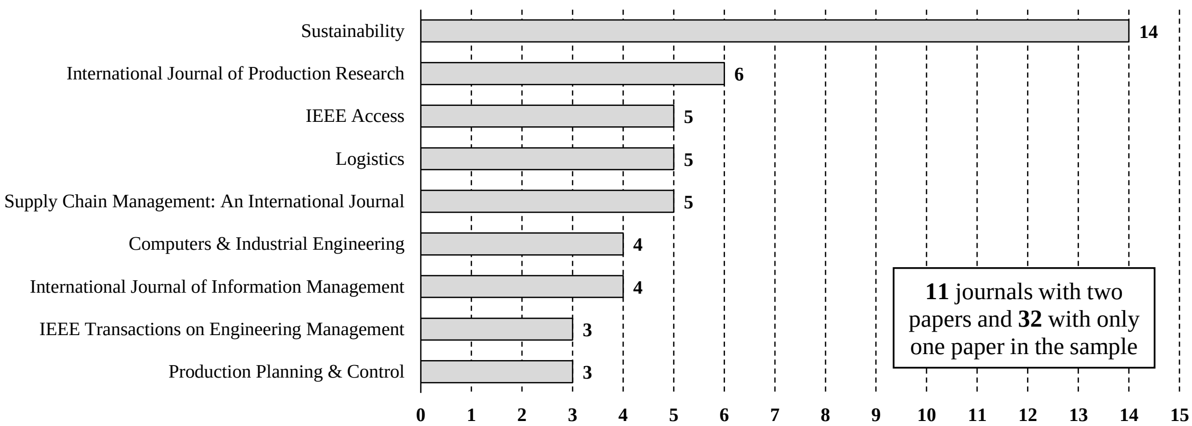
The number of reviews published per year, distinguished between systematic and narrative ones, is shown in Figure 11. The first review was published in 2017 and included blockchain as a technology to combat counterfeit issues in pharmaceutical supply chains (MACKEY; NAYYAR, 2017). Significant increases are noticed in 2019 and 2020. The numbers of 2021 reveal a small decrease, but the abnormal conditions caused by the Covid-19 pandemic have to be considered. In addition, the numbers of reviews about blockchain in supply chain management published in 2019 and 2021 are higher than the numbers of reviews about sustainable supply chains released during 2013 and 2016, respectively, according to Martins and Pato (2019). This comparison with a well-established research topic indicates that the topic is consolidating its space in the literature. The ascendancy of systematic reviews is another signal of knowledge consolidation since we notice that 2019 was the last year to register a higher number of the narrative over systematic reviews.

Figure 11 - Distribution of review papers per year and review type




The papers were collected from 52 journals, and 32 of those contributed with only one paper. The two sources with the highest number of publications are ‘Sustainability’, from ‘Environmental Science’, and the ‘International Journal of Production Research’, from ‘Business, Management, and Accounting’ subject area. Among others, the third position also includes ‘IEEE Access’ from ‘Computer Science’ subject area. This information reinforces the theme’s interdisciplinary profile. Figure 12 shows a list of journals with at least three papers in the sample.

Figure 12 - Number of review papers by journal




Concerning papers’ objectives, over 90% of the sample provides a state-of-the-art synthesis. A total of fifty-seven reviews supplies appointments for future research and then were assigned to the category ‘Gaps and directions’. Indeed, sixteen of them even mention it in their titles. In terms of ‘Factors listing’, forty-seven papers adopted thirty-two different combinations, as listed in Table 6. A total of twenty-three papers presented conceptual and categorical frameworks, which are described in Table 7. For additional information about each paper, see Table A1, in the Appendix.

Table 6 - Categories of factors listed

| Factors | References |
|---|---|
| Advantages and challenges | Li *et al.* (2020) |
| Advantages, disadvantages, and constraints | Tokkozhina, Martins and Ferreira (2022) |
| Applications | Dobrovnik *et al.* (2018) |
| Applications, benefits, and challenges | Dutta *et al.* (2020) |
| Applications, benefits, and limitations | Hughes *et al.* (2019) |
| Applications and challenges | Liu, Zhang, and Zhen (2021) and Zhao *et al.* (2019) |
| Barriers | Paliwal, Chandra, and Sharma (2020) and Saberi *et al.* (2019) |
| Benefits | Rufino Júnior *et al.* (2022) |
| Benefits and challenges | Chen *et al.* (2020), Duan *et al.* (2020), Fosso Wamba *et al.* (2020), Gonczol *et al.* (2020), Srivastava and Dashora (2022), Tharatipyakul and Pongnumkul (2021), Tijan *et al.* (2019), and Varriale *et al.* (2021) |
| Business requirements and critical success factors | Hastig and Sodhi (2020) |
| Capabilities | Nandi *et al.* (2020) |
| Challenges | Astill *et al.* (2019), Galvez, Mejuto, and Simal-Gandara (2018), Nurgazina *et al.* (2021), and Reddy *et al.* (2021) |
| Challenges and opportunities | Bamakan *et al.* (2021), Chang, Iakovou and Shi (2019), Kamilaris, Fonts, and Prenafeta-Boldὐ (2019), and Upadhyay *et al.* (2021) |
| Connectivity inhibitors and functionalities | Vivaldini and Sousa (2021) |
| Contributions | Khanfar *et al.* (2021) |
| Disruptions and challenges | Queiroz, Telles, and Bonilla (2019) |
| Drivers, barriers, and applications | Vu, Ghadge, and Bourlakis (2021) |

| Factors | References |
|---|---|
| Drivers, challenges, and barriers | Wang, Han, and Beynon-Davies (2019) |
| Enablers | Kayikci, Usar, and Aylak (2021) |
| Enablers, benefits, and challenges | Li, Lee, and Gharehgozli (2021) |
| Enablers and constraints | Hald and Kinra (2019) |
| Enablers, risks, and challenges | Karakas, Acar, and Kucukaltan (2021) |
| Impact and challenges | Lezoche *et al.* (2020) |
| Methods, benefits, and challenges | Feng *et al.* (2020) |
| Mitigable risks | Alkhudary, Queiroz, and Féniès (2022) |
| Potential uses | Cole, Stevenson, and Aitken (2019) |
| Potentials and barriers | Lohmer, Ribeiro da Silva, and Lasch (2022) |
| Potential and challenges | Rejeb *et al.* (2020) |
| Practices, potentials, and perspectives | Kouhizadeh and Sarkis (2018) |
| Solutions and applications | Vivaldini (2020) |
| Success factors | Shoaib, Lim, and Wang (2020) |
| Sustainable and unsustainable aspects | Varriale *et al.* (2020) |

Table 7 - Frameworks description

| Type | Focus | Reference |
|---|---|---|
| Conceptual | | |
| | Aircraft engine supply chain management | Ahmad *et al.* (2021) |
| | Operationalization of blockchain-based traceability | Feng *et al.* (2020) |
| | Implications of blockchain adoption | Karakas, Acar and Kucukaltan (2021) |
| | Blockchain application in green supply chain processes | Kouhizadeh and Sarkis (2018) |
| | Perspective of dynamic capabilities | Lambourdiere and Corbin (2020) |
| | Supplier selection | Li *et al.* (2020) |
| | Blockchain implementation in automotive food supply chains | Reddy *et al.* (2021) |
| | Integration of blockchain characteristics | Rejeb *et al.* (2021a) |
| | Potential and challenges of blockchain for food supply chain | Rejeb *et al.* (2020) |
| | Influences of blockchain features on transaction costs and supply chain governance | Schmidt and Wagner (2019) |

| Type | Focus | Reference |
|---|---|---|
| | Incorporating four middle-range theories | Treiblmaier (2018) |
| | Blockchain implementation in food supply chains | Vu, Ghadge, and Bourlakis (2021) |
| Categorical | | |
| | Processes, benefits, and challenges regarding blockchain adoption in food supply chains | Chen *et al.* (2020) |
| | Transformation phases and effects on organizational structures and processes | Dobrovnik *et al.* (2018) |
| | Opportunities for blockchain technology application in hospitality operations | Filimonau and Naumova (2020) |
| | Applications, values, and other attributes | Fosso Wamba *et al.* (2020) |
| | An innovation view to understand the development and acquisition of blockchain solutions | Hughes *et al.* (2019) |
| | People, process, and technology (PPT) model | Kayikci *et al.* (2022) |
| | Supply chain capabilities and performance outcomes of blockchain systems | Nandi *et al.* (2020) |
| | Technology readiness level (TRL) | Paliwal, Chandra, and Sharma (2020) |
| | Technology, trust, trade, and traceability/transparency | Pournader *et al.* (2020) |
| | Grouping barriers of blockchain adoption in sustainable supply chain as intra-organizational, inter-organizational, internal, and system-related | Saberi *et al.* (2019) |
| | Success factors prioritization | Shoaib, Lim, and Wang (2020) |

‘New issues’ encompasses forward-looking topics such as sustainable performance in the airport industry (DI VAIO; VARRIALE, 2020), financial inclusion in rural India (SCHUETZ; VENKATESH, 2020); United Nations Sustainable Development Goals (HUGHES *et al.*, 2019), application in hospitality operations (FILIMONAU; NAUMOVA, 2020), and the conditions provoked by the COVID-19 pandemic (NABIPOUR; ÜLKÜ, 2021). Results about objectives are summarized in Figure 13.

Figure 13 - Number and percentage of review papers according to the type of objective

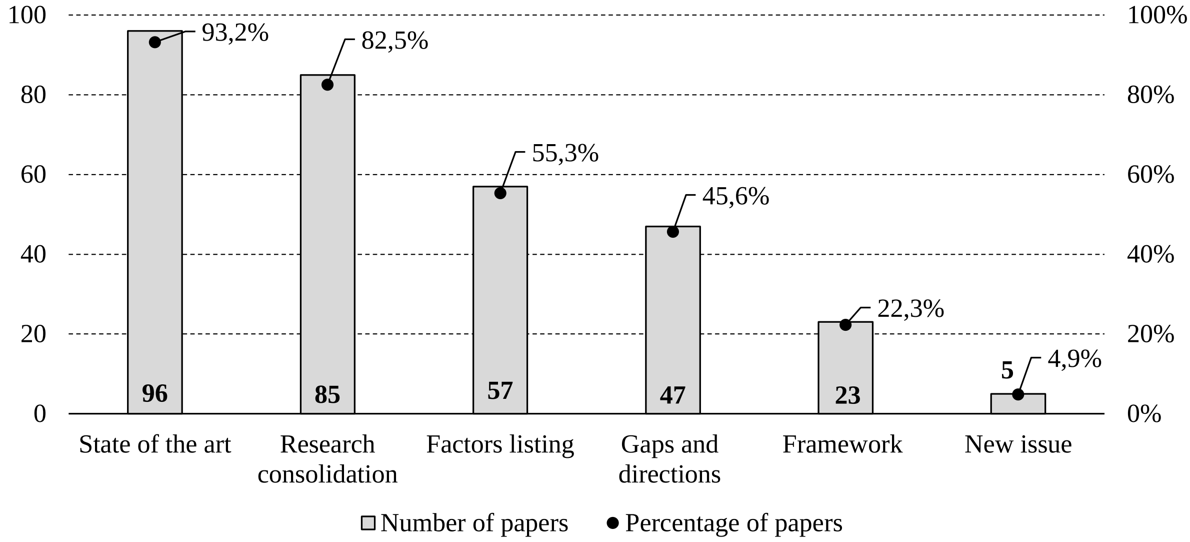



Figure 14 exhibits the number of reviews assigned to codes found in the systematic map, which supports the content analysis presented in Section 4. The numbers in the right column refer to the review papers associated with each subcategory. The label of the subcategory and the number of corresponding papers appear over the grey-shaded bars, and the total number is shown in parentheses. The total number of papers associated with each subcategory determines the size of each grey bar. For example, the text "Cost (78) - 1-2, 5, 7-9, 12-9, …" means that papers 1 until 2, 5, 7 until 9, and 12 until 19, and so on, approach issues related to cost, while this subcategory is embraced in a total of 78 papers. For additional information about each paper, see Table A1, in the Appendix.

Among the supply chain general metrics, cost, security, quality, and sustainability are the most addressed, while in terms of supply chain requirements, transparency, trust, and anticounterfeit are the most recurring. Smart contracts, traceability, and real-time processing are the blockchain features that most emerged in the sample.

Particularly for RQ1.3, a subsample of 57 papers is considered, corresponding to those assigned to the objective of providing 'Gaps and directions'. The dashed line in Figure 14 indicates the limit according to the subsample size. Adoption and contextual factors, technology integration, sustainability, and governance, are the most frequent categories considering the directions found.

Figure 14 - Overview of assessment results

| C | Subcategories (Quantity) - Paper numbers |
|---|---|
| Supply chain general metrics | **Cost (78)** - 1-2, 5, 7-9, 12-9, 21-3, 25-6, 28-30, 32-3, 36, 38-40, 43-54, 56-8, 60, 63-6, 68-72, 74-7, 79-84, 87-95, 97-8, 100, 103 |
| | **Security (70)** - 1-3, 5, 7-13, 15-6, 21, 23-6, 28, 32-6, 38-41, 47-53, 55-6, 58-61, 63-6, 68-70, 72-5, 77-8, 80, 82-3, 85-90, 93, 95-8, 100, 102 |
| | **Quality (57)** - 4-5, 7-9, 13-6, 20, 23-4, 28-9, 31-2, 35-6, 38-40, 42-3, 46-8, 52, 54-5, 58, 60, 63-4, 66, 70-1, 73-6, 79, 82, 84-8, 90-3, 96-8, 100, 102-3 |
| | **Sustainability (57)** - 2, 4, 7, 9, 11, 15-6, 18-22, 24-6, 31-3, 35-6, 38, 40, 42-3, 48, 50-3, 57, 61-2, 64-8, 70-1, 74-7, 79-82, 85, 88, 90, 93-5, 98, 100, 102-3 |
| | **Safety (38)** - 4, 8, 14-6, 21-4, 28, 34-40, 43, 48-9, 51, 58, 60-1, 63-4, 66, 70, 74-6, 83, 85, 87-8, 90, 98, 100 |
| | **Speed (27)** - 5, 8-9, 21, 25-6, 29-30, 32, 34, 36, 39-40, 48-9, 52, 56, 63, 73, 87, 90, 92-3, 95, 97-8, 102 |
| | **Flexibility (22)** - 11, 23, 31, 33, 35-6, 39-40, 47, 59, 63, 65, 72, 74-5, 78, 80, 82, 92, 97, 101, 103 |
| | **Reliability (21)** - 1, 23-4, 26, 30, 36, 40, 46-7, 49, 64, 73, 81-2, 87-90, 95, 98, 100 — N = 103 |
| Supply chain requirements | **Transparency (94)** - 1-17, 19-29, 31-3, 35-45, 47-9, 51-3, 55-9, 61-79, 81-96, 98-103 |
| | **Trust (78)** - 1-2, 4-6, 9-16, 18, 20-1, 23-33, 35-6, 38, 40, 42-8, 51-3, 56-7, 59, 64-6, 68-9, 71-84, 86-7, 89-93, 95, 97-103 |
| | **Anticounterfeit (48)** - 1, 3, 5-6, 8, 11, 13, 15-6, 19, 21-4, 26-9, 32, 34, 36-7, 42, 48, 50, 52, 55-6, 64-6, 68-71, 73-74, 76, 78-9, 84-5, 87, 89-90, 97-8, 100 |
| | **Disintermediation (40)** - 5, 8, 11-2, 14-15, 26-7, 31, 33, 35-6, 39, 42-6, 53, 56, 60, 63, 69-72, 74, 77, 80-3, 87, 90, 93, 95, 100-3 |
| | **Compliance (37)** - 1-2, 5-8, 13, 21, 24, 26, 29, 31-2, 36, 40, 42, 47, 49, 52, 56, 58, 63-4, 67, 72, 75, 76, 78-9, 81, 85, 87, 95-6, 98, 100, 102 |
| | **Decentralization (37)** - 2, 4-6, 11, 14-5, 20-2, 24, 26-7, 31-2, 36, 39-40, 43, 45-6, 52-3, 69, 72-3, 76, 78, 81-2, 89-90, 93, 95, 99-100, 102 |
| | **Provenance (33)** - 1-2, 5, 8, 12, 14, 16, 23, 28, 32, 36-9, 43, 54, 58, 65-6, 69, 73-6, 79, 87, 90, 96-100, 102 |
| | **Dispute resolution (27)** - 1-3, 12-3, 32, 35-6, 41, 56, 58, 60, 68, 72, 74, 76, 80-1, 84, 88, 92, 94, 97-8, 100, 102-3 |
| | **Property rights (14)** - 3, 5, 12-3, 16, 39, 53, 75, 78, 81, 84, 87, 97, 103 — N = 103 |
| Blockchain features | **Smart contracts (86)** - 1-2, 4-10, 12-3, 15-7, 19-25, 27-8, 30-1, 33-44, 47-53, 56-66, 68-73, 75-82, 84-5, 87-100, 102 |
| | **Traceability (83)** - 1-17, 20-4, 27-9, 31-2, 34-6, 38-43, 47-9, 51-4, 56-8, 60-1, 63-76, 78-9, 81-90, 93, 95-100, 102-3 |
| | **Real-time processing (54)** - 2-3, 5, 9, 13-6, 20-3, 26, 28-9, 31-2, 36, 40, 45-9, 51-3, 56, 60, 62-5, 69, 71-8, 81, 87-8, 90, 92, 96-102 |
| | **Immutability (43)** - 1-2, 4-5, 9-10, 13, 15, 20, 22, 24, 26, 32-3, 36, 39, 43, 47-8, 52-3, 56, 58-9, 64, 66, 68, 70-1, 73, 76-7, 79-80, 82-3, 87, 90-2, 94-5, 102 |
| | **Consensus mechanism (25)** - 2, 5, 13, 18, 21-2, 24, 31, 34, 36, 38-9, 43, 50-1, 53, 59, 64, 66, 71, 73, 77, 79, 82, 87 |
| | **Permanent availability (24)** - 1, 3, 5, 10, 14, 16, 26, 31, 35, 45, 49, 54, 56, 59, 64, 66, 70, 79, 82-4, 87, 94, 96 |
| | **Verifiability (22)** - 2, 13, 22, 26, 28, 30, 33-4, 40, 42, 47, 52, 54-5, 63-5, 71-2, 77, 87, 94 |
| | **Peer-to-peer network (13)** - 8, 25, 43, 51, 69, 72-3, 77, 80, 83, 93, 100, 102 |
| | **Chronological chain (12)** - 15, 19, 37-8, 41-2, 45, 48, 56, 92, 95, 100 |
| | **Digital signature (10)** - 1, 5, 12, 22, 24, 49-50, 76, 92, 95 — N = 103 |
| Research directions | **Adoption and contextual factors (30)** - 3, 5, 8, 11-2, 15, 21, 23, 29, 33, 36, 40-2, 44, 51, 53, 63, 65, 78-80, 90-1, 93, 95, 97-8, 102-3 |
| | **Technology integration (26)** - 8-9, 11-2, 17, 22-3, 27, 29, 42, 51-3, 58, 64-5, 69, 71-3, 75, 78, 95-7, 102 |
| | **Sustainability (22)** - 11, 16, 21, 31, 36, 40-2, 51, 53, 58, 62, 65, 69, 71, 74, 77, 79, 95, 98, 102-3 |
| | **Governance (21)** - 1-2, 12, 16, 31, 33, 36, 52-3, 58, 65, 69, 71, 77-9, 87, 95, 98, 100, 103 |
| | **Security (19)** - 1-2, 5, 11-3, 23, 33, 51, 58, 64, 69, 72-3, 75, 86-7, 95, 102 |
| | **Relationships (17)** - 8, 15, 21, 42, 44, 51, 68-9, 72, 75, 77-8, 91, 97-8, 100, 103 |
| | **Information / Data management (16)** - 1, 8, 11, 13, 16, 23, 31, 41, 51, 64, 72-3, 79, 87, 98, 102 |
| | **Structural complexity (16)** - 2, 3, 8, 16, 31, 36, 45, 51-2, 68, 74, 87, 90, 95, 97-8 |
| | **Costs (13)** - 6, 9, 16, 27, 33, 44, 69, 71, 86-7, 91, 96, 103 |
| | **Traceability (13)** - 3, 6, 9, 16, 23, 27, 29, 31, 36, 71, 73, 75, 102 |
| | **Theoretical developments (10)** - 15, 36, 42, 51, 65, 72, 77, 79, 91, 103 |
| | **Competitiveness (8)** - 5, 36, 44, 63, 69, 75, 91, 103 — N = 57 |

Number of literature reviews associated to each subcategory, as indicated in parenthesis

For additional information about each paper, see Table A1, in the Appendix. Table 8 indicates whether review papers focus on specific industries or segments. For additional information about each paper, see Table A1, in the Appendix.

Table 8 - Review papers focused on industries or segments

| Cat. | Subcategory | References |
|---|---|---|
| Industry/Segment specific | | |
| | Aerospace and defense | Ahmad *et al.* (2021) |

| Cat. | Subcategory | References |
|---|---|---|
| | Agriculture | Demestichas *et al.* (2020) and Kamilaris, Fonts, and Prenafeta-Boldύ (2019) |
| | Agri-food | Antonucci *et al.* (2019), Feng *et al.* (2020), Kramer, Bitsch, and Hanf (2021), Lezoche *et al.* (2020), Menon and Jain (2021), Rana, Tricase, and De Cesare (2021), Srivastava and Dashora (2022), Tharatipyakul and Pongnumkul (2021), and Zhao *et al*. (2019) |
| | Airport | Di Vaio and Varriale (2020) |
| | Automotive | Reddy *et al.* (2021) and Upadhyay *et al.* (2021) |
| | Battery | Rufino Júnior *et al.* (2022) |
| | Construction | Kiu, Chia, and Wong (2020) and Scott, Broyd, and Ma (2021) |
| | Diamonds | Thakker *et al.* (2021) |
| | Food | Astill *et al.* (2019), Chen *et al.* (2020), Duan *et al.* (2020), Galvez, Mejuto, and Simal-Gandara (2018), Kayikci *et al.* (2022), Kayikci, Usar, and Aylak (2021), Li, Lee, and Gharehgozli (2021), Longo, Nicoletti, and Padovano (2020), Nurgazina *et al.* (2021), Pandey, Pant, and Snasel (2022), Rejeb *et al.* (2020), Tanwar *et al.* (2022), and Vu, Ghadge, and Bourlakis (2021) |
| | Global/International trade | Chang, Iakovou, and Shi (2019) and Juma, Shaalan, and Kamel (2019) |
| | Healthcare | Kassab *et al.* (2021) |
| | Hospitality | Filimonau and Naumova (2020) |
| | Logistics | Dobrovnik *et al.* (2018) and Tijan *et al.* (2019) |
| | Manufacturing | Khanfar *et al.* (2021) and Santhi and Muthuswamy (2022) |
| | Maritime | Lambourdiere and Corbin (2020) and Liu, Zhang, and Zhen (2021) |
| | Maritime and shipping | Li and Zhou (2021) |
| | Pharmaceutical | Bamakan, Moghaddam, and Manshadi (2021) and Mackey and Nayyar (2017) |
| | Shipping and port management | Tsiulin *et al.* (2020) |
| | Transportation | Astarita *et al.* (2020) |
| Multiple industries/segments | | |
| | | Berneis, Bartsch, and Winkler (2021), Casino, Dasaklis, and Patsakis (2019), Chang and Chen (2020), Dasaklis *et al.* (2022), Dutta *et al.* (2020), Fosso Wamba *et al.* (2020), Gonczol *et al.* (2020), Li *et al.* (2021), Maesa and Mori (2020), Mistry *et al.* (2020), Nandi *et al.* (2020), and Sunny, Undralla, and Pillai (2020) |
| Non-segment/industry specific | | |
| | | Al-Farsi, Rathore, and Bakiras (2021), Alkhudary, Queiroz, and Féniès, (2022), Asante *et al.* (2021), Bekrar *et al.* (2021), Cole, Stevenson, and Aitken (2019), Esmaeilian *et al.* (2020), Etemadi *et al.* (2021), Fosso Wamba and Queiroz (2020), Gurtu and Johny (2019), Hald and Kinra (2019), Hastig and Sodhi (2020), Hughes *et al.* (2019), Karakas, Acar, and Kucukaltan (2021), Kouhizadeh and Sarkis (2018), Kummer *et al.* |

| | |
|---|---|
| | (2020), Li *et al.* (2020), Lim *et al.* (2021), Lohmer, Ribeiro da Silva, and Lasch (2022), Mahyuni *et al.* (2020), Min (2019), Müßigmann, von der Gracht, and Hartmann (2020), Nabipour and Ülkü (2021), Paliwal, Chandra, and Sharma (2020), Park and Li (2021), Pournader *et al.* (2020), Queiroz, Telles, and Bonilla (2019), Rejeb *et al.* (2021a), Rejeb, Keogh, and Treiblmaier (2019), Rejeb *et al.* (2021b), Saberi *et al.* (2019), Schmidt and Wagner (2019), Schuetz and Venkatesh (2020), Shoaib, Lim, and Wang (2020), Sun *et al.* (2021), Tokkozhina, Martins, and Ferreira (2022), Treiblmaier (2018), Varriale *et al.* (2020), Varriale *et al.* (2021), Vivaldini (2020), Vivaldini and Sousa (2021), Wan, Huang, and Holtskog (2020), Wang, Han, and Beynon-Davies (2019), Yin and Ran (2021), and Zhu, Bai, and Sarkis (2022) |

## 3.4 Findings

### *3.4.1 Supply chain topics (RQ1.1)*

#### 3.4.1.1 Supply chain general metrics

Blockchain impact on cost-related issues must be considered since implementation costs include high investments in hardware and software for information collection (SABERI *et al.*, 2019; ZHAO *et al.*, 2019), as well as for customization and training (LI; LEE; GHAREHGOZLI, 2021). Thus, small and medium organizations depend on incentives and strategies for cost distribution and cost sharing (COLE; STEVENSON; AITKEN, 2019). However, besides considering the product value (CHEN *et al.*, 2020) and expenses with intermediaries (WANG; HAN; BEYNON-DAVIES, 2019), a viability evaluation must also encompass amounts saved with security and reconciliation (GURTU; JOHNY, 2019), verification of authenticity (SABERI *et al.*, 2019), and recordkeeping (FOSSO WAMBA *et al.*, 2020). Moreover, individual solutions may overcome the implementation costs of a blockchain collective system (VU; GHADGE; BOURLAKIS, 2021).

Through a specific viewpoint, Astill *et al.* (2019) emphasize possible reductions in healthcare costs and improvements in public perception in case of food illness outbreaks. For manufacturing companies, reductions in maintenance costs can be obtained (COLE; STEVENSON; AITKEN, 2019), and for logistics operations, transportation costs can be minimized (TIJAN *et al.*, 2019). In terms of operational costs, blockchain offers savings with paperwork and with the execution of contracts among parties (POURNADER *et al.*, 2020; GONCZOL *et al.*, 2020), leading to less complex systems (FILIMONAU; NAUMOVA, 2020). Hughes *et al.* (2019) consider cost implications associated with blockchain-based smart contract solutions, and Cole, Stevenson, and Aitken (2019) see automation as an alternative to reduce transaction costs. Treiblmaier (2018), Schmidt and Wagner (2019), and Kummer *et al.* (2020) investigate transaction costs through a theoretical approach.

Blockchain applications assume ways to provide security for both processes and products in virtual and physical environments, respectively. According to Wang, Han, and Beynon-Davies (2019), decentralization is a crucial mechanism to provide data security which, combined with auditability, minimizes the chances of opportunistic behavior (SABERI *et al.*, 2019). Logistics operations security can be enhanced (TIJAN *et al.*, 2019; MÜßIGMANN; VON DER GRACHT; HARTMANN, 2020), mainly considering cargo integrity (CHANG; IAKOVOU; SHI, 2019).

In addition, security is vital for handling valuable information in traceability management processes (FENG *et al.*, 2020) by assuring data privacy (ASTILL *et al.*, 2019) and confidentiality (REJEB; KEOGH; TREIBLMAIER, 2019). These conditions can help avoid the leakage of business-sensitive information in the communications between brands and franchises (FILIMONAU; NAUMOVA, 2020). Al-Farsi, Rathore, and Bakiras (2021) highlight that blockchain offers protection against both computational and communication attacks. Asante *et al.* (2021) discuss security including aspects of risk management, compliance, and cyber resilience.

For quality management and control, besides checking origins, blockchain applications can monitor products during transportation and storage (GONCZOL *et al.*, 2020), as far as information about batches brings agility and assertiveness to recalls (COLE; STEVENSON; AITKEN, 2019). Kouhizadeh and Sarkis (2018) suggest that payments may be conditioned to quality level records. For expensive products, certification of attributes is essential to combat fraud (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018).

Blockchain is seen as a promising technology to promote sustainable innovations (HALD; KINRA, 2019). Opportunities are identified for environmental, economic, and social pillars (WANG; HAN; BEYNON-DAVIES, 2019; LI; LEE; GHAREHGOZLI, 2021; PARK; LI, 2021). Social aspects are benefited from immutable information to monitor working conditions (SABERI *et al.*, 2019; COLE; STEVENSON; AITKEN, 2019). Hughes *et al.* (2019) discuss blockchain's possible contributions to achieving the United Nations Sustainable Development Goals.

Kouhizadeh and Sarkis (2018) explore opportunities to use blockchain to support green supply chains, considering vendor selection, supplier development, purchasing, materials management, production operations, lifecycle assessment, outbound logistics, waste management, reverse logistics, and energy. Zhao *et al.* (2019) describe an application for water management, mentioning its importance for agriculture, while Di Vaio and Varriale (2020) investigate sustainable operations in the airport industry. From an economic standpoint, Astill *et al.* (2019) stress the relevance of blockchain for sharing benefits among stakeholders.

Food safety is a topic considered in several reviews (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018; KAMILARIS; FONTS; PRENAFETA-BOLDÝ, 2019; FENG *et al.*, 2020; CHEN *et al.*, 2020; SUNNY; UNDRALLA; PILLAI, 2020; SRIVASTAVA; DASHORA, 2022), due to its relevance for customers and to the large quantity of products involved. In another context, users of automotive batteries can be safely protected from dangerous situations (RUFINO JÚNIOR *et al.*, 2022). Despite some scalability issues, transaction validation speed is an attractive aspect as it increases the agility of product movements (GURTU; JOHNY, 2019). Furthermore, Gonczol *et al.* (2020) see blockchain speed as a driver for standardization. Faster digital payments and accurate billings also strengthen the relationship between a brand and its franchises (FILIMONAU; NAUMOVA, 2020).

Flexibility is assessed from controversial standpoints. Min (2019) links flexibility to supply chain resilience. Hald and Kinra (2019) indicate administrative lead time reductions, which increase flexibility, Schuetz and Venkatesh (2020) argue that blockchain enables financial services to facilitate informal transfers for customized demands, and Rejeb *et al.* (2021b) point to an increase in agility through data integration in business processes. On the other hand, Hughes *et al.* (2019) stress the immutability principle as a barrier to flexibility when minor adjustments are needed, and Esmaeilian *et al.* (2020) mention that smart contracts can impose inflexibility to adjust to unpredicted scenarios.

Reliability is described mainly through systems and data (FENG *et al.*, 2020), as blockchain improves information flows by reducing errors, additional costs, and delays (TIJAN *et al.*, 2019). Tokkozhina, Martins, and Ferreira (2022) stress the benefits of increasing the reliability of transactions and Rejeb, Keogh, and Treiblmaier (2019) affirm that IoT has a central role in assuring the integrity of the information, while Wang, Han, and Beynon-Davies (2019) associate reliability as an essential driver to lead trust to higher levels. Table 9 presents the key findings concerning supply chain general metrics. For additional information about each paper, see Table A1, in the Appendix.

Table 9 - Summary of key findings related to supply chain general metrics

| Metric | Key findings | References |
|---|---|---|
| Cost | The return on investment (ROI) must be carefully evaluated, to cover both implementation costs and operational savings, including transaction costs, and other reductions achieved through improvements, also considering the challenges of including small and medium enterprises (SMEs) in the blockchain network | Astill *et al.* (2019), Chen *et al.* (2020), Cole, Stevenson, and Aitken (2019), Gonczol *et al.* (2020), Gurtu and Johny (2019), Hughes *et al.* (2019), Li, Lee and Gharehgozli (2021), Pournader *et al.* (2020), Saberi *et al.* (2019), Tijan *et al.* (2019), Vu, Ghadge, and Bourlakis (2021), Wang, Han, and Beynon-Davies (2019), and Zhao *et al.* (2019) |
| Security | Based on the principle of decentralization, a higher level of information security is provided, avoiding leakages, and communication attacks, while also monitoring products' integrity in transit | Al-Farsi, Rathore, and Bakiras (2021), Asante *et al.* (2021), Astill *et al.* (2019), Feng *et al.* (2020), Filimonau and Naumova (2020), Rejeb *et al.* (2019), Saberi *et al.* (2019), Tijan *et al.* (2019), and Wang, Han, and Beynon-Davies (2019) |
| Quality | Product monitoring, certification, and urgent recalls, as well as pricing adjustments, are among the possible benefits obtained for quality management | Cole, Stevenson, and Aitken (2019), Galvez, Mejuto, and Simal-Gandara (2018), Gonczol *et al.* (2020), and Kouhizadeh and Sarkis (2018) |
| Sustainability | Opportunities for environmental, economic, and social perspectives are described in different scales and approaches revealing the potential of blockchain | Astill *et al.* (2019), Cole, Stevenson, and Aitken (2019), Di Vaio and Varriale (2020), Hald and Kinra (2019), Hughes *et al.* (2019), Kouhizadeh and Sarkis (2018), Li, Lee and Gharehgozli (2021), Park and Li (2021), Saberi *et al.* (2019), Wang, Han, and Beynon-Davies (2019), and Zhao *et al.* (2019) |
| Safety | Final customer safety is considered for food products, embracing health and contamination issues, and also for automotive batteries, covering the risk of accidents | Chen *et al.* (2020), Feng *et al.* (2020), Galvez, Mejuto, and Simal-Gandara (2018), Kamilaris, Fonts, and Prenafeta-Boldú (2019), Rufino Júnior *et al.* (2022), Srivastava, and Dashora (2022), and Sunny, Undralla, and Pillai (2020) |
| Speed | Scalability issues and information standards are technical aspects under debate to unlock higher volumes of interactions in proper ways to expand blockchain diffusion | Filimonau and Naumova (2020), Gonczol *et al.* (2020), and Gurtu and Johny (2019) |
| Flexibility | Information sharing can leverage flexibility, however smart contracts clauses programmed through algorithm logic can establish some kinds of inflexibility | Esmaeilian *et al.* (2020), Hald and Kinra (2019), Hughes *et al.* (2019), Min (2019), Rejeb *et al.* (2021b), and Schuetz and Venkatesh (2020) |
| Reliability | A reliable data-capturing procedure is essential to determine the reliability level of transactions and assure the trust embedded in the system | Feng *et al.* (2020), Rejeb *et al.* (2019), Tijan *et al.* (2019), Tokkozhina, Martins, and Ferreira (2022), and Wang, Han, and Beynon-Davies (2019) |

3.4.1.2 Supply chain requirements

Blockchain is highlighted as a technology to promote end-to-end transparency (COLE; STEVENSON; AITKEN, 2019; MAHYUNI *et al.*, 2020) on business, product, and item levels (GURTU; JOHNY, 2019), including even interfaces with last-mile suppliers (NANDI *et al.*, 2020). Pseudonymity is supported to protect sensitive information sharing, avoiding the recognition of parties involved in transactions (WANG; HAN; BEYNON-DAVIES, 2019; TIJAN *et al.*, 2019), which is relevant for players that possess competitive information and deal with risks (ASTILL *et al.*, 2019). Moreover, transparency is linked to the assessment of supply chain performance (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018; KAYIKCI *et al.*, 2022), and synchronization among parties requires a good reengineering scheme (DUTTA *et al.*, 2020) based on the Internet of Things and devices connectivity (TSIULIN *et al.*, 2020).

In addition, transparency embraces elements of social sustainability related to working conditions and offers data such as carbon footprints to handle financial decisions considering the product lifecycle (VARRIALE *et al.*, 2020; PANDEY; PANT; SNASEL, 2022). A transparent lifecycle enhances the participation of different stakeholders and the implementation of a circular economy, in addition to gains of efficiency through bullwhip effect reduction, extended producer responsibility (EPR) promotion, and food safety assurance (ESMAEILIAN *et al.*, 2020). Other benefits include audit checking, operations monitoring, logistics tracking (FENG *et al.*, 2020), and opportunistic behavior inhibition (SABERI *et al.*, 2019).

Trust is another distinctive aspect of blockchain in supply chain management (VARRIALE *et al.*, 2021), and is an influential driver of its adoption (WANG; HAN; BEYNON-DAVIES, 2019), as the technology is described as a 'digital institution of trust' (KAMILARIS; FONTS; PRENAFETA-BOLDὙ, 2019). According to Galvez, Mejuto, and Simal-Gandara (2018), blockchain is connected to different classes of trust in terms of transparency (authentication, resource access, provision, and delegation), infrastructure for security (encryption and decentralization), and restriction (rules set by protocols).

Trust is essential to support implementation since it requires and relies on accessing external resources (YIN; RAN, 2021), increases both intra- and inter-organization visibility (GURTU; JOHNY, 2019), and improves collaboration (FENG *et al.*, 2020). After that, paradoxically, blockchain can leverage trust and make it an irrelevant component, as it assures the integrity of information shared and promotes reliable transactions among unknown parties, who usually do not have ways to share standardized information (WAN; HUANG; HOLTSKOG, 2020; POURNADER *et al.*, 2020). Moreover, in business-to-business (B2B) scenarios, smart contracts enhance trust by decreasing opportunistic behavior (SCHMIDT; WAGNER, 2019), just as tracking products' paths also impacts consumers (SABERI *et al.*, 2019).

Blockchain contributes to combating counterfeit issues (ALKHUDARY; QUEIROZ; FÉNIÈS, 2022; ETEMADI *et al.*, 2021), as it improves information sharing and data storage, mainly when assisted by complementary data-acquisition technologies (MACKEY; NAYYAR, 2017). Potential applications related to authenticity include pharmaceutical (KASSAB *et al.*, 2021; ESMAEILIAN *et al.*, 2020; SCHMIDT; WAGNER, 2019), aerospace and defense (AHMAD *et al.*, 2021), batteries (RUFINO JÚNIOR *et al.*, 2022), and food supply chains (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018). Dutta *et al.* (2020) suggest e-commerce operations as another possibility of application. Besides helping to identify fake products (TIJAN *et al.*, 2019), a blockchain platform can also help the customer obtain ownership proof before purchasing a product (GONCZOL *et al.*, 2020).

Disintermediation may face opposition since actors can try to keep their position in the supply chain or even make changes to establish reintermediation (WANG; HAN; BEYNON-DAVIES, 2019). Indeed, besides costs and time, eliminating central authorities can reduce complexity (COLE; STEVENSON; AITKEN, 2019; SRIVASTAVA; DASHORA, 2022), and improve both risk management (SABERI *et al.*, 2019) and vendor selection processes (KOUHIZADEH; SARKIS, 2018), at the cost of eliminating skilled jobs (KAMILARIS; FONTS; PRENAFETA-BOLDỲ, 2019). Smart contracts are considered an alternative to automate disintermediation (QUEIROZ; TELLES; BONILLA, 2019). For suppliers, smart contracts contribute to on-time payments and incentives releases, besides leveraging transparency and accountability (REDDY *et al.*, 2021).

Blockchain assists in compliance through new policies and regulations (SCHMIDT; WAGNER, 2019; ASTILL *et al.*, 2019) by both avoiding executing additional procedures (HALD; KINRA, 2019) and by dealing with non-compliant documentation (CHANG; IAKOVOU; SHI, 2019). In contrast, there is an urge for regulations to drive blockchain applications' compliance (ZHAO *et al.*, 2019; FENG *et al.*, 2020). Other advantages are reducing auditing and compliance for 'bonded warehouses' (KOUHIZADEH; SARKIS, 2018) and applications to assure halal food compliance (SUNNY; UNDRALLA; PILLAI, 2020).

Decentralization is widely noted as a data storage security mechanism against a 'single point of failure' (ASTILL *et al.*, 2019; REJEB; KEOGH; TREIBLMAIER, 2019) and malicious attacks (CHEN *et al.*, 2020). In addition, the term also denotes authority to access, control, and validate transactions without a central entity (ESMAEILIAN *et al.*, 2020), enabling information sharing and information tracing (WAN; HUANG; HOLTSKOG, 2020), and thus promoting the decentralization of power and information (HASTIG; SODHI, 2020). However, decentralization is a complex characteristic since it depends on the blockchain configuration and the roles attributed to the blockchain participants (JUMA; SHAALAN; KAMEL, 2019). This feature may bring integration to industries with scattered resources and set open manufacturing, leading to improved social and environmental sustainability (HALD; KINRA, 2019).

Provenance refers to tracking the path and frequency of movement and is relevant for sensitive industries (WANG; HAN; BEYNON-DAVIES, 2019). This condition fulfills regulatory demands and brings food security to consumers (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018; CHEN *et al.*, 2020). Besides food supply chains, diamonds, and pharmaceuticals are other examples that can benefit from information of origin to avoid adulteration and counterfeits (SCHMIDT; WAGNER, 2019). Reductions in healthcare costs and improvements in quality of life can be expected from provenance data (QUEIROZ; TELLES; BONILLA, 2019), and blockchain also enhances provenance information accuracy (MENON; JAIN, 2021).

Several capabilities support blockchain's potential to reduce disputes. Smart contracts can be set to assure the accomplishment of agreements (WANG; HAN; BEYNON-DAVIES, 2019; KHANFAR *et al.*, 2021), but as a limitation, it cannot resolve disputes that are not programmed in the logic (AL-FARSI; RATHORE; BAKIRAS, 2021). Transparency (KAMILARIS; FONTS; PRENAFETA-BOLDÝ, 2019) and traceability (ZHAO *et al.*, 2019) of information, and validation of documents (CHANG; CHEN, 2020) are among other factors that mitigate conflicts. Those enable possibilities of keeping real-time registers to support provenance, ownership, legalities, and safety (CHANG; IAKOVOU; SHI, 2019), and assist practices related to volume incentives (MISTRY *et al.*, 2020).

Blockchain is also seen to be developed as an alternative to the verification and digitalization of property rights (CHANG; CHEN, 2020; SUN *et al.*, 2021). In the construction industry, it can assign copyrights to building information modeling (BIM) objects (SCOTT; BROYD; MA, 2021). Moreover, it can be used to protect the intellectual property of files used for additive manufacturing processes (CHANG; IAKOVOU; SHI, 2019). Table 10 summarizes the key findings related to supply chain requirements. For additional information about each paper, see Table A1, in the Appendix.

Table 10 - Summary of key findings related to supply chain requirements

| Requirement | Key findings | References |
|---|---|---|
| Transparency | Multiple levels of end-to-end transparency are achieved, enabling gains of performance, while pseudonymity preserves sensitive information | Astill *et al.* (2019), Cole, Stevenson, and Aitken (2019), Dutta *et al.* (2020), Esmaeilian *et al.* (2020), Feng *et al.* (2020), Galvez, Mejuto, and Simal-Gandara (2018), Kayikci *et al.* (2022), Mahyuni *et al.* (2020), Nandi *et al.* (2020), Pandey, Pant, and Snasel (2022), Saberi *et al.* (2019), Tijan *et al.* (2019), Tsiulin *et al.* (2020), Varriale *et al.* (2020), and Wang, Han, and Beynon-Davies (2019) |
| Trust | Different classes of trust change the stakeholders' perception of business interactions, assisted by the robustness of the smart contracts mechanism | Feng *et al.* (2020), Galvez, Mejuto, and Simal-Gandara (2018), Gurtu and Johny (2019), Kamilaris, Fonts, and Prenafeta-Boldú (2019), Pournader *et al.* (2020), Saberi *et al.* (2019), Schmidt and Wagner (2019), Varriale *et al.* (2021), Wan, Huang, and Holtskog (2020), Wang, Han, and Beynon-Davies (2019), and Yin and Ran (2021) |
| Anticounterfeiting | When combined with appropriate data capture technologies, blockchain improves processes of authenticity checking through information sharing and real-time access | Ahmad *et al.* (2021), Alkhudary, Queiroz, and Féniès (2022), Dutta *et al.* (2020), Esmaeilian *et al.* (2020), Etemadi *et al.* (2021), Galvez, Mejuto, and Simal-Gandara (2018), Gonczol *et al.* (2020), Kayikci *et al.* (2022), Mackey and Nayyar (2017), Rufino Júnior *et al.* (2022), Schmidt and Wagner (2019), and Tijan *et al.* (2019) |
| Disintermediation | Disruptive changes occur with the removal of intermediaries or with reintermediation approaches, impacting both power relations and skilled jobs | Cole, Stevenson, and Aitken (2019), Kamilaris, Fonts, and Prenafeta-Boldú (2019), Kouhizadeh and Sarkis (2018), Queiroz, Telles, and Bonilla (2019), Reddy *et al.* (2021), Saberi *et al.* (2019), Srivastava, and Dashora (2022), Wang, Han, and Beynon-Davies (2019) |
| Compliance | Blockchain assists the enforcement of regulations, but there is a claim for specific and global rules for the interactions performed in the platform | Astill *et al.* (2019), Chang, Iakovou, and Shi (2019), Feng *et al.* (2020), Hald and Kinra (2019), Kouhizadeh and Sarkis (2018), Schmidt and Wagner (2019), Sunny, Undralla, and Pillai (2020), and Zhao *et al.* (2019) |
| Decentralization | Besides the security function, power and authority are dissolved when the information is spread, even entirely, according to the blockchain configuration | Chen *et al.* (2020), Esmaeilian *et al.* (2020), Hald and Kinra (2019), Hastig and Sodhi (2020), Rejeb *et al.* (2019), and Wan, Huang, and Holtskog (2020) |
| Provenance | Accurate information supports attending to the regulations of sensitive industries to monitor the path of materials | Chen *et al.* (2020), Galvez, Mejuto, and Simal-Gandara (2018), Menon and Jain (2020), Queiroz, Telles, and Bonilla (2019), Schmidt and Wagner (2019), and Wang, Han, and Beynon-Davies (2019) |
| Dispute resolutions | Smart contracts clauses and information transparency and traceability are able to minimize or even avoid some frictions between trading partners | Al-Farsi, Rathore, and Bakiras (2021), Chang and Chen (2020), Chang, Iakovou, and Shi (2019), Kamilaris, Fonts, and Prenafeta-Boldú (2019), Mistry *et al.* (2020), Wang, Han, and Beynon-Davies (2019), and Zhao *et al.* (2019) |

| Requirement | Key findings | References |
|---|---|---|
| Property rights | Digitalizing creation rights gives new boundaries to innovation processes by protecting the designers and establishing possible new markets | Chang and Chen (2020), Chang, Iakovou, and Shi (2019), Scott, Broyd, and Ma (2021), and Sun *et al.* (2021) |

*3.4.2 Blockchain features*

Smart contract is considered to have a transformative potential to change the supply chain and organizational structures, as it can support fragmentation and temporary relations (WANG; HAN; BEYNON-DAVIES, 2019). Changes in governance models will also emerge with high security and visibility (QUEIROZ; TELLES; BONILLA, 2019) since it automates both intra- and inter-organizational processes (DUTTA *et al.*, 2020; VIVALDINI, 2020).

Using smart contracts allows operational parameters to be monitored and alerts to be sent to prevent damage during transportation (ANTONUCCI *et al.*, 2019; POURNADER *et al.* 2020, DUAN *et al.*, 2020; GALVEZ; MEJUTO; SIMAL-GANDARA, 2018), thus improving the safety of flexible and scalable deliveries (KAMILARIS; FONTS; PRENAFETA-BOLDÝ, 2019). Paradoxically, information hiding can contribute to information sharing among supply chain players by avoiding risks of leakage (WAN; HUANG; HOLTSKOG, 2020). Furthermore, smart contracts assist continuous process improvement among parties (SABERI *et al.*, 2019; FENG *et al.*, 2020), including conditions to trigger purchase orders for replenishment (POURNADER *et al.*, 2020) and to determine payments of loans when funds are available (SCHUETZ; VENKATESH, 2020).

Smart contracts are also used to release payments automatically when products are received (MISTRY *et al.*, 2020; ASTARITA *et al.*, 2020; POURNADER *et al.*, 2020; WANG; HAN; BEYNON-DAVIES, 2019). It can use external data, exclude intermediaries, and eliminate opportunistic behavior by setting prices under dynamic conditions by automatically incorporating new rules, influencing the principal-agent relationship (SCHMIDT; WAGNER, 2019), and providing the alignment of conflicting objectives and the mitigation of information asymmetries (TREIBLMAIER, 2018). This reliable information can be consulted for supplier selection (KOUHIZADEH; SARKIS, 2018). However, the writers' ability and the lack of social aspects are discussed as limitations of smart contracts (COLE; STEVENSON; AITKEN, 2019), since problems in specifications lead to potential losses (LIU; ZHANG; ZHEN, 2021).

Product traceability is classified as a relevant outcome to propagate blockchain adoption (WANG; HAN; BEYNON-DAVIES, 2019), and the integration with RFID, IoT, and QR codes represents the evolution of alternative mechanisms (RANA; TRICASE; CESARE, 2021). It is built upon the immutability principle and covers the entire product life cycle throughout the supply chain, being able to support quality monitoring, despite a lack of clear standards (GONCZOL *et al.*, 2020). The records available support adjustments and partners' confidence is achieved (COLE; STEVENSON; AITKEN, 2019; GALVEZ; MEJUTO; SIMAL-GANDARA, 2018). For inventory management, traceability contributes to keeping data on movements and provides feedback about 'what/when/where' transfers occurred (POURNADER *et al.*, 2020). These data offer a base for the ownership of assets (HALD; KINRA, 2019), enhance warehouse operations, and avoid material losses (KOUHIZADEH; SARKIS, 2018).

Traceability also reduces risks (SCHMIDT; WAGNER, 2019), disputes, and information asymmetries, and an essential decision is about determining how to include blockchain in existing traceability systems (ZHAO *et al.*, 2019), considering that confidentiality issues are relevant and can be solved by anonymity (FENG *et al.*, 2020). In addition, the knowledge released can be retrieved through smart contracts, and among social and environmental concerns, since traceability also assists in remanufacturing and reverse logistics through returning flow planning (KOUHIZADEH; SARKIS, 2018; BEKRAR *et al.*, 2021). Some specific aspects of food products make tracing difficult, such as transformation processes made by joining (ASTILL *et al.*, 2019). In contrast, Karakas, Acar, and Kucukaltan (2021) discuss whether traceability can stimulate monopolies.

Real-time goes beyond the automatic alerts and payments made through smart contracts. Blockchain enables paper document digitalization, offering the possibility to track events, especially when combined with sensors, whose data cannot be altered (WANG; HAN; BEYNON-DAVIES, 2019; LI; ZHOU, 2021). Fast updates also reduce disputes, support audits (CHANG; IAKOVOU; SHI, 2019), provide secure connectivity to share information (GONCZOL *et al.*, 2020), and improve efficient decision-making processes (WAN; HUANG; HOLTSKOG, 2020; LIU; ZHANG; ZHEN, 2021). Moreover, real-time sharing of customs documents brings agility and cross-border collaboration to global chains (HALD; KINRA, 2019; COLE; STEVENSON; AITKEN, 2019). In a broader scope, collecting data from each stage can drive the creation of a digital twin and, consequently, support the creation of new business models (RUFINO JÚNIOR *et al.*, 2022).

Immutability helps to detect fraud and tampering (HUGHES *et al.*, 2019; SCHMIDT; WAGNER, 2019), decreases the frequency of reconciliations among partners in comparison with traditional siloed databases (CHANG; CHEN, 2020), and offers data of credit history (SCHUETZ; VENKATESH, 2020). From a broader standpoint, immutability improves auditability (COLE; STEVENSON; AITKEN, 2019), leverages information accuracy (THAKKER *et al.*, 2021), and strengthens products' traceability (MAESA; MORI, 2020). Combined with IoT devices, immutability facilitates the flow of heterogeneous information and enhances recall operations and provenance checks (REJEB; KEOGH; TREIBLMAIER, 2019). Immutable data is also vital to promote social sustainability (SABERI *et al.*, 2019), contributes to dealing with environmental uncertainties (SCHMIDT; WAGNER, 2019), and assures raw information legitimacy at the cost of limiting corrections (POURNADER *et al.*, 2020; DUAN *et al.*, 2020).

Applying consensus mechanisms is emphasized as a key component to guarantee trust through verification processes (SABERI *et al.*, 2019). This validation enables trust between unknown parties (SCHMIDT; WAGNER, 2019), and the high level of information consistency leverages the traceability process by avoiding data tampering (FENG *et al.*, 2020). Moreover, considering blockchain implementation, it is argued that consensus mechanisms and supply chain networks should be designed following an integrated approach to maximize suitability (LOHMER; RIBEIRO DA SILVA; LASCH, 2022).

After being included in blockchain, data are established as permanent, and this irreversibility condition presents some drawbacks, such as the need to set a new block to adjust input errors (POURNADER *et al.*, 2020). Moreover, this high visibility can cause privacy issues and leverage surveillance opportunities, for example, for influential buyers and governmental authorities (KAMILARIS; FONTS; PRENAFETA-BOLDÝ, 2019; HALD; KINRA, 2019).

Verifiability is typically associated with validation and authentication purposes (FOSSO WAMBA *et al.*, 2020), making blockchain an alternative to reduce the time required to audit trails, for example, to check sustainability and the actor responsible for an action (GURTU; JOHNY, 2019). Other possible applications are related to specific products to verify kosher, organic, or allergen-free characteristics (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018) and the authenticity of high-value items (SABERI *et al.*, 2019). In addition, verifiability can be addressed to monitor buyers' and sellers' reputations regarding suppliers' management (CHANG; IAKOVOU; SHI, 2019) and ISO 14001 certifications, through the aggregation and validation of documents (KOUHIZADEH; SARKIS, 2018).

Peer-to-peer configuration promotes financial transactions between involved parties without intermediaries (SABERI *et al.*, 2019; SCHUETZ; VENKATESH, 2020). It also mitigates asymmetrical information issues while stimulating both lending negotiations and asset trading (WANG; HAN; BEYNON-DAVIES, 2019) as well as business models based on sharing economy (FILIMONAU; NAUMOVA, 2020). Queiroz, Telles, and Bonilla (2019) stress that the integration of supply chain actors through the combination of blockchain and the Internet of Things is a powerful alternative, but Zhao *et al.* (2019) call attention to regulations needed.

Despite these potential issues, keeping chronological records of events by using timestamps benefits information completeness (WANG; HAN; BEYNON-DAVIES, 2019) and facilitates real-time auditing (COLE; STEVENSON; AITKEN, 2019). Timestamps assign approval and record information such as time, place, and condition, bringing agility to load board releases and document workflow as a whole (TSIULIN *et al.*, 2020). Moreover, time-based issues, such as lead time, delivery, and perishability, can be accurately managed, leading to higher levels of traceability and transparency (KOUHIZADEH; SARKIS, 2018). The digital signature is briefly mentioned as an alternative to avoid document falsification (CHANG; CHEN, 2020) and to provide validations and trust without central authorities (FENG *et al.*, 2020). Table 11 exhibits the key findings concerning blockchain features. For additional information about each paper, see Table A1, in the Appendix.

Table 11 - Summary of key findings related to blockchain features

| Feature | Key findings | References |
|---|---|---|
| Smart contracts | Besides changes in organizational structures and governance models, smart contracts can activate business actions, such as payments, but it relies on programmer ability and there are still claims for the establishment of legal rules | Antonucci *et al.* (2019), Astarita *et al.* (2020), Cole, Stevenson, and Aitken (2019), Duan *et al.* (2020), Dutta *et al.* (2020), Feng *et al.* (2020), Galvez, Mejuto, and Simal-Gandara (2018), Kamilaris, Fonts, and Prenafeta-Boldύ (2019), Kouhizadeh and Sarkis (2018), Liu, Zhang, and Zhen (2021), Mistry *et al.* (2020), Pournader *et al.* (2020), Queiroz, Telles, and Bonilla (2019), Saberi *et al.* (2019), Schmidt and Wagner (2019), Schuetz and Venkatesh (2020), Treiblmaier (2018), Vivaldini (2020), Wan, Huang, and Holtskog (2020), and Wang, Han, and Beynon-Davies (2019) |
| Traceability | There are challenges concerning the integration with existing systems, to assist reverse flows, quality monitoring, and inventory management, and it still | Astill *et al.* (2019), Bekrar *et al.* (2021), Cole, Stevenson, and Aitken (2019), Feng *et al.* (2020), Galvez, Mejuto, and Simal- |

| Feature | Key findings | References |
|---|---|---|
| | requires standards and ways to deal with non-discrete productive processes | Gandara (2018), Gonczol *et al.* (2020), Hald and Kinra (2019), Karakas, Acar, and Kucukaltan (2021), Kouhizadeh and Sarkis (2018), Pournader *et al.* (2020), Rana, Tricase, and Cesare (2021), Schmidt and Wagner (2019), Wang, Han, and Beynon-Davies (2019), and Zhao *et al.* (2019) |
| Real-time processing | Fast updates promote event tracking and bring agility to data-based decision-making, stimulating new business models | Chang, Iakovou, and Shi (2019), Cole, Stevenson, and Aitken (2019), Gonczol *et al.* (2020), Hald and Kinra (2019), Li and Zhou (2021), Liu, Zhang, and Zhen (2021), Rufino Júnior *et al.* (2022), Wan, Huang, and Holtskog (2020), and Wang, Han, and Beynon-Davies (2019) |
| Immutability | Information stability and legitimacy are incontestable aspects, but they impose limitations in terms of mistakes and corrections that must be considered | Cole, Stevenson, and Aitken (2019), Duan *et al.* (2020), Hughes *et al.* (2019), Maesa and Mori (2020), Pournader *et al.* (2020), Rejeb *et al.* (2019), Saberi *et al.* (2019), Schmidt and Wagner (2019), Schuetz and Venkatesh (2020), and Thakker *et al.* (2021) |
| Consensus mechanism | Based on different schemes, it assures trust between unknown parties and articulates information uniformity, but it has to be designed in line with the application purpose and deal with scalability, latency, and energy consumption issues | Feng *et al.* (2020), Lohmer, Ribeiro da Silva, and Lasch (2022), Saberi *et al.* (2019), and Schmidt and Wagner (2019) |
| Permanent availability | Constant visibility helps surveillance by interested parties and regulatory agents, but it can compromise privacy protection | Hald and Kinra (2019) and Kamilaris, Fonts, and Prenafeta-Boldú (2019) |
| Verifiability | Auditability is enhanced for sustainable practices, authenticity checking, and suppliers' evaluation, as well as the validation of products' characteristics | Chang, Iakovou, and Shi (2019), Galvez, Mejuto, and Simal-Gandara (2018), Gurtu and Johny (2019), Kouhizadeh and Sarkis (2018), and Saberi *et al.* (2019) |
| Peer-to-peer network | This configuration supports processes' disintermediation, reduces information asymmetries, and enables other business models | Filimonau and Naumova (2020), Queiroz, Telles, and Bonilla (2019), Saberi *et al.* (2019), Schuetz and Venkatesh (2020), Wang, Han, and Beynon-Davies (2019), and Zhao *et al.* (2019) |
| Chronological chain | Timestamps expand the workflow spectrum, improving traceability and transparency, and assisting time-based management decisions | Cole, Stevenson, and Aitken (2019), Kouhizadeh and Sarkis (2018), Tsiulin *et al.* (2020), and Wang, Han, and Beynon-Davies (2019) |
| Digital signature | As the technology maturity and the companies' readiness level increase, the potential uses of digital signatures are going to be increasingly explored | Chang and Chen (2020) and Feng *et al.* (2020) |

### 3.5 Research directions for primary future research

With a comprehensive set of research directions, Schmidt and Wagner (2019) structure their suggestions into four main parts. First, the authors list opportunities for design science research, including blockchain design and network, and associations with other distributed ledger technologies (DLT). The second part considers factors identification concerning the industry, environment, relationship/networks, and organization. The next part indicates possibilities for adapting and creating mid-range theories and embraces the following groups: adoption/participation, information sharing, purchasing, organizational forms, sustainability, and business models. Extending the range, the last part regards validating grand theories such as agency theory, network theory, and social exchange theory.

Also taking theoretical lenses, Treiblmaier (2018) proposes a solid agenda encompassing principal-agent theory, transaction cost analysis, resource-based view, and network theory. The proposal indicates research questions focused on purposes of analysis, explanation, prediction, and design and action. Theory-based approaches are likewise called for by Wang, Han, and Beynon-Davies (2019), whose paper presents research directions associated with supply chain finances (digital currency and smart contracts), consequences of disintermediation (regarding the emergence of new forms of intermediation), relationship management issues (under the trust paradigm), opportunities linked to social sustainability, controversial issues (governance, law, ethics, and security), and advances in design. Zhu, Bai, and Sarkis (2022) discuss the opportunities related to a broad set of theories, divided into antecedents, decisions, and outcomes.

Cole, Stevenson, and Aitken (2019) recommend six key themes, including blockchain development, incentives for adoption, trade-off evaluation, aspects of implementation, relationship impacts, and theory application/development. Hald and Kinra (2019) derive propositions focused on exploring the capabilities of blockchain for information management, considering possible contributions and constraints, for example, in terms of structural changes and relationship dynamics. Saberi *et al.* (2019) enumerate multiple possible opportunities, such as distributed coordination, material and information flow coordination, virtual enterprises, agility, flexibility, performance measurement, resilience, risk, ripple effect, real-time control, and service-oriented supply chains.

Dutta *et al.* (2020) call for research related to blockchain adoption and implementation, supply chain reengineering, resilience, coordination, and sustainability issues; security enhancement, and business process management, and also gives a detailed agenda with topics assigned to ten sectors. According to Nandi *et al.* (2020), future research should assess the particularities of industry characteristics for blockchain acceptance. Besides this theme, Paliwal, Chandra, and Sharma (2020) reinforce the call for theory-based developments and suggest examining trade-off considerations, governance structures, and mainly blockchain contributions to establish an information system that encompasses the three pillars of sustainability in parallel.

Queiroz, Telles, and Bonilla (2019) also list statements about multiple topics, highlighting implementation issues, smart contracts particularities, and integration with technologies such as big data, Internet of Things, and cyber-physical systems. Zhao *et al.* (2019) also make claims for studies centered on integrating blockchain with the Internet of Things. Alternatively, Kouhizadeh and Sarkis (2018) call attention to the innovation process and the integration with legacy systems and other information technologies currently used, while Schuetz and Venkatesh (2020) prioritize the adoption behavior of rural Indians considering the disruptive potential of blockchain.

In an integrative approach, Pournader *et al.* (2020) call for case studies to address the integration and combination of hardware and software technologies, embracing adoption and implementation issues. The same authors also suggest that trust should be considered beyond information sharing, access, and accuracy, while trade should be studied in terms of the impacts of smart contracts. In addition, from their point of view, traceability/transparency encompasses inventory information, risk plans, and sustainability issues. A structural model covering implementation, values, and impact is proposed as a closing remark.

In terms of challenges for using blockchain for traceability, Galvez, Mejuto, and Simal-Gandara (2018) set four main themes, which include real-time visibility to provide speed and flexibility for the supply chain, fraud, and provenance transparency to assure safety, non-redundant and complete data to avoid 'information silos', and enterprise integration to reduce disputes and friction. Fosso Wamba and Queiroz (2020) suggest the study of relations between social variables and supply chain members and the possibilities for food supply chains and healthcare systems. Moreover, the authors mention the impacts on business models and the costs saved with disintermediation. Kiu, Chia, and Wong (2020) list possibilities to combine blockchain and Building Information Modeling (BIM) in the construction industry to improve projects and contracts performance.

From a post-application angle, Vivaldini (2020) addresses opportunities for platform evaluation, considering the solutions offered and the comparison between benefits expected and obtained, as well as cost-benefit analysis. Demestichas *et al.* (2020) ask for research focused on the creation of pilot applications and platforms, and Hughes *et al.* (2019) request in-depth analyses of use cases and research about the transition process toward blockchain adoption. Adopting a previous standpoint, Chang, Iakovou, and Shi (2019) argue that academia, industry, and government should join efforts to improve the processes of management and analysis of information flows by combining their expertise on technology, business, and policy, respectively. Chang and Chen (2020) indicate social impact and exploration of business reengineering process. Aiming to consolidate the future directions found, Table 12 lists the directions indicated for further research on blockchain in supply chain management. For additional information about each paper, see Table A1, in the Appendix.

Table 12 - Summary of directions proposed for future studies

| Research direction | Description | References |
|---|---|---|
| Adoption and contextual factors | In addition to comprehending the drivers, enablers, and adopters' contexts, interoperability issues and possible trade-offs need to be considered | Casino *et al.* (2019), Cole, Stevenson, and Aitken (2019), Dutta *et al.* (2020), Kiu, Chia, and Wong (2020), Nandi *et al.* (2020), Paliwal, Chandra, and Sharma (2020), Schmidt and Wagner (2019), and Schuetz and Venkatesh (2020) |
| Technology integration | Besides the integration with Industry 4.0 technologies, such as big data, Internet of Things, artificial intelligence, additive manufacturing, and cyber-physical systems, the consolidation with legacy systems and off-chain interplays must also be investigated | Casino *et al.* (2019), Chang and Chen (2020), Demestichas *et al.* (2020), Fosso Wamba and Queiroz (2020), Gonczol *et al.* (2020), Kouhizadeh and Sarkis (2018), Paliwal, Chandra, and Sharma (2020), Queiroz, Telles, and Bonilla (2019), and Zhao *et al.* (2019) |
| Sustainability | Opportunities encompass the perspectives of the triple bottom line, green practices, and reverse flows, on the other hand, the sustainability of blockchain protocol calls for attention | Casino *et al.* (2019), Dutta *et al.* (2020), Kiu, Chia, and Wong (2020), Paliwal, Chandra, and Sharma (2020), Queiroz, Telles, and Bonilla (2019), Saberi *et al.* (2019), Schmidt and Wagner (2019), and Zhao *et al.* (2019) |
| Governance | Standardization of information and integration with partners are highlighted as essential aspects to compensate for the disruption proposed by the digitalization of processes | Hughes *et al.* (2019), Hughes *et al.* (2019), Queiroz, Telles, and Bonilla (2019), and Wang, Han, and Beynon-Davies (2019) |
| Security | Exploring the level of security provided, alert mechanisms for attacks, and possible gaps | Al-Farsi, Rathore, and Bakiras (2021), Casino *et al.* (2019), Chang and Chen (2020), Hughes *et al.* (2019), Lim *et al.* (2021), and Queiroz, Telles, and Bonilla (2019) |
| Relationships | Operationalization of buyer-supplier relationships under the changes promoted by the blockchain paradigm, considering the interactions performed, reputation building, and collaboration between parties | Cole, Stevenson, and Aitken (2019), Dutta *et al.* (2020), Queiroz, Telles, and Bonilla (2019), Saberi *et al.* (2019), Treiblmaier (2018), and Wang, Han, and Beynon-Davies (2019) |
| Information / Data management | Privacy issues as well as data capturing solutions to leverage information sharing, | Bamakan *et al.* (2021), Casino *et al.* (2019), Hald and Kinra (2019), Kiu, Chia, and Wong (2020), Thakker *et al.* |

| Research direction | Description | References |
|---|---|---|
| | improve supply chain coordination, and mitigate information asymmetries | (2021), and Vu, Ghadge, and Bourlakis (2021) |
| Structural complexity | Challenges of implementation in complex and distributed supply chain networks, inclusion of small and medium enterprises (SME), capabilities development, and workers' learning curves are aspects highlighted | Bamakan *et al.* (2021), Hald and Kinra (2019), Pournader *et al.* (2020), and Varriale *et al.* (2021) |
| Costs | Identification of investment drivers, changes in transaction costs, and costs of disintermediation, among other financial components before and after implementation | Fosso Wamba and Queiroz (2020), Hughes *et al.* (2019), Queiroz, Telles, and Bonilla (2019), Reddy *et al.* (2021), Treiblmaier (2018), and Vivaldini (2020) |
| Traceability | Understanding the gains that traceability brings to operations efficiency and decision-making processes, and specific practices to promote traceability in the food industry | Bekrar *et al.* (2021), Etemadi *et al.* (2021), Fosso Wamba and Queiroz (2020), Hald and Kinra (2019), and Zhao *et al.* (2019) |
| Theoretical developments | Multiple theories are indicated to address adoption, decisions, and outcomes under different prisms and purposes | Cole, Stevenson, and Aitken (2019), Hughes *et al.* (2019), Saberi *et al.* (2019), Schmidt and Wagner (2019), Treiblmaier (2018), and Zhu, Bai, and Sarkis (2022) |
| Competitiveness | Investigate the gains and impacts on business competition, due to the launch of new business models for value addition | Asante *et al.* (2021), Kummer *et al.* (2020), Nandi *et al.* (2020), Queiroz, Telles, and Bonilla (2019), and Treiblmaier (2018) |

## 3.6 Discussion

Results of this review of reviews offer a consolidated portrait of literature reviews related to the interplay between blockchain and supply chain management, considering the general metrics impacted, specific requirements, and technological features, as well as future directions. The content analyzed embraces technological aspects in business contexts and reveals the interdisciplinary and multilevel attributes of the topic. As shown in Figure 13, among the objectives to perform a review, 'Research consolidation' achieved 83%. This high percentage reflects the importance of connecting multiple views through the consolidation provided by this review of reviews. The main points concerning the research questions are discussed as follows.

### *3.6.1 RQ1.1. What are the main supply chain topics approached in reviews about blockchain in supply chain management?*

Cost is depicted as the most discussed supply chain general metric, found in about 76% of 103 papers. Financial issues are considered from several viewpoints, including investment evaluation and post-implementation expenses. Finding remarks about security in about 68% of the sample can be related to the fact that both public and private blockchains prioritize protection over performance (JUMA; SHAALAN; KAMEL, 2019), but attention is still required to the problem of the 'over 50% hacker attack' (WANG; HAN; BEYNON-DAVIES, 2019). Regarding the discussion about sustainability, which is found in about 55% of the sample, we agree with the position stressed by Esmaeilian *et al.* (2020) that blockchain is just a tool and improved results rely primarily on business decisions and actions executed. Quality also appeared in about 55% of the papers, embracing links among trust, transparency, and traceability issues (POURNADER *et al.*, 2020), while product safety (37%) is revealed to be an essential aspect, particularly for food, diamond, and pharmaceutical supply chains. On the other hand, impacts on supply chain speed, flexibility, and reliability deserve more in-depth exploration since about 25% of the sample briefly approached these subjects.

According to our sample, transparency and trust are the most frequent supply chain requirements supported by blockchain, and are discussed in about 91% and 76% of the sample, respectively. Both have connections with anticounterfeit issues (46,6%) and with changes for disintermediation (38,8%) and decentralization (36%), which are requirements that were discussed consistently. The amplitude and the relation of those topics explain the expressive mentions found in the sample. Also, offering information about compliance (36%) as well as provenance (32%) and dispute resolutions (26%) are other promising possibilities discussed for blockchain to attend to supply chain needs. However, some other issues must be considered. Paliwal, Chandra, and Sharma (2020) and Dutta *et al.* (2020) make claims for the integration and interoperability with legacy ERP systems, and Chang, Iakovou, and Shi (2019) considered the connection between different blockchains. Moreover, blockchain is essentially a database, so the quality of data acquisition processes must include the usage of specific devices, like RFID tags and sensors (SCHMIDT; WAGNER, 2019), especially to handle last-mile or endpoint vulnerability problems (ESMAEILIAN *et al.*, 2020). We see that the development of property rights (13,5%) policies deserves more attention in order to attract companies to adopt or participate in a blockchain.

Several reviews focused on agriculture (2) and food (13), or even agri-food (9) supply chains, aiming to leverage operations' performance through the distinctive possibilities offered by blockchain. Transportation and logistics represent another area of interest, while the sample also embraces airport and maritime contexts. Healthcare and hospitality applications are cases of reviews focused on scenarios of the service sector. The diversity still includes international trade, pharmaceutical, battery, and construction industries. Besides 47 industry or segment-specific review papers (45,6%), 12 review papers (11,6%) provided brief discussions about multiple practical contexts, while 44 papers are non-industry or segment-specific review papers. These numbers reveal a trend to derive opportunities and findings associated with particular characteristics of application fields.

### *3.6.2 RQ1.2. What are the blockchain features studied in reviews about blockchain in supply chain management?*

Massive interest in smart contracts is noticed as 86 out of 103 papers (83,5%) discuss aspects of its versatility to offer a customizable and automatic executing mechanism. The appearance in the top position was previously expected since smart contracts represent a transformative potential of blockchain due to its ability to assure the accomplishment of predefined conditions. Traceability is also widely discussed (80,5%), through the possibility of achieving a spatial and/or a temporal record of the path (ASTILL *et al.*, 2019), depending on the industry and product characteristics, considering that the near real-time processing of information (52,4%) creates conditions for fast reactions to make readjustments (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018).

Regarding the principle of immutability (41,7%), which builds the ground for verifiability (21,3%), attention must be given to the reliability of the information kept in the network and to the difficulties in providing simple corrections. We believe that studies on permanent availability (23,3%) can be linked to continuous and exhaustive supplier evaluation processes in the near future. Also, after being approached in only 11,6% of the sample, we indicate that the contributions to be provided by chronological data to support decision-making processes can be more deeply explored to capture the value contained in reliable timestamped registers. Despite having few mentions, we think that peer-to-peer configuration (12,6%) and digital signature (9,7%) tend to expand their range of exploration with the establishment of platforms among multiple supply chain partners, which will call for a deeper exploration of the properties of consensus mechanisms (24,3%) to advance blockchain diffusion.

### *3.6.3 RQ1.3. Which directions for future research have been reported in reviews about blockchain in supply chain management?*

Blockchain perspectives of supply chain management are currently facing a stage of rapid evolution, which presents plenty of opportunities and research directions to be considered according to the subsample of 57 papers that report ‘Gaps and directions’.

Adoption issues and contextual factors were indicated as a path in 52,6% of the papers, also including particularities of specific segments. This topic holds relevance to unlock valuable insights concerning both the individual and the enterprise perception of the potential of blockchain. Integration with other technologies is another prospect to be developed since the synergy with complementary alternatives will provide gains in performance for both data acquisition and data analytics. Suggestions to integrate blockchain to technologies such as artificial intelligence, big data, cyber-physical systems, and Internet of Things, and also to legacy systems, were mentioned in about 45,6% of the research agendas.

Possibilities concerning sustainability have been found in 38,6% of the papers in the subsample, which is reasonable if we consider the momentum of research on themes like green/sustainable supply chain management and circular economy, and the gains that blockchain can provide to bring these concepts into practice on larger scales. Assessments considering the triple bottom line (TBL) are also outlined. Moreover, studies related to the costs of blockchain implementation were proposed in 22,8% of the cases, showing another avenue that deserves deeper investigation, mostly based on quantitative data about investments required and savings obtained, also including the transaction costs angle.

We noticed a trend of asking for future works to supply empirical and practical evidence to confirm the benefits and effects discussed around blockchain, which reveals an intention to move the literature closer to applications (QUEIROZ; TELLES; BONILLA, 2019; CHANG; IAKOVOU; SHI, 2019; DUTTA *et al.*, 2020). On the other hand, both exploratory issues and conceptual proposals are found alongside directions grounded on theoretical foundations, as indicated in 17,5% of the papers allocated to the subsample. We believe that after the development of confirmatory research works, the literature will gradually support opportunities for studies focused on decisions of blockchain implementation and configuration in more precise and robust ways.

From managerial standpoints, we highlight research directions related to governance structures and competitiveness found in 36,8% and 14% of the subsample, respectively. A concern with relationship management is also raised in 29,8% of the papers analyzed, as traditional interfaces are going to undergo significant changes. From another angle, exploring blockchain features such as consensus mechanisms and immutability in the context of supply chain management is also a path that could provide interesting findings to contribute to security performance and information/data management, as mentioned in 33% and 28% of the cases evaluated, respectively. We believe that topics such as supply chain structural complexity and traceability are going to offer other promising advances, regardless of being mentioned in only 28% and 22,8% of the eligible cases, respectively.

### 3.7 Research agenda for future literature reviews

Based on the analyses performed, some gaps were identified, so we suggest the following research topics (RT) as directions for future literature reviews:

(1) Identification of standards to provide access and inclusion for the highest number of supply chain players into blockchain collaboration.
(2) A combined review of adoption drivers and strategies for implementation, including gradual and full-scale approaches, also considering constraints and solutions.
(3) An exploration of the status of the development of rules and regulations and their respective impacts on supply chain configuration and operations.
(4) An assessment of changes in governance structures and the impacts that a decentralized blockchain-based system can bring to market, modular, relational, captive, and hierarchy models in terms of operation performance.
(5) Identification and description of business models suitable or adaptable for blockchain implementation to maximize the benefits of its capabilities and leverage the supply chain and its members' performance.
(6) An assessment of blockchain through the lens of specific theories, like Nandi *et al.* (2020), which built on top of the resource-based view, and Schmidt and Wagner (2019), on transaction cost theory, as Treiblmaier (2018), Cole, Stevenson, and Aitken (2019), Kummer *et al.* (2020), Karakas, Acar, and Kucukaltan (2021), and Zhu, Bai, and Sarkis (2022) address promising theories.
(7) Specific reviews approaching the integration of blockchain with other technologies, such as big data, artificial intelligence, enterprise resource planning (ERP), electronic data interchange (EDI), and additive manufacturing, like the one provided by Rejeb, Keogh, and Treiblmaier (2019) that link Blockchain and Internet of Things.
(8) Exploration of either public or permissioned blockchains usage into supply chain operations, or a structured evaluation of applications of both types, as only Sunny, Undralla, and Pillai (2020), Gonczol *et al.* (2020), and Juma, Shaalan, and Kamel (2019) briefly considered these configurations.

(9) An in-depth exploration focused on smart contracts, including criteria being adopted and the decision processes automated after its establishment in supply chain management contexts.
(10) An appointment of the assets being currently digitalized, either individually or in an integrated approach through a multichain configuration (i.e., with multiple blockchains interconnected).
(11) An appointment of the type of information and data that companies are willing to share on a blockchain, its frequency of update, visibility, and purpose.
(12) Overviews related to other industry sectors, such as electronics, oil and gas, and non-durable manufacturing, considering applications and industry-related characteristics.
(13) A risk assessment with potential aspects to be mitigated by different actors during blockchain implementation and usage.
(14) An aggregated post-implementation analysis to list lessons learned with failures and good experiences to extend the discussion around the critical success factors listed by Shoaib, Lim, and Wang (2020) and Hastig and Sodhi (2020).
(15) Identification of alternatives adopted to deal with interoperability, mistake correction, incompatibility of information, and other issues without going deeper into computing aspects.

Although this set of research topics (RT) is primarily devoted to guiding the development of literature reviews, some topics can still be adapted and then taken as a starting point for primary works, which would also be valuable to bring contributions to the literature.

## 3.8 Conclusions and final remarks

Based on a systematic approach, this study presents a comprehensive review of secondary works that encompass the interplay between blockchain and supply chain management at different levels. In addition to the innovativeness of the technology and its promising potential for the business domain, finding a sample of 103 papers performing literature reviews published in top journals in about five years emphasizes the relevance of the analyzed interface.

The contributions provided by this paper are divided into three main categories. First, a comprehensive and up-to-date overview of the state of the art is offered, which posits blockchain as a suitable technology for production and logistics applications. Then, gathering the analysis of reviews helps researchers identify contents to be examined and avoid developing overlapping reviews. In addition, the set of directions found in the sample is a relevant starting point to guide the development of upcoming research works and the set of research topics described provides directions for further literature reviews to be produced.

After reviewing multiple aspects and possibilities surrounding blockchain in supply chain management, it is important to highlight that blockchain is a technology mainly indicated as a solution for inter-organizational issues (WANG; HAN; BEYNON-DAVIES, 2019) and cannot be wrongly assumed as 'a solution looking for a problem' (HUGHES *et al.*, 2019). Furthermore, supply chain digitalization typically guides the establishment of common objectives among parties (CHANG; CHEN, 2020), and synchronized efforts from different groups of entities are essential for blockchain success (NANDI *et al.*, 2020). We also emphasize that radical and unpredictable changes in business models can take place (PALIWAL; CHANDRA; SHARMA, 2020), leading to changes in the skill profiles of workers and organizations (HALD; KINRA, 2019). These conditions should be considered in assessments and monitored both during and after implementation.

Although the methodology adopted was carefully structured, this paper has its limitations. Even after performing a complementary search following the snowball procedure, some relevant review papers could have been left out of the sample due to the search criteria established. Moreover, we hope that the cycles of refinement performed have dealt with the multiple terminologies employed in the sample collected, which is typical of emerging themes.

# 4 A FRAMEWORK FOR MODELING AND SIMULATING BLOCKCHAIN-BASED SUPPLY CHAIN TRACEABILITY SYSTEMS

In this chapter, a methodological framework was developed and tested through a proof-of-concept application regarding the execution of a recall.

The content presented in this chapter was submitted for a double-blind peer-review evaluation and is currently under review on February 9th, 2024.

**Abstract:** Traceability improves supply chain operations transparency, benefiting the overall performance and the end customer perception. Blockchain technology is a promising alternative to create robust traceability systems as it promotes trust and supports information sharing based on data immutability. Despite the hype surrounding blockchain technology, the effectiveness and efficiency of blockchain-based supply chain traceability systems remain uncertain across multiple industry sectors. The scientific literature on blockchain is vast, but it lacks empirical evidence due to the novelty of the technology and the relevant complexity of implementing such systems. Considering its characteristics, simulation is a valuable tool to evaluate the performance of supply chain management processes and technology alternatives. However, a structured guide to support the building process of simulation models regarding blockchain in the supply chain is still missing, making it hard for modelers to create realistic simulation models involving the multiple elements required. Thus, this work presents a novel methodological framework with guidelines to develop hybrid simulation (HS) models regarding supply chain traceability considering blockchain. Scenarios with different granularity levels may be designed through the combination of discrete-event and agent-based simulation paradigms. Our approach integrates concepts and terminologies from foundational references for practitioners and academics, such as the Supply Chain Operations Reference (SCOR) model and the Global Traceability Standard (GTS). In addition, it is anchored on the ADACOR holonic architecture for the agentification process. Following the proposed framework, we present a proof-of-concept application based on a real-scale industrial case of a live lobster supply chain from Canada. The results obtained reflect the framework's versatility to assist the development of a hybrid simulation model, as traceability is explored through the perspectives of time to react, item separation, criterion for screening, and blockchain participation rate.
**Keywords:** blockchain; supply chain traceability; SCOR; GTS; simulation modeling.

## 4.1 Introduction

Traceability encompasses practices to follow an entity's path, such as a product, a vehicle, or a load, by monitoring its attributes, transitions, and states. In the supply chain context, a traceability system offers performance gains in terms of quality assurance, regulatory compliance, initiatives of sustainability, and provenance data (AHMED; MACCARTHY, 2023). The benefits obtained are deployed into reduced costs with distribution systems, higher efficiency in recalls, and marketing due to customer awareness (KSHETRI, 2018).

Data collection and retrieval are relevant parts of a traceability system, alongside unique identification, lot integrity, and product transformation (THAKUR *et al.*, 2011). Thus, instead of relying on unstructured processes based on phone calls and emails to record and share information, companies must adopt standardized processes to reduce data redundancies and chances of error (STORØY *et al.*, 2013). Moreover, information must be handled electronically through effective, precise, and secure procedures. This required robustness makes blockchain technology a promising application for supply chain traceability due to its working logic which promotes trustable and real-time information sharing by operating on top of principles of data immutability, disintermediation of processes, and power decentralization (COLE; STEVENSON; AITKEN, 2019).

In the era of Industry 4.0/5.0 and its emerging technologies, achieving the full and disruptive potential of blockchain for traceability in complex flows depends on combining the application of data-capturing technologies such as bar codes, RFID, NFC, and QR codes (CORALLO *et al.*, 2020). Both researchers and practitioners from information technology and supply chain management are interested in debating the benefits of traceability and the contributions of blockchain to traceability systems (AHMED; MACCARTHY, 2023). However, although research concerning blockchain has been released at high rates, the connection with supply chain traceability is currently limited (GALVEZ *et al.*, 2018; Feng *et al.*, 2020). In addition, despite all the hype surrounding blockchain technology, the effectiveness and efficiency of blockchain-based supply chain traceability systems are uncertain in several industry sectors. The scientific literature fails to provide empirical evidence in many fields due to the novelty of the technology and the complexity of such a system (RISSO *et al.*, 2023a).

Considering its characteristics, simulation is a valuable tool to evaluate the performance of supply chain management processes. It allows modelers and decision-makers to understand the potential behavior of complex supply chain systems (OLIVEIRA; LIMA; MONTEVECHI, 2016; KONOVALENKO; LUDWIG, 2019). Moreover, simulation models also have the potential to support the adoption of emerging technologies in operations management, digital transformation, and Industry 4.0/5.0, as suggested by Ferreira, Armellini, and Santa-Eulalia (2020). Recent research proposes guidelines for developing both blockchain applications (BAHARMAND *et al.*, 2021; ISAJA *et al.*, 2023) and simulation models in supply chain management (DORIGATTI *et al.*, 2016; FERNÁNDEZ *et al.*, 2016). However, there is no framework available, to the best of our knowledge, to guide simulation modeling integrating blockchain in supply chain management, making it hard for modelers to create realistic simulation models involving the multiple elements required. Thus, this work presents a novel methodological framework with guidelines to develop hybrid simulation (HS) models regarding supply chain traceability considering blockchain.

Following a Design Science Research methodology, the proposed framework is submitted for validation in a real-scale proof-of-concept application case in a live lobster supply chain from Canada. We integrate the Supply Chain Operations Reference (SCOR) (APICS, 2017) model and the Global Traceability Standard (GTS) (GS1, 2017), which are well-accepted by the business and research communities. The proposed framework supports modeling traceability from the perspectives of origin, process, movement, and after delivery, from the source of raw materials to the final consumption. We focus on addressing hybrid simulation models, combining both agent-based and discrete-event paradigms. Since the models are anchored on the agent-based paradigm, the ADACOR architecture (LEITÃO; RESTIVO, 2006) is taken to support the agentification process. The proposed modeling approach allows the consideration of different blockchain configurations, levels of granularity, traceability information types, and smart contract conditions.

This chapter is structured as follows. Section 4.2 provides a literature review concerning the use of blockchain in supply chain management. Section 4.3 describes the research design adopted. Section 4.4 presents the hybrid simulation framework for supply chain traceability considering blockchain. Section 4.5 exhibits a proof-of-concept application. Finally, Section 4.6 outlines conclusions and directions for future studies.

## 4.2 Related works

A simulation is an imitation of a real process or system over time, considering decisions related among others to resource allocation and prioritization, aiming to obtain gains in performance. Discrete-event simulation is a process-oriented approach involving passive entities which trigger events that determine states in discrete time points. System dynamics is a continuous approach that uses differential equations to model relations through stock, flows, and feedback loop diagrams. The agent-based approach relies on autonomous and interactive entities that follow protocols and rules besides sensing the environmental conditions, coming to a high level of abstraction. Hybrid simulation is adopted when a single paradigm is not enough to represent the complexity and the particularities of a problem or situation (FERREIRA; ARMELLINI; SANTA-EULALIA, 2020; MORGAN *et al.*, 2017).

Among the applications of discrete-event simulation to model blockchain in the supply chain, Wang *et al.* (2020) propose a framework for information management and smart contracts algorithms, including a case study in a precast construction supply chain. It encompasses information sharing management, real-time scheduling, and information traceability, improving deliveries and dispute resolutions. In a case study of an automotive supply chain, Ada *et al.* (2021) prospect blockchain as an alternative to enhance responsiveness based on traceability, following real-time updates of both inventory status and goods movements to reduce waiting time.

Martinez *et al.* (2019) study the customer order management process and the impact of blockchain usage in different time horizons. Their framework indicates resources needed and its results highlight improvements in performance efficiency and information visibility. Manupati *et al.* (2022) adopt blockchain as a communication platform to anticipate disruptions and initiate mitigation actions, according to conditions distinguished by smart contracts. Ashraf and Ali (2022) aim to quantify the benefits of blockchain for a traceability system in a project-based supply chain, involving smart contracts to track packages' ownership and evaluate completion estimates in scenarios with disruptions. Tozanli *et al.* (2020) investigate the end-of-life of game consoles and their components to identify the feasibility of trade-in-to-upgrade policies in a disassembly-to-order system. Scenarios considering remanufacturing, inventory, and transportation costs were consolidated, and the information is gathered from smart products with IoT-embedded. Varriale *et al.* (2021) raise the impacts of integrating IoT, RFID, blockchain, and smart contracts to enhance sustainability issues. According to their results, regular processes such as receiving, modification, and order processing, have brought order management improvements in both ideal and disrupted conditions.

Among system dynamics applications, Xue *et al.* (2020) present a framework related to information asymmetry and synergy in a home supply chain. Their proposal modifies the hierarchical relationship between parties, putting the customer as the focal point. As the main result, the bullwhip effect is reduced, and cost, quality, and efficiency improvements are obtained through blockchain usage. Mangla *et al.* (2021) study the societal elements in a milk supply chain, supporting blockchain to promote social sustainability. Besides providing higher traceability, this work addresses Sustainable Development Goals such as food safety and well-being.

Under the agent-based paradigm, Lohmer *et al.* (2020) focus on risk management and develop a theoretical study to address the ripple effect through resilience strategies. The approach adopted considers collaboration enabled by smart contracts and explores disruption propagation, the network recovery time, and the possibility of total cost reduction.

In a hybrid approach, Longo *et al.* (2019) combine agent-based and discrete-event paradigms to reproduce supply chain operations and analyze information asymmetry impacts. A connection with an Ethereum-like blockchain provides trust through the certification of information authenticity, and smart contracts are used to allow data insertion. Besides the orders' fill rate, metrics about inventory and financial aspects are gathered, and the results revealed that blockchain is a convenient alternative to enhance collaboration.

Table 13 synthesizes the main contributions provided by these works and the simulation paradigms adopted.

Another research stream on blockchain applied to the supply chain is related to frameworks focused on representing information flows and interactions among involved parties. Dolgui *et al.* (2020) present a cyber-physical scheduling control framework for smart contract design involving multiple logistics service providers. Feng *et al.* (2020) introduce an architecture design framework associating blockchain and IoT to structure a traceability system. Attributes are to be recorded in each stage and the information flow between business, traceability, blockchain, and application layers are specified.

Moreover, Liu and Li (2020) depict a blockchain-based framework inspired by a cross-border e-commerce supply chain which describes a structure with multiple blockchains (namely multichain) and a data management model alongside the data flow. In addition, governance and implementation issues are discussed. Cui *et al.* (2019) outline a framework to stress the provenance of electronic parts in a non-destructive way, relying on traceability information kept on a permissioned blockchain. Agrawal *et al.* (2023) propose a collaborative framework for resource sharing using smart contracts to assist outsourcing and surplus allocation decisions. A demonstration focuses on interactions between procurement and distribution processes.

We found that different simulation modeling approaches comprising blockchain applications in the supply chain domain have recently been released. From the simulation perspective, the discrete-event, agent-based, and system dynamics paradigms have been adopted, even in combination, leading to hybrid models. Part of those works only describe the

Table 13 - Works involving simulation and blockchain in supply chain management

| Reference | Main contribution | Simulation paradigm | | | |
|---|---|---|---|---|---|
| | | DES | SD | ABMS | HS |
| Ada *et al.* (2021) | Investigates blockchain's role in enhancing responsiveness through traceability | ✓ | | | |
| Ashraf and Ali (2022) | Focuses on the benefits of a real-time blockchain-enabled traceability system in a project-based supply chain, employing smart contracts | ✓ | | | |
| Lohmer *et al.* (2020) | Explores the role of blockchain and smart contracts on resilience strategies to deal with the ripple effect | | | ✓ | |
| Longo *et al.* (2019) | Evaluates the impacts of blockchain usage on information asymmetry with updates controlled by smart contracts | ✓ | | ✓ | ✓ |
| Mangla *et al.* (2021) | Addresses elements of social sustainability through traceability supported by blockchain | | ✓ | | |
| Manupati *et al.* (2022) | Assesses the potential of blockchain and smart contracts to mitigate disruptions | ✓ | | | |
| Martinez *et al.* (2019) | Examines the impact of blockchain on customer order management | ✓ | | | |
| Tozanli *et al.* (2020) | Studies blockchain application on remanufacturing operation in a disassembly-to-order system | ✓ | | | |
| Varriale *et al.* (2021) | Embraces the integration of blockchain and smart contracts with other technologies to improve sustainability | ✓ | | | |
| Wang *et al.* (2020) | Proposes a framework for information management including smart contracts and information traceability based on blockchain | ✓ | | | |
| Xue *et al.* (2020) | Brings a framework regarding information asymmetry and synergy considering blockchain | | ✓ | | |
| **This work** | Provides guidelines to develop hybrid simulation models for supply chain traceability using blockchain | ✓ | | ✓ | ✓ |

Where: DES - discrete-event simulation; SD - system dynamics; ABMS - agent-based modeling and simulation; HS - hybrid simulation.

model, while others present a situation-driven framework. In addition, some studies rely on a simulation model to study technical aspects related to performance or energy consumption, as well as numerical simulations or simulations performed exclusively on a blockchain platform. Those are not aligned with our research direction, which considers supply chain management.

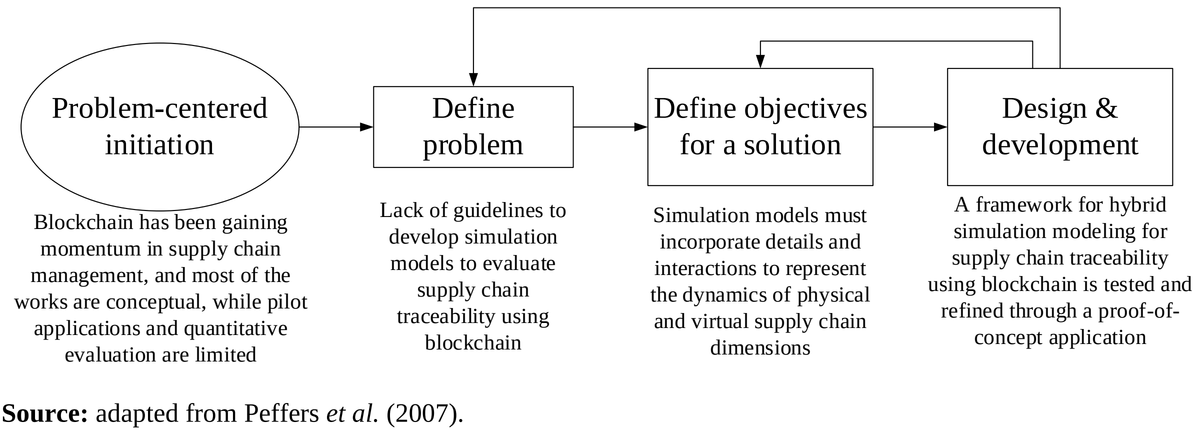
Finally, in some studies, the framework proposed does not embrace simulation modeling but does provide relevant guidelines for model building, making a second group for our analysis.

Despite providing relevant contributions, none of these works provides detailed guidelines about how to build a hybrid simulation model anchored on the agent-based paradigm to address supply chain traceability considering different types of blockchain. Therefore, we propose a step-by-step guide that contributes to improving communication during the model development as it suggests a standard decision-making sequence regarding the model scope and its working logic. As a result, the level of complexity is reduced since we adopt the strategy of "divide-to-conquer". We also expect to decrease the time needed to conclude the model building by indicating consistent decisions. As a final note, the details provided concerning agents' interactions and their hierarchy also assist the modelers in integrating concepts from the supply chain, traceability, and blockchain domains.

## 4.3 Research method

This work adopts the Design Science Research approach, which is essentially prescriptive and focused on proposing artifacts such as systems, algorithms, models, and frameworks to deal with field problems to achieve specific outcomes by making knowledge instrumental (VAN AKEN *et al.*, 2016). The procedure starts with identifying a problem or opportunity with practical relevance. The problem is the current lack of a structured guide to help modelers develop refined hybrid simulation models to provide quantitative analysis of supply chain traceability using blockchain. Then, a framework is proposed as an alternative solution designed and refined in iterative cycles, as depicted in Figure 15, following the approach of Peffers *et al.* (2007).

Figure 15 - Design Science Research approach




**Source:** adapted from Peffers *et al.* (2007).

An application case using real data collected from a live lobster supply chain was taken for an empirical evaluation. In addition, an assessment of practical relevance and pragmatic validity was performed to attest to the framework's effectiveness, which is defined as its versatility in assisting the creation of simulation models of supply chain traceability for different purposes. These steps led to new insights as part of the iterative design cycle, embracing aspects of supply chain traceability, as the application domain, and the proposed framework for building simulation models, concerning the assessment of its practical contribution.

The artifact development is considered complete as soon as the framework is evaluated as suitable to assist simulation modeling for supply chain traceability considering blockchain. The live lobster supply chain was chosen as the context for the proof-of-concept due to several reasons. First, seafood catches and transformation are economically important for many coastal communities across the world, and its precise administration benefits a sustainable future. According to recent studies by the Food and Agriculture Organization (FAO) – United Nations (BLAHA; KATAFONO, 2020) and the World Wide Fund (COOK, 2018), supply chain traceability may be a central aspect since traditional trace and track systems cannot guarantee food safety, prove legality, and verify sustainability. In addition, the sector has revealed a recent interest in evaluating traceability practices using data-sharing alternatives. Finally, the research team had access to real data about this supply chain through the development of industrial partnerships.

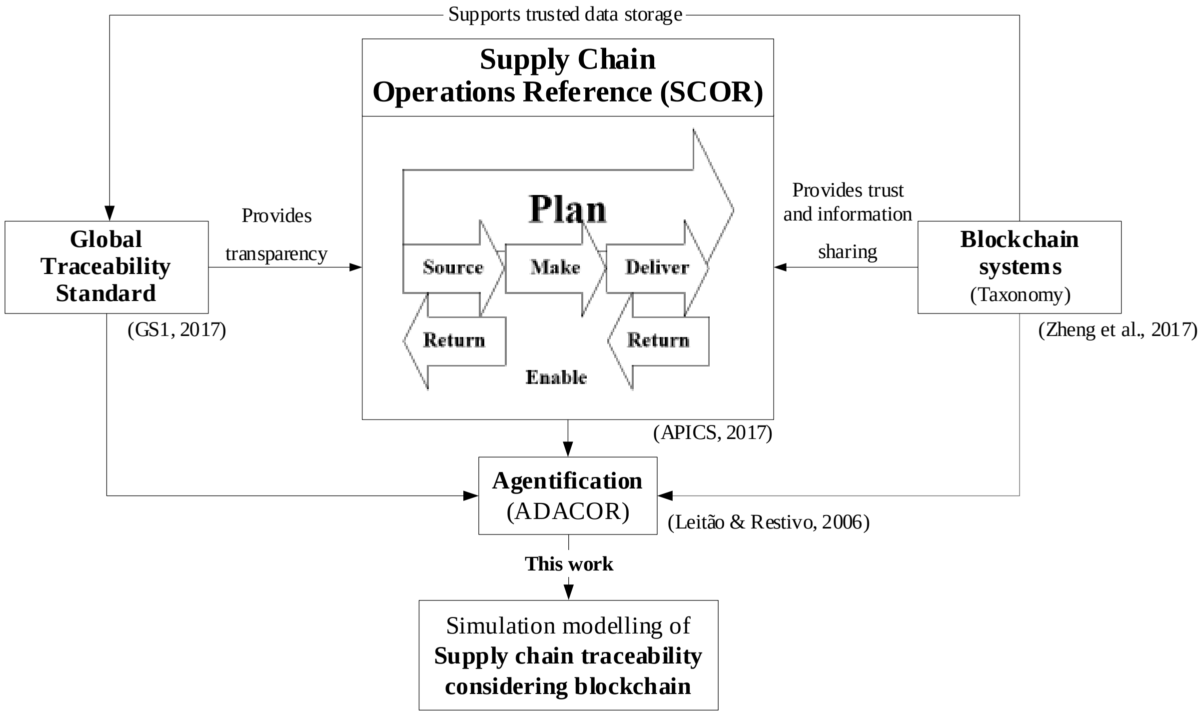
## 4.4 Framework for supply chain traceability simulation using blockchain

In this section, we first present an overview concerning how different concepts are integrated into our proposal. In the second part, we describe the phases and steps of our framework, alongside recommendations for its better usage.

### *4.4.1 Overview*

The framework for hybrid simulation for supply chain traceability using blockchain consists of an integrated approach. The guidelines assist in modeling traceability for different supply chain configurations, from dedicated to flexible networks. Hence, the proposal combines consolidated and versatile modeling approaches. SCOR model can be used to model almost any supply chain, with different levels of complexity (APICS, 2017). GTS standard contains traceability concepts that are not segment-specific and is largely used in industry (GS1, 2017). The taxonomy of blockchain systems and definitions of features are adopted from Zheng et al. (2017), due to its completeness. The combination of these building elements is translated into agent-based modeling anchored on the ADAptive holonic COntrol aRchitecture (ADACOR), which is originally related to distributed manufacturing systems (LEITÃO; RESTIVO, 2006), and has recently been used in the literature for the agentification process in modeling frameworks in the context of Industry 4.0 (FERREIRA et al., 2022). Figure 16 outlines the main components' integration and their respective roles in the proposed framework.

Figure 16 - Integrated approach proposed




*4.4.2 Proposed steps*

The framework contains eight steps and three phases, as shown in Figure 17. As intrinsic to simulation modeling, iterative processes are recommended during the design process, so the user can return and review any previous decision if needed (LAW, 2005). This interactivity is reasonable since the modeler learns about the problem during its exploration. This recursiveness is indicated by the shaded arrows contained in the two first phases. The description of each step is detailed next and the numbers in parenthesis refer to the guideline being explained.

Figure 17 - Framework for hybrid simulation for supply chain traceability using blockchain

| **Step** | **Guidelines** |
| --- | --- |
| **● MODEL DESIGN ●** | |
| **1.** Problem statement | 1.1 Define the simulation purpose<br>1.2 Establish the simulation scope |
| **2.** Supply chain configuration | 2.1 Specify members and their roles<br>2.2 Define supply chain initial structure<br>2.3 Set possibilities of structural changes (opt.) |
| **3.** Traceability configuration | 3.1 Specify the traceability purpose<br>3.2 Assign Critical Tracking Events (CTE)<br>3.3 Assign Key Data Elements (KDE)<br>3.4 Delimit levels of granularity |
| **4.** Blockchain configuration | 4.1 Define type(s) and number of blockchains<br>4.2 Define membership criteria<br>4.3 Set access permissions profiles<br>4.4 Set actions allowed rules<br>4.5 Define smart contracts storage (opt.) |
| **5.** Performance measures and scenarios definition | 5.1 Specify KPIs considered<br>5.2 Define the strategy of experimentation |
| **● MODEL DEVELOPMENT ●** | |
| **6.** Model specifications | 6.1 Define simulation paradigm<br>6.2 Define agents' classes<br>6.3 Describe structural and behavioral parameters<br>6.4 Set interactions rules and flows<br>6.5 Include logic to measure performance<br>6.6 Provide model documentation |
| **7.** Model implementation | 7.1 Select simulation platform<br>7.2 Build the simulation model<br>7.3 Perform model verification<br>7.4 Perform model validation |
| **● OUTPUT EVALUATION ●** | |
| **8.** Results and analysis | 8.1 Build charts for graphical analysis<br>8.2 Perform statistical analysis<br>8.3 Communicate results |

The model design phase is essential to establishing the context aiming to find a coherent and well-situated integration among supply chain, traceability, and blockchain domains.

In Step 1, to get started, the modeler must define the problem statement. As enumerated by Edmonds *et al.* (2019), a simulation model is built to achieve the purpose of prediction, explanation, description, and/or illustration, among others. Then, after setting the model purpose (1.1), the model scope must be established to guide decision-making in the next steps, which can be done by formulating a question to be answered (1.2).

In Step 2, a general configuration of the supply chain under consideration must be defined. Following Long (2014), we recommend that each party be represented by agents corresponding to appropriate processes of the SCOR model, namely plan, source, make, deliver, and return, as well as their role in information and physical flows (2.1). Notice that not all SCOR processes apply to all cases; modelers need to understand the traceability problem and pick up only the required modeling entities. For example, a make process is not assigned to represent a distributor agent since no transformation is performed. The supply chain's initial structure, i.e., the links between parties, must be specified (2.2). This structure may be assumed as an initial modeling input and be kept as a fixed network structure during the simulation or some degree of flexibility to establish connections may be allowed (2.3).

In Step 3, aspects of traceability configuration are addressed following the GTS (GS1, 2017). Concerning traceability purposes (3.1), the types are non-exclusive and are typically associated with SCOR processes as indicated in parenthesis: Origin traceability (source), process traceability (make/deliver), movement traceability (deliver), and after delivery traceability (source return/deliver return). The assignment of Critical Tracking Events (CTEs) determines the main events of interest to describe the sequence of processes in which a traceable object is submitted (3.2). These CTEs are associated with Key Data Elements (KDE), embracing five dimensions, namely who (actor), what (object), where (location), when (instant), and why (business process). Other dynamic and static attributes of interest are optionally associated with the CTEs, representing the information required to complement the respective KDEs (3.3). The type of information supports the delimitation of the levels of granularity required (3.4) for both information data and physical entities. This is an essential aspect of the agents' hierarchical relationships. Traceable objects such as logistic units (e.g., palletized goods, parcels), assets (e.g., trucks, vessels, trains, forklifts), and product items (e.g., consumer goods, medicines, electronic devices) may be correlated under any perspective. This assumption is also linked to the Assets agents (machines, vehicles, employees, and so on) that are associated with their respective supply chain business processes.

In Step 4, blockchain configuration is established, according to the terminologies found in Zheng *et al.* (2017). First, the user should address the type(s) of blockchain(s) adopted, which designates the possibility of using specific types of smart contracts. In the case of a multichain arrangement, the number of blockchain platforms is also defined (4.1). Each blockchain will have its criteria for membership (4.2), access permission profile (public/private/consortium) (4.3), and actions allowed rules (permissioned/permissionless) (4.4). In addition, smart contracts are optionally stored to automate traceability or decision-making processes (4.5). Here it is important to make some remarks. From the SCOR standpoint, blockchain is seen as an enabler for information management. In terms of simulation modeling, a blockchain and a smart contract can be considered agents to model the communication flow and interactions among supply chain parties. The parameters of a blockchain agent determine information writing and sharing, while the parameters of a smart contract agent trigger logic statements to automate processes and assure the accomplishment of rules. From another perspective, the model can alternatively be connected to an external and dedicated blockchain platform, such as EOSIO, Ethereum, or Hyperledger Fabric, similar to the approach adopted by Longo *et al.* (2019).

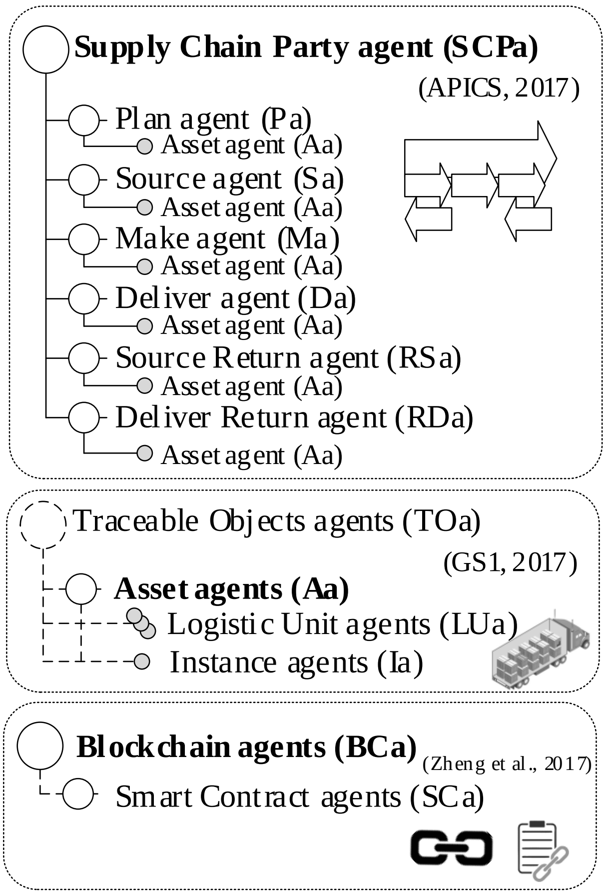
Step 5 consists of defining the performance indicators selected and the strategy of experimentation. Examples of supply chain indicators are found in the SCOR model (APICS, 2017), such as “Delivery performance cycle time” and “Perfect order fulfillment”, while the GTS standard (GS1, 2017) provides performance indicators related to traceability, such as “number of items produced” and “number of logistics units shipped” that have a unique ID. From another perspective, performance indicators concerning blockchain refer to its members’ performance and association time (5.1). In general, performance measures impact agent properties regarding sensing abilities, collective formation, and memory capabilities (GRIMM *et al.*, 2020). Moreover, in terms of experimentation, the modeler must decide which design of experiments strategy is going to be conducted (5.2), such as one-factor-at-a-time, screening, and factorial experiments. Designed experiments are suitable to evaluate both incremental and disruptive innovation proposals, as the latter is the case of blockchain technology, and for detailed instructions, we recommend Montgomery (2017).

After having the previous definitions, the phase of model development deals with building the simulation model. In Step 6, model specifications are defined. First, there is the decision about the simulation paradigm adopted, concerning whether a solely agent-based or a hybrid simulation model, combining agent-based and discrete simulation approaches is going to be built (6.1). Further discussion about five designs for paradigms’ mixing is found in Morgan, Howick, and Belton (2017), described as parallel, sequential, enrichment, interaction, and integration. In the sequence, the modeler must specify the classes of agents and/or entities considered (6.2).

When entities are modeled as agents, parent classes can optionally be decomposed in a hierarchy, guarding linkages with their child classes. In the case of supply chain processes, this strategy provides specialization for the decision-making, while the Traceable Objects agents (TOa) assign the desired level of granularity. Blockchain agents are not decomposed, but they are taken as host for mining, storing, and sharing data, and, in some cases, managing a smart contract agent.

As shown in Figure 18, classes and subclasses of agents are indicated to assist the modeling and simulation of supply chain traceability using blockchain.

Figure 18 - Agents' hierarchical deployment




A Supply Chain Party agent (SCPa) represents either an organization or a service provider in a supply chain. These agents have subclasses corresponding to the SCOR model's business processes (APICS, 2017), according to their specific roles. They are also taken as references to store organizational information and manage blockchain membership and permissions.

Plan agents (Pa) focus on matching supply with demand for different products and channels and making decisions to support the other processes (APICS, 2017). Source agents (Sa) deal with receiving and transferring any kind of material and service, including the emission of purchase orders, the scheduling of deliveries, and the storage of units, as well as reporting inspections and payment authorizations (APICS, 2017). Make agents (Ma) manage the material conversion to add value and generate deliverables. This term encompasses different categories, such as assembly, maintenance, and remanufacturing (APICS, 2017). Deliver agents (Da) handle both order management and order fulfillment activities, and warehouse activities such as picking goods, packaging logistics units, and taking transportation decisions (APICS, 2017). The return process is divided into Source Return agents (SRa) and Deliver Return agents (DRa). These two designate cases when a company is sending material back (SRa) and a material is received from a customer (DRa). Return agents comprise the reverse flow for replacement, maintenance, or disposition. It still includes identifying the reason and scheduling the actions for returning.

In the next level, any Business Process agent (BPa) optionally embraces the execution resources employed. Asset agents (Aa) represent the resources allocated to perform a business process, e.g., a machine agent and a truck agent are subclasses of Make (Ma) and Deliver (Da) agents, respectively.

Traceable Object agents (TOa) represent the level of granularity considered as flowing entities, including an asset agent (Aa), a logistic unit agent (LUa), or an instance agent (Ia) that represents a single item (GS1, 2017), comprising hierarchical relations of composition or decomposition. For example, in a bottom-up perspective, a group of single products, namely instances, form a logistic unit, and an asset may transport either one or multiple logistic units. Instances are also associated with a batch as an intermediary level. These agents' relations are essential to access provenance and correspond to the materials in transit, which are exposed to processes and changing conditions. Despite being mostly passive in decision-making, when equipped with sensors, they turn into smart objects that record and send data to a blockchain.

TOa must have an "identification number" for reference and information retrieval, regardless of its hierarchical level. In addition, those agents may have "Memory to keep KDEs", which implies recording data either to be used as parameters for interactions or to be analyzed as results. These data can be organized in arrays, as shown in Eq. 1, which consolidates the information of multiple CTEs. In Eq. 2, after including the KDEs and additional attributes, the use of an "array of arrays" also known as a "jagged array" is recommended.

$$CTE = \{CTE_1, CTE_2, \dots, CTE_N\} = \{KDE_1, KDE_2, \dots, KDE_n\} \quad (1)$$
$$KDE_i = \{who_i, what_i, where_i, when_i, why_i, attribute_i, \dots, attribute_m\} \quad (2)$$

Blockchain agents (BCa) have attributes to control information sharing and communication among members, by managing permissions of permissioned or permissionless access to read and write data, as well as regulating the public or private participation of new members. Hybrid configurations are also possible (ZHENG *et al.*, 2017). They also address the information to be stored.

Smart Contract agents (SCa) contain conditions to be matched to trigger forthcoming events, following deterministic parameters (CHRISTIDIS; DEVETSIKIOTIS, 2016), that are either predetermined or set after Supply Chain Party agents (SCPa) interactions. These agents are an optional feature and must be linked to a blockchain. They are modeled as agents because they contain parameters that influence the path of other agents.

Blockchain agents and smart contract agents can be subbed in case the user connects the simulation model to an external blockchain platform. Moreover, supply chain parties that are not blockchain members can co-exist in a simulation model. Those have the same characteristics as an SCPa but rely on exchanging information through another database management system co-existing in the model.

Concerning the agentification process, the ADACOR architecture comprises four classes of holons: product, task, operational, and supervisor holons. In a short definition, holons can be understood as the constituent part of a hierarchy. The holons categories from ADACOR are analogously contained in the framework proposed. The Tracing Object agents comprehend entities in transit, similar to product holons. According to their scopes, source, make, deliver, and return agents assume the role of task holons, intermediating the allocation of tasks by transferring dynamic information. A Plan agent coordinates its hierarchical agents, corresponding to a supervisor holon. Asset agents act like operational holons, executing work orders. At last, the interactions are assisted by blockchain and smart contract agents.

Then, the initial and overall parameters of the structure are set, as well as the agents' behavior and attributes (6.3). Flows and rules of interactions must be outlined, considering supply chain situations and traceability conditions (6.4).

The proposed classes of agents offer several possibilities for configuration. Figure 19 exhibits UML collaboration diagrams containing typical examples of agents' interactions.

These interactions are addressed to represent supply chain flows supported by a blockchain to achieve different types of traceability. Both informational and physical flows between the agents are included. The sequence in which the interactions are performed is given by the numbers found nearby the respective arrows. Required flows are indicated through continuous lines, while dashed lines represent optional flows.

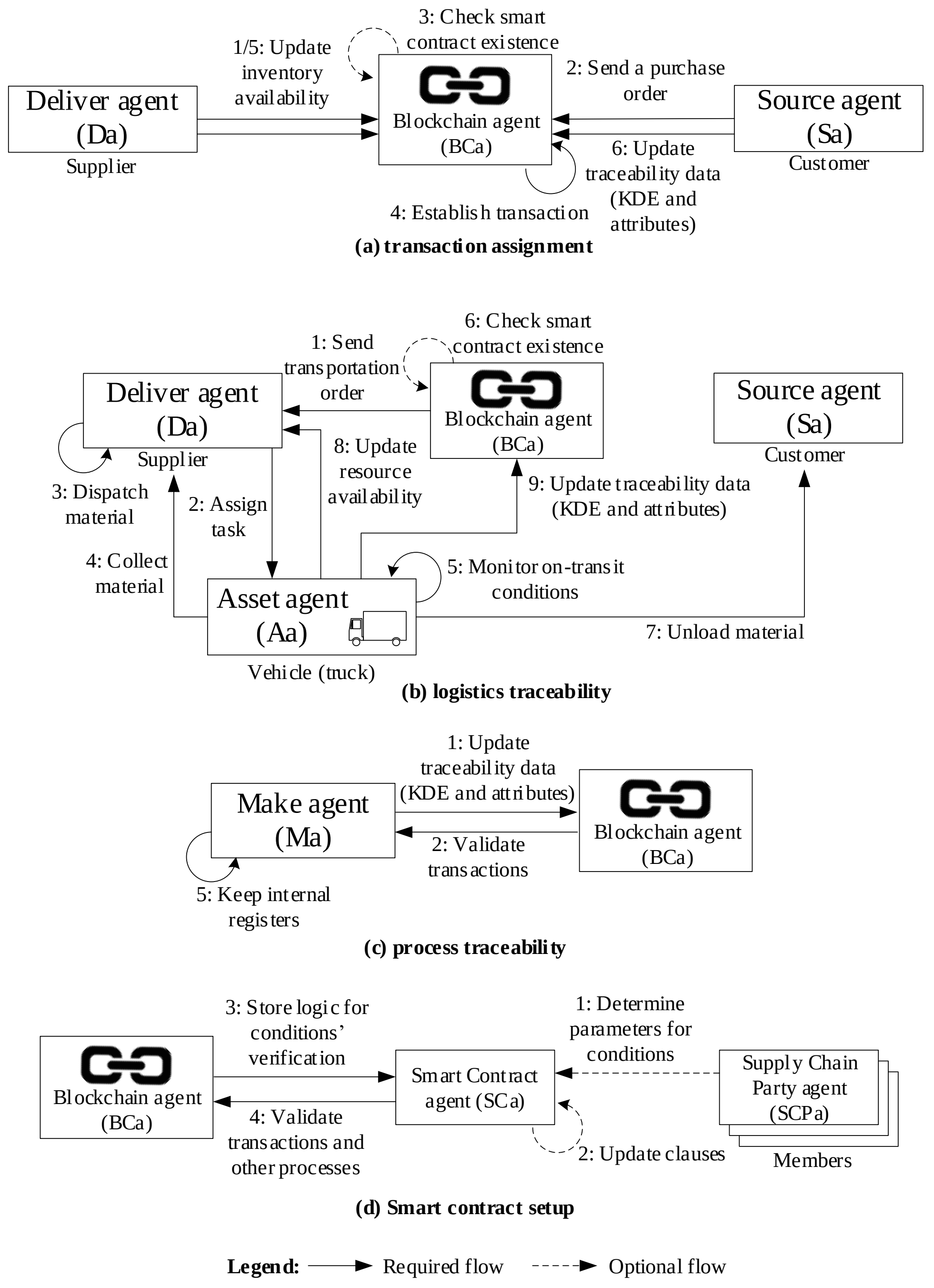
In Figure 19.a, the deliver and source agents of possible unknown supply chain parties establish a transaction at the virtual level, following information about product availability. In case the order is not attended, a backlog is appended to the blockchain for a possible transaction. The dashed line indicates that a smart contract is optional; if it exists, it must be triggered to state the agreement. This interaction involves capturing information about the origin of Traceable Objects agents (TOa), bringing transparency and provenance to the supply chain by keeping the product history concerning one-step-back and one-step-forward flows.

Figure 19.b represents the transference of material between facilities. This case considers the assignment of an asset, i.e., a truck agent. Monitoring the on-transit conditions is possible, assuming the assets involved (vehicles or products) are equipped with sensors and technologies to collect data automatically. Different types of monitoring can be set, namely time-based, location-based, or event-based, for attributes such as temperature, pressure, humidity, and so on. These data may be linked to a smart contract.

Figure 19.c refers to an internal perspective regarding keeping data about transformation processes. Thus, the Make agent gathers traceability information about its subclass of Asset agents (i.e., machines or employees) designated to handle the Traceable Object agents (TOa). From a practical standpoint, this information assists in the identification of root causes and supports initiatives for improvement, considering the resource used and the process itself. In this case, the KDE "where" is related to locations inside the facility.

Figure 19.d refers to defining smart contract updates. The clauses to be checked are either prespecified or defined according to the Supply Chain Parties agents' interactions. In the latter case, updates occur, and the conditions are input into a Blockchain agent, through the inclusion of the optional flow 2. Finally, the smart contract is assigned to validate the clauses' accomplishment. The information traced can be addressed as either raw data or in consolidation. An example is the temperature range during material transportation. Simulation experiments are useful to evaluate smart contracts.

Figure 19 - Examples of typical agents' interactions




The model logic must still contain a way to capture the performance measures previously determined (6.5). Finally, to facilitate communication and keep the model history registered, we recommend providing model documentation according to a structured procedure, such as the ODD protocol (GRIMM *et al.*, 2020) (6.6).

In Step 7, the emphasis is on model implementation. According to the user preference, either an open or a commercial simulation tool is selected (7.1). A list of criteria to assist the selection process is found in Guimarães *et al.* (2018). The simulation is then built (7.2). It is worth mentioning that visual components need to be implemented only if distances are considered under a Geographic Information System or a graph representation. The whole model checking includes examining the agents' social behavior protocols and individual characteristics, as well as the process logic related to discrete-event components (SANTA-EULALIA *et al.*, 2012). According to Sargent (2013), this process is composed of two parts. Verification (7.3) consists of evaluating if the model executes the expected logic statements, while validation (7.4) corresponds to checking the model's accuracy within its domain of application.

In Step 8, the results are analyzed to obtain valid and objective conclusions instead of judgmental ones. Since the techniques for this phase are beyond the scope of this work, we recommend and ground our indications on guidelines found in Montgomery (2017). Building graphical charts is suggested and considered essential due to the support provided for data interpretation (8.1), to observe trends and dispersion, for example.
In terms of statistical analysis (8.2), the approach to be used is defined according to the strategy of experimentation previously set. The performance measure(s) are frequently depicted through the figures of average or standard deviation (MONTGOMERY, 2017). At the last, the user can communicate the results (8.3), while also deriving practical insights to support decision-making processes.

## 4.5 Proof-of-concept application

This section is organized in three parts. First, we describe the main goals of the proof-of-concept. Second, we present a step-by-step application of our framework. Finally, we provide a discussion about the modeling possibilities of the framework proposed.

### *4.5.1 Main goals*

The proof-of-concept application aims to showcase some modeling possibilities offered by our framework, based on an industry-scale application from a live lobster supply chain in Canada. Focusing on the reverse flow, recall effectiveness is evaluated through the experimentation of conditions related to traceability policies and the level of blockchain technology adoption. A blockchain is modeled to represent information sharing and manage distinct profiles of both access and permission.

We address the context situation of a processing company aiming to define the conditions to perform a recall after noticing quality issues. The company is uncertain about the number of lobsters to be recalled and the random formation of lobster batches scatters the units unpredictably. Then, when the recall is initiated, according to the retailers' membership, communication through either a blockchain or a manual method process is provided about which units the retailers must be searching and returning to the processing company. The recall success depends on avoiding end customers receiving products with quality issues.

Based on that, the proof-of-concept application reveals an innovative approach to handling issues of supply chain traceability under different perspectives by integrating the physical and information flows. Our analysis relies on varying the parameters related to four simulation factors, described as follows:

- Time to recall: according to Hall and Johnson-Hall (2021), this is the time comprised between the production or first sale and the recall announcement. Therefore, the instant of initiation refers to the company's agility to react and affects the probability of success by anticipating the selling to the end customers. This element represents the company's ability to quickly benefit from the traceability data stored.
- Maximum per batch: specifying the maximum number of lobsters with quality issues put in a single batch, allowing us to study the product scattering impact on recall effectiveness. In a practical context, this condition outlines an explanation for implementing work standards to control and limit product mixing to deal with conditions of exception. The assumption is that the recall execution would be facilitated by previously separating the units with issues.
- Fishing day: as indicated in the GTS standard (GS1, 2017), determining the KDE "when" is essential to address the collecting of units with quality issues previously released. This parameter refers to the fishing period assumed as a criterion for screening and moderates the volume recalled by setting a temporal range to the lobsters caught.
- Retailers' blockchain membership rate: refers to the number of retailers participating in the private blockchain, i.e., contrasting with the non-blockchain members that share information through manual processes, requiring a longer time. Therefore, this element also embraces information-sharing conditions.

These factors have particularities that complement the proof-of-concept in terms of accomplishing the purpose of emphasizing some of the framework potentialities to model the main components of the Global Traceability Standard (GTS), namely identify, capture, and share (GS1, 2017), while also employing blockchain working scheme.

*4.5.2 Step-by-step application*

In what follows, we present the steps contained in the framework from Figure 17. The model design starts with the problem statement (Step 1). The model is designed to evaluate the effectiveness of a recall strategy (1.1), and its scope is about answering the following question (1.2): “Among factors related to (1) traceability policies and (2) traceability technology usage, which one is the most impactful to recall effectiveness?”

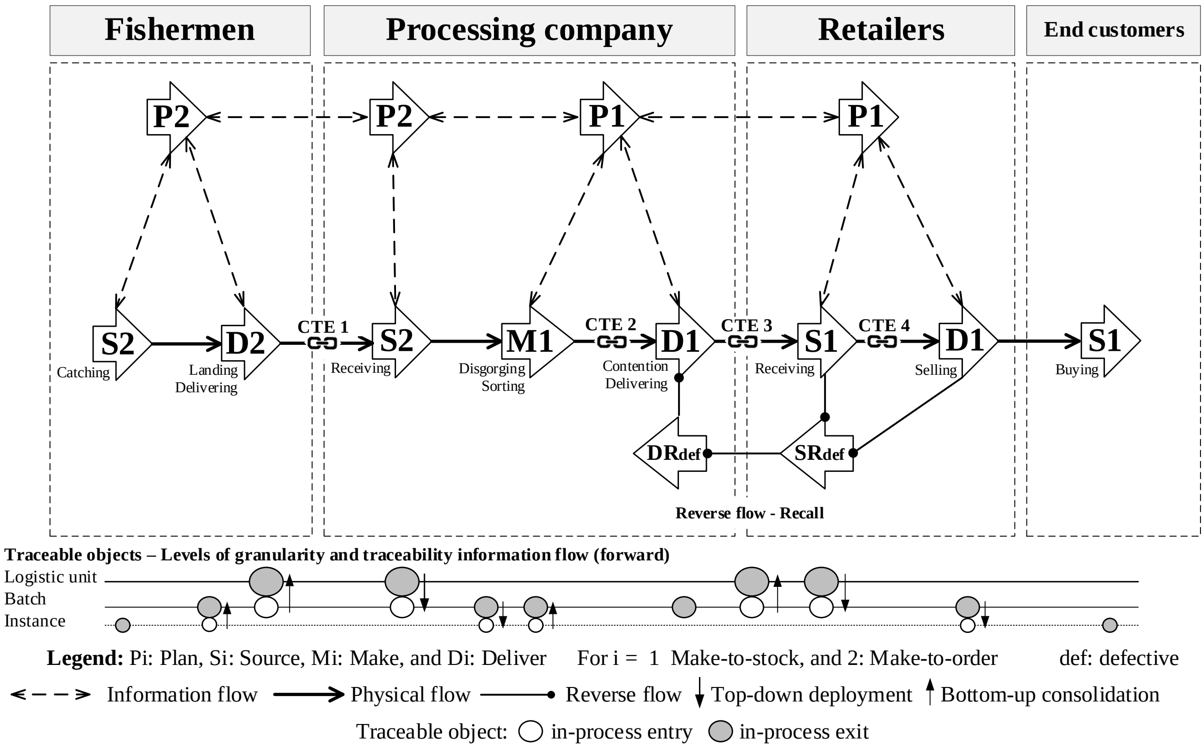
Regarding the context, live lobster fishing is a seasonal activity that lasts about ten weeks during Canadian summer and relies on flexible business agreements. The supply chain operates in a make-to-order scheme since the processing companies establish agreements with fishermen to buy their catch. An individual tag is attached to each live lobster, which will alternatively be transported and handled alive until the point of sale. After landing, the live lobsters are transported in boxes to the buying processing company. The simulation baseline exposed in the next section represents the scenario of this company in terms of traceability practices currently adopted.

After arriving in the processing facilities, the sequence follows a make-to-stock scheme, operated by the order pulled by the retailers. The transformation step comprises a disgorging process in a tank. In the sequence, the live lobsters are sorted according to weight and put in new boxes before being sent to a contention tank for a minimal period. The boxes are transported to the buying retailers, to be finally sold to the end customers. Lobsters reproved in the inspection performed after contention are sent to alternative markets and sold at lower values after being cooked or frozen.

Figure 20 shows a representation of a four-tier live lobster supply chain involving companies from Canada, which also contains information about Steps 2, 3, and 4. Starting with supply chain configuration (Step 2), the overall supply chain structure (2.1) and its members’ roles (2.2) are represented by the business processes from the SCOR model, alongside a brief description posited below the arrows. Structural or role changes are not allowed during the model run (2.3).

In terms of traceability configuration (Step 3), the traceability purpose is classified as “after-delivery” (3.1), since the recall relies on getting items back from the next tier, based on information of destination, involving return processes that compose the reverse flow, indicated by arrows with round ends. Although four CTEs are assigned, the simulation focus is on the last one, posited between the retailers’ internal processes (3.2). This focus is determined as a scope delimitation due to the CTE 4 position in the supply chain flow sequence. Regarding KDEs, the “what” is important to identify the exact lobster. The KDE “who” is essential to link the retailer blockchain membership. At the last, the KDE "when" is required to consider the fishing data as a reference for filtering product identification. KDEs "why" and "where" are not part of the model scope (3.3). The bottom part of Figure 20 provides the granularity level considered across the supply chain (grey circles), and how the traceability information is consolidated in a bottom-up or deployed in a top-down approach, according to the arrow's indications. After these packing and unpacking processes, the recall is performed at the lowest level of granularity, i.e., considering individual live lobsters as products (3.4).

Figure 20 - Live lobster supply chain representation with traceability and blockchain indications




Regarding blockchain configuration (Step 4), a single (4.1) private (4.3) blockchain controlled by the processing company is considered. Membership is predetermined as a controllable factor and kept until the end of the model run (4.2). Both fishermen and retailers can write information on the blockchain, but only the processing company can read the information written (4.4). Smart contracts are not included (4.5).

Concerning performance measuring (Step 5), the response variable (5.1) considered is "Recall effectiveness", which refers to the percentage of affected products removed from the supply chain before reaching the end customer. This value represents the performance of the traceability system, considering the policies and practices adopted. Completing Step 5, once we are not interested in exploring the interaction between factors, we adopt the experimentation strategy "one-factor-at-a-time" (OFAT) (5.2). As indicated by Montgomery (2017), this strategy consists in establishing a baseline, containing the initial values for each factor. In the sequence, one factor is varied, while the others are kept constant. This approach helps to analyze the impact that each factor has on the response variable. Table 14 lists the baseline values and the range of the parameters utilized for each factor, which are described in Section 5.1. Three factors are controllable and represent managers' decisions. In contrast, the only exception is the second factor, namely "products mixing", which is a "virtual limit" that aims to reproduce environmental conditions for testing purposes, but it is impossible to be controlled in practice.

Table 14 - Values for the one-factor-at-a-time experimentation

| Factor | Baseline | Range | Increment | Controllable | Category |
|---|---|---|---|---|---|
| Time to recall | 105 | 100-125 | 5 hours | Yes | Managerial |
| Maximum per batch | 3 | 1 - 6 | 1 unit | No | Managerial |
| First fishing day considered | 2 | 2-5 | 1 day | Yes | Managerial |
| Retailers' blockchain membership rate | 0% | 0-100% | 25% | Yes | Technological |

After having a suitable picture of the application context, the model development is initiated. Starting model specifications (Step 6), the simulation model is defined as a hybrid one (6.1). The flow of lobsters follows the discrete-event paradigm, and the traceability practices under blockchain communication rely on the agent-based simulation approach.

To understand the agents' deployment (6.2), it is essential to observe Figure 20. Supply Chain Party agents, i.e., fishermen, processing companies, retailers, and customers are decomposed according to the SCOR processes, and for the sake of simplicity, no asset agents are included. Regarding Traceable object agents, the focus of the recall is on Instance agents, which represent the individual live lobsters. However, the packing, unpacking, and repacking processes are indicated in the bottom part of Figure 20, and transient logistic units (batches) are fundamental to set product mixing. The characteristics of the single blockchain are as parameters of an agent, and no smart contract agent is included. A recall order agent is also added to regulate the actions to be performed.

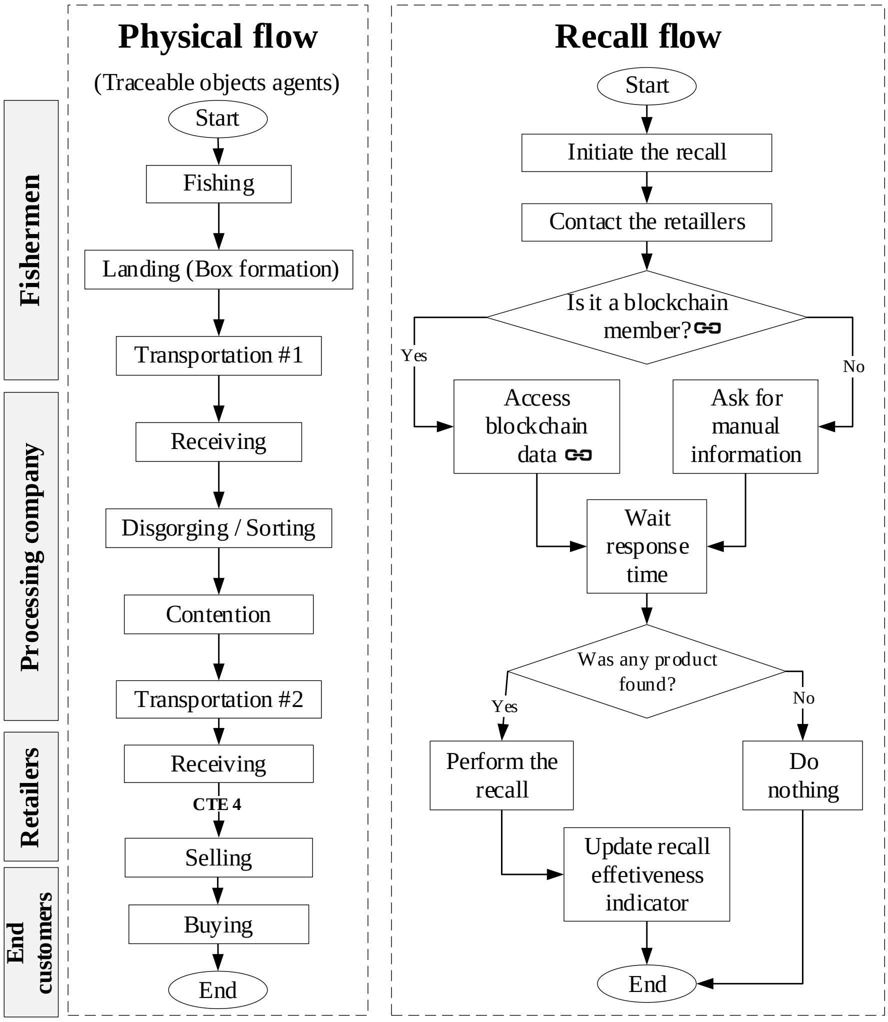
Table 15 contains the structural and behavioral parameters input in the hybrid simulation model (6.3). Figure 21 synthesizes the interactions to represent a recall in the live lobster supply chain (6.4). On the left-hand side, the physical flow indicates the path of product agents from fishing until reaching the end customer. On the right-hand side, the recall order agent is released in the instant of recall initiation and sets communication with retailer agents, regulating parameters for the search of products to be collected, whether the retailer uses manual-based or blockchain-based traceability processes, according to its attribute of membership. Therefore, according to ADACOR architecture (LEITÃO; RESTIVO, 2006), the recall order agent assumes the role of a supervisor holon, in charge of articulating the activities related to the return processes. In the last part of this flow, the performance indicator "recall effectiveness" is updated (6.5). Both Table 15 and Figure 21 contain important components of model documentation (6.6).

Table 15 - Overview of simulation model parameters

| Cat. | Parameter description | Value or range of values | Type |
|---|---|---|---|
| *Supply chain structure* | | | |
| | Fishermen | 10 parties | C |
| | Processing company | 1 party | C |
| | Retailers | 100 parties | C |
| | Fishing generation rate | 270-320 units/fisherman/day (discrete uniform dist.) | R |
| | Load assignment to retailers | 1-100 (discrete uniform dist.) | R |
| | End customer demand rate | $60 \pm 25$ hours (normal dist.) | R |
| | Box capacity | 30 lobsters | P |
| | Vessel capacity | 20 boxes | P |
| | Truck capacity | 40 boxes | P |
| | Maximum per batch | 1/2/3/4/5/6 quality issues | E |
| | Transportation time 1 | $4 \pm 2$ hours | R |
| | Transportation time 2 | $10 \pm 2$ hours | R |
| *Quality issues generation* | | | |
| | Days 2/3/4/5 | 30/60/100/70 units | P |
| *Blockchain and traceability information* | | | |
| | Retailers' membership rate | 25/50/75/100% | E |
| | Response time blockchain members | 8 hours | P |
| | Response time non-blockchain members | 60 hours | P |
| *Recall configuration* | | | |
| | Instant of initiation | 100/105/110/115/120/125 hours | E |
| | Fishing day (period considered KDE when) | 2-5/3-5/4-5/5 days | E |

Where: C: constant, P: predetermined, R: random parameter, and E: factor under experimentation.

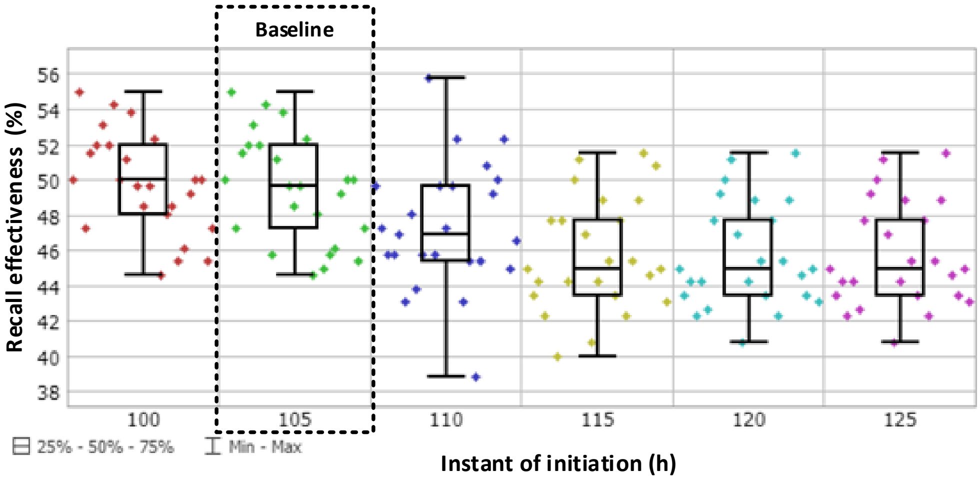
Figure 21 - Model overview



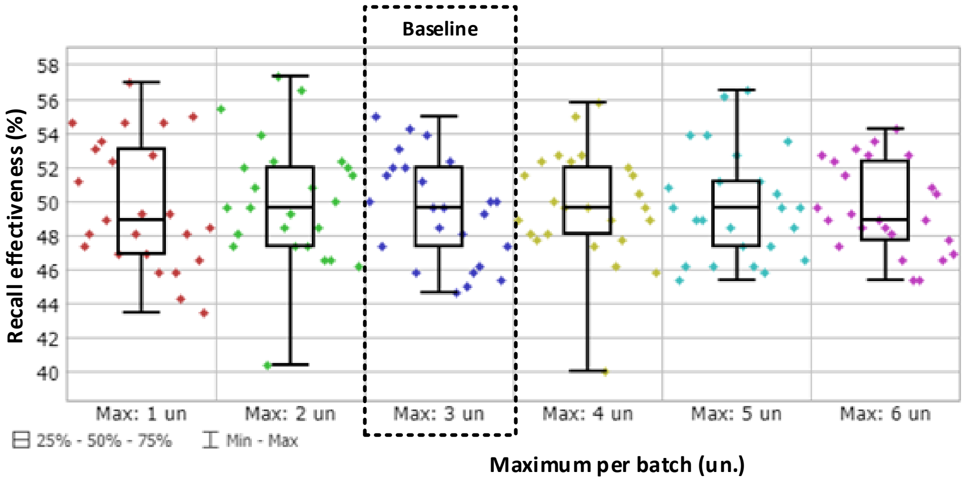

For the model implementation (Step 7), we have used FlexSim® and its "Process Flow" tool, with a 2D interface (7.1). Once the model was built (7.2), we carefully performed verification (7.3) rounds, starting with small quantities of agents and varying parameters to observe the behavior of parts of the logic separately. Similarly, validation was taken by checking the model's ability to recall product agents under expected conditions and within the due time (7.4). The model is run as a finite horizon simulation since the focus is on the recall actions.

For output evaluation (Step 8), we build the graphics (8.1) presented in Figure 22, containing the results obtained with one-factor-at-a-time experimentation. The boxplots consider 25 replications.

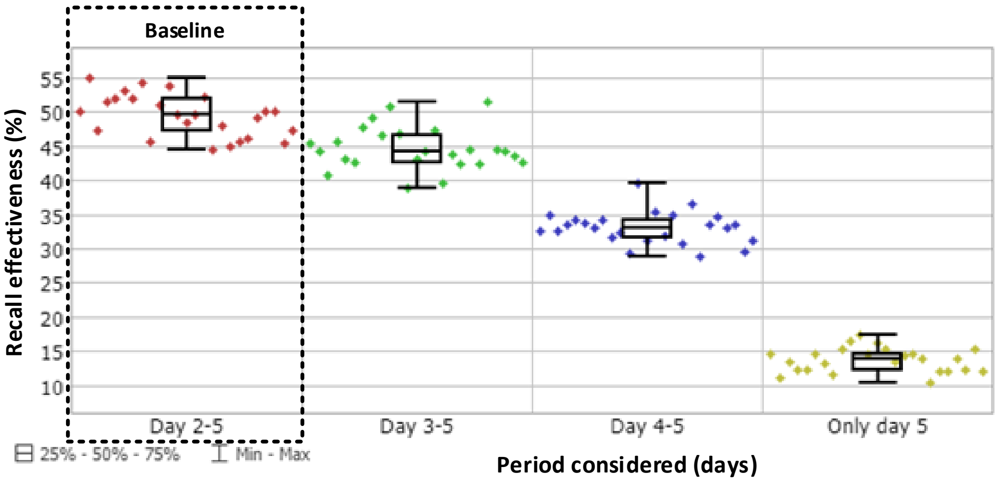
Figure 22 - Scenarios results varying the factors individually



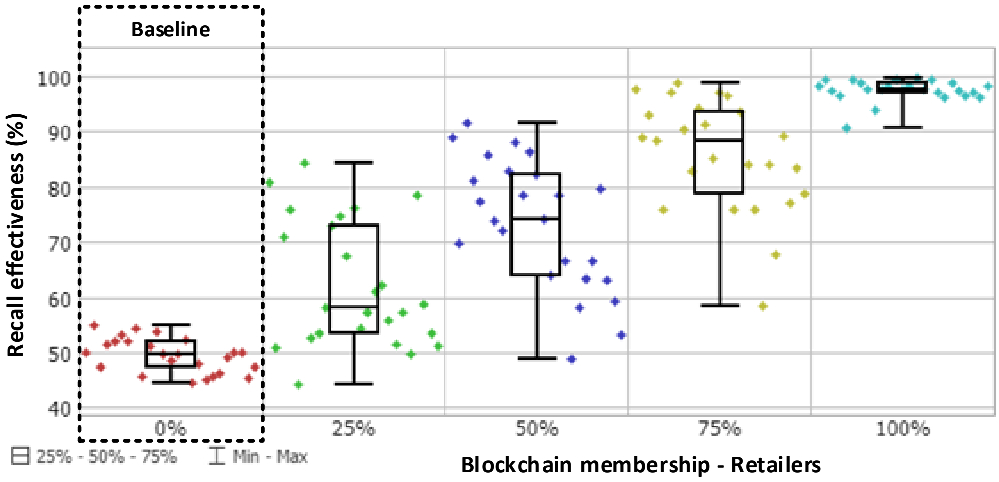

(a) Time to recall – Instant of initiation




(b) Maximum per batch – number of units with quality issues




(c) Fishing day – KDE when




(d) Retailers' blockchain membership rate

Regarding the recall initiation, Figure 22.a reveals that anticipating the collection before instant 105h seems to not bring any significative impact because the searched units have not gone through the supply chain steps. On the other hand, as expected, taking longer to initiate recalls negatively affects recall effectiveness. So, this modeling approach measures the processing company's agility to react and start the recall.

For the only non-controllable factor, Figure 22.b shows that the fact that items had been randomly distributed in batches has a low impact on the response variable. Based on that, it is possible to indicate that efforts to keep the live lobsters separated or grouped by provenance are not recommended, mainly considering that a recall is not a regular task. Despite that, this modeling approach reveals its ability to deal with the lowest granularity level, i.e., product agents.

Concerning traceability information, Figure 22.c highlights the importance of having the fishing date of individual products. This data is employed to set the temporal boundaries for the product search to perform a recall. As it is shown, keeping day three apart from the recall screening, and thus starting to consider live lobsters caught from Day 4 onwards, brings a negative impact on recall effectiveness. This impact is even more critical if day four is also omitted, and only live lobsters caught on Day 5 were considered. In this case, the modeling approach highlights its potential to align physical and virtual flows by showing the value of identifying and capturing proper information, as recommended by the GTS standard (GS1, 2017), involving the KDE "when".

Figure 22.d focuses on the usage of blockchain technology in the traceability process to assist the recall. In the ideal conditions of full blockchain participation, recall effectiveness is

near 100%, about two times higher than the baseline, and relevant improvements are also obtained from rates of 50% and 75% of retailers' membership.

In conclusion, this section communicates (8.3) that the level of blockchain technology adoption is individually more impactful to the baseline traceability practices. However, the recall performance still relies on the correct assessment of recall policies to maximize the blockchain potential for sharing information.

*4.5.3 Discussion*

From the simulation standpoint, the proof-of-concept has demonstrated the framework's suitability to model different aspects of supply chain traceability considering blockchain communication. In terms of traceability practices, the "time to recall" factor depicts an agent's autonomous behavior, while "Maximum in a batch" reflects a rule attached to product agents, and "fishing day" is an example of a communication parameter. Regarding the technology perspective, the retailers' blockchain membership rate embodies a parameter of the supply chain taken as an environment, further delineating interactions of communication between the processing company and retailers, situated in different tiers.

A principle of modularity is noted, since some logic blocks can be optionally included according to the model scope, i.e., the traceability purpose adopted. Moreover, submodels play an important role in setting the behavior and configuring the interactions among agents. So far, adopting ADACOR architecture (LEITÃO; RESTIVO, 2006) provides interesting features of modularity and scalability to the model and of decentralization and autonomy to the agents, which supports our integrative approach among different classes of physical and logical agents, established at the individual and social levels, as stressed by Santa-Eulalia *et al.* (2012), and addressed in Figure 19.

Beyond the quality-related example provided in the proof-of-concept, from the traceability perspective, the framework versatility covers logistics, sustainability, processing, and provenance issues. Regarding blockchain aspects, modeling possibilities include assessing implications such as membership acceptance criteria, the number of members involved, permissions conceived, and frequency of information updates. Additional possibilities embrace validating smart contract parametrization and a multiple blockchain arrangement. Thus, the framework reveals its practical relevance by being versatile in building simulation models to explore traceability regarding methodology, technology, instrument, and solution, aspects listed by Corallo *et al.* (2020), and thus assist modelers, decision-makers, and policymakers.

Lastly, it is important to emphasize that, according to the requirement analysis provided by Dorigatti *et al.* (2016), our framework puts forward all five valuable capabilities for simulation modeling of collaborative supply chains, as explained next:

- Reusable components: a variety of scenarios may be derived from a basic model structure, allowing the exploration of both physical and virtual aspects of a supply chain.
- Dynamic links: a predefined and fixed network structure is not demanded; in contrast, the dyads are set in a flexible and updatable way considering information sharing.
- Business process orientation: the SCOR model and the GTS standard are integrated to address the orchestration and componentization of supply chain and traceability elements, respectively.
- Explicit Control and Decision Making: the interface of decision rules with physical flows is set through attributes and logic assigned separately to specific classes of agents.
- Message-Based Interaction Protocols: based on the level of granularity and context particularities, different configurations may be used to transfer and access information, establishing a flow of communication between involved agents to achieve traceability.

## 4.6 Conclusions

This work proposed a methodological framework comprising guidelines to develop hybrid models to simulate supply chain traceability practices under blockchain communication, which were applied in a real proof-of-concept case in a live lobster supply chain from Canada. Blockchain technology was considered due to its potential to leverage supply chain traceability performance through its distinctive characteristics.

We have integrated different well-established approaches to propose a novel framework to model and simulate supply chain traceability, which is adaptable to specific problems through definitions of granularity and information sharing. Moreover, the simulation models built with the support of the framework proposed can assist the design, configuration, and selection of traceability systems and the determination of information-sharing schemes, thus collaborating with decision-making processes.

From the simulation standpoint, the agent-based architecture supports the agentification process, while the model scope and agent characteristics are also explored. Another important contribution comprises the possibility of developing hybrid models, by combining the agent-based with the discrete-events simulation paradigm.

Among the limitations, this work does not include technical aspects of blockchain working logic. Since the focus is on the managerial implications of blockchain for supply chain management, the consensus mechanism is not part of the scope. Smart contracts would also be simplified in the modeling. Including these components would permit the evaluation of issues of security and latency through simulation models.

Future research should focus on applying the framework in different contexts, such as a non-discrete transformation process, to address its inherent particularities for traceability. Alternatively, incorporating learning abilities into agents through advanced algorithms would also enrich the agents' decision capabilities and contribute to more sophisticated configurations.

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# 5 EXTENDING SUPPLIER EVALUATION HORIZONS THROUGH BLOCKCHAIN-BASED TRACEABILITY: A SIMULATION APPROACH

In this chapter, a hybrid simulation model is developed to evaluate supply chain network structures considering traceability data stored on a blockchain representation. The model development is made based on the framework presented in the previous chapter, and a multicriteria method is included to enrich the agents' decision-making ability.

The content presented in this chapter is intended to be submitted to an international peer-reviewed journal.

**Abstract:** Supply chain networks emerge from contracts and transactions, creating both steady and temporary links. In contrast, supplier evaluation may lead to a link interruption if the performance is considered inadequate or insufficient according to the previously agreed-upon standards. Therefore, the virtual information network inherently influences the physical network configuration and its alterations. In this context, this paper explores the impact of blockchain-based traceability for single- and multi-level supplier evaluation. To achieve this objective, we developed a hybrid agent-based discrete simulation model following the Design Science Research paradigm. Agents representing supply chain nodes encapsulate a cognitive decision-making model based on the multicriteria method known as the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). We investigate a real four-tier live lobster supply chain from Canada, initiating with a pre-fixed structure. Three scenarios are proposed from different traceability practices and information-sharing schemes, which are analyzed through the lens of network theory. Our results reveal that blockchain enables and extends a single-level supplier evaluation process, as well as enhances a multi-level supplier evaluation process, going beyond a one-step-back traceability approach, thereby bringing higher supply chain visibility, and ultimately influencing its network structure and dynamics.

**Keywords:** supply chain management, supplier selection, agent-based modeling and simulation, distributed-ledger technology, traceability system, performance evaluation, TOPSIS.

## 5.1 Introduction

A supply chain comprises the alignment of information, capital, and product flows, leading to the coexistence of virtual and physical networks. Different configurations are established according to the interactions performed between parties, following trading agreements and business strategies (MENTZER *et al.*, 2001).

In the current digital transformation and Industry 4.0/5.0 era, disruptive technologies have emerged as potential alternatives to leverage supply chain management, bringing more assertiveness to decision-making by offering consistent information capturing and sharing possibilities, even in real-time (CORALLO *et al.*, 2020). One of the alternatives that have been widely discussed in the literature and practice is blockchain, which is classified as a distributed ledger technology and possesses a particular working logic that makes information immutable, permanent, and verifiable, allowing disintermediation and changing trust paradigms (RISSO *et al.*, 2023a; COLE; STEVENSON; AITKEN, 2019; KSHETRI, 2018).

In practical terms, blockchain is assumed to be an inter-organizational information system that embodies a data network to promote information sharing between trading partners, thus reducing information asymmetries (TAN *et al.*, 2023). Moreover, blockchain enhances transparency and enables end-to-end traceability (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018). These distinctive features are suitable to a context in which successive trades derive unpredictable networks and require a structured approach to the performance evaluation of involved parties. While the interplay of blockchain technology and supply chain management has been largely examined in the literature, a recent tertiary review of the literature (RISSO *et al.*, 2023a) suggests there is a research gap in understanding its implications from the perspective of both single and multi-level supplier evaluation processes, going beyond a traditional “one-step-back” traceability approach, especially when viewed through the lens of network theory (TREIBLMAIER, 2018).

Supplier evaluation is a crucial aspect of supply chain management and influences decisions regarding contract renewals and the establishment of new partnerships. Network theory offers a framework to comprehend the intricate interactions, relations, and dependencies among parties in a supply chain (HALLDÓRSSON; HSUAN; KOTZAB, 2015). Network evolution was previously studied under the network theory prism through a retrospective analysis to evaluate risks (LI *et al.*, 2023). However, the authors have neither considered blockchain technology nor performance evaluation. In this context, the intersection of blockchain technology, supplier evaluation processes at both single and multi-levels, and network theory remains underexplored.

This research void leaves critical questions about how blockchain-based traceability systems can impact supplier evaluation processes and, consequently, the structure and dynamics of supply chain networks. Therefore, this paper aims to explore the impact of blockchain-based traceability for both single- and multi-level supplier evaluation.

We adopted a Design Science (HEVNER *et al.*, 2004) research design, allowing us to develop a novel hybrid simulation model, combining agent-based and discrete-event paradigms. Such combination is widely recommended to represent supply chain networks (SURANA *et al.*, 2005; PATHAK *et al.*, 2007; HEARNSHAW; WILSON, 2011; OLIVEIRA; LIMA; MONTEVECHI, 2016; PERSSON, 2011), due to the possibility of setting the individual behaviors and decision rules to the actors. Agents representing nodes in the supply chain incorporate a cognitive decision-making model grounded in the multicriteria method Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), originally proposed by Hwang and Yoon (1981). Instead of relying on post-fact data, a dynamic accumulation of performance data is considered, achieving high visibility and transparency. The integration of simulation modeling and multicriteria decision-making also presents relevant research opportunities (LIM *et al.*, 2021).

Our proposal also includes communication protocols among agents to represent a blockchain platform, aiming to investigate the impact of sharing traceability data to achieve higher precision in supplier performance evaluation. In addition, a novel dynamic approach is introduced since we are interested in analyzing supplier performance throughout a time frame. In contrast to a cross-sectional approach that uses data reported at one point in time, a dynamic approach reduces the chances of obtaining biased findings when dealing with non-linear relationships (PAUL *et al.*, 2021).

This chapter is structured as follows. Section 5.2 provides the background concerning supply chain traceability and network theory in the context of blockchain technology. Section 5.3 presents the research design adopted. Section 5.4 describes the hybrid simulation model based on a real case application, including its working logic, parameters considered, and scenarios deployed. Section 5.5 brings the results obtained, and Section 5.6 presents the discussion. Finally, Section 5.7 closes our research with the final remarks, limitations of the work, and suggestions for future research directions.

## 5.2 Conceptual and theoretical background

### *5.2.1 Supply chain traceability and blockchain technology*

Blockchain technology has been extensively studied in terms of its huge potential for supply chain management (RISSO *et al.*, 2023a), which goes beyond operations and encompasses aspects of supply chain design and organization (SABERI *et al.*, 2019). More specifically, supply chain traceability is among the most promising applications of blockchain (AHMED; MACCARTHY, 2023), considering that it can recognize the source and reproduce the transactions' timeline of a product (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018).

In addition to identifying the actor responsible for each action, information about time and location is also stored (KSHETRI, 2018). The visibility provided is extended, as blockchain can also be employed as an inventory and registry system for recording, monitoring, and transacting tangible, intangible, or digital assets (WANG *et al.*, 2019), embracing documents such as purchase orders, shipping manifests, and invoices (COLE, STEVENSON, AITKEN, 2019).

Supply chain particularities such as the number of suppliers and the characteristics of production, packaging, warehousing, and distribution processes make standardization essential for establishing a traceability process (BEHNKE; JANSSEN, 2020). Another relevant decision regarding traceability practices is related to the number of stages considered and the level of granularity monitored (AHMED; MACCARTHY, 2023). There is also a need for a consensus among the parties about the type of data captured, and its level of detail (BEHNKE; JANSSEN, 2020) since data integration typically follows a one-to-many scheme (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018).

The working logic of blockchain leverages transparency and information security, improving traceability safety, and efficiency (FENG *et al.*, 2020). Furthermore, the embedded principle of immutability assures the reliability and authenticity of information and enables data traceability, but there is still a dependency on other technologies to capture real-time information (SABERI *et al.*, 2019).

In another perspective, the blockchain promotes continuous traceability supervision. Besides simplification, automating traceability-related functions through smart contracts enables cost reductions. The identification of the cause and extent of problems also benefited from the information found in traceability systems. However, due to trust issues, attention must be paid to the integration of heterogeneous data and non-sharable traceability records kept by supply chain parts (CASINO *et al.*, 2020).

In practical terms, traceability is related to three types of information across value-adding stages: “provenance and sourcing”, “product-related environmental impact information”, and “product transportation and storage conditions”. Moreover, factors regarding product characteristics, such as value and safety, and supply network configuration characteristics, such as size, geographical expansion, and complexity influence the traceability system configuration (AHMED; MACCARTHY, 2023; TREIBLMAIER, 2018).

Alternatively, traceability comprises five categories of information, namely: product-related, process-related, facility-related, transport-related, and sustainability-related information (UNECE, 2021). In a comprehensive approach, the definition of which category must be captured is determined by the traceability scope, also considering aspects of purpose, regulatory compliance requirements, supply chain configuration, and capabilities of technologies available (AHMED; MACCARTHY, 2023).

The potential of blockchain-IoT combination is stressed for cold chain applications, by providing control of physical parameters such as temperature and pressure and attending to issues of perishability (POURNADER *et al.*, 2019). Applicability is also mentioned for measuring product parameters during transportation, monitoring quality (KSHETRI, 2018), handling product shelf life in stores and delivery contracts based on logistics performance (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018), exploring the accelerated sharing of data provided by blockchain (TAN *et al.*, 2022).

In a broader view, other applications designated for blockchain in supply chain management include players’ identification and newcomers’ validation (FERREIRA; PALAZZO; CARVALHO, 2023) and players classification and efficiency measurement (PAUL *et al.*, 2021), collaborating for the continuous improvement of parties involved (FENG *et al.*, 2020).

Transformations provided may also impact inter-organizational relationships and consequently bring other management issues mainly by offering trustful information flows and by linking unknown parties (TREIBLMAIER, 2018). In the same direction, dynamic changes in relationships are expected, based on possible benefits from better visibility of information (SABERI *et al.*, 2019). Aspects related to inter-organizational relationships in supply chains are frequently studied under the lens of the network theory, as explained in the next subsection.

*5.2.2 Network theory and blockchain-based traceable supply chains*

A network is formed by a set of nodes linked by a set of connections, which establish or restrain paths for flows. These links can be seen as pipes or roads that can interconnect nodes that are not straightly tied. Each network has a structure and its characteristics' implications (HEARNSHAW; WILSON, 2011).

Connections are divided into two categories. State-based connections are described according to strength, duration, and intensity, being open and terminable. Event-based connections are discrete and countable, characterized by their frequency of occurrence, and suitable to represent recurring patterns (BORGATTI; HALGIN, 2011). In terms of continuation, a business network is maintained by exchange processes, including information, social, and business interactions, as well as by adaptation processes, regarding products, routines, and outputs (PAUL *et al.*, 2021).

Network theory primarily focuses on the processes and mechanisms governing inter-organizational interactions within a network configuration, which yield outcomes for individuals or groups. These outcomes are influenced by the number of connections within the network (TREIBLMAIER, 2018). According to this framework, there are two categories of outcomes. The first, "choice", pertains to behaviors, attitudes, and internal structural characteristics. The second, "success", is assessed at either the node or network level and encompasses performance and rewards (BORGATTI; HALGIN, 2011).

One topic of interest in the network theory is the impact of an actor's position on the quantity or timing of flows received, aiming to correlate the role of the network structure and the nodes' attributes on the outcomes obtained (HALLDÓRSSON; HSUAN; KOTZAB, 2015). Moreover, network theory also embraces topics related to inter-organizational trust, information sharing, and mutual adaptation of relations structures (TREIBLMAIER, 2018).

Different insights are found among the works that address blockchain through a network theory lens. With an analytical approach, Yousefi and Tosarkani (2022) focus on identifying blockchain adoption enablers and their impact on minerals supply chain performance, embracing sustainability aspects. The use of smart contracts to increase traceability and transparency is emphasized. Similarly, Paul *et al.* (2021) also investigate sustainability issues, considering the organic tea supply chain, and indicate that competitive advantage and quality of business relationships positively link transparency and reliability.

Ferreira, Palazzo, and Carvalho (2023) explore the implication of blockchain to the structure of additive symbiotic networks, mainly on the strength of relationships. Besides reducing intermediaries and adapting value flows, changes in stakeholders' power distribution are also expected. Tan *et al.* (2023) focus on the possible improvements that blockchain provides, mainly considering the impact of supply chain integration. According to the perspective adopted, the visibility achieved collaborates to support the synchronization between partners, leading to performance enhancements.

In addition, Treiblmaier (2018) indicates several research directions anchored on the network theory concerning both the role and the management of inter-organizational relationships, highlighting the analysis and explanation of changes stimulated by blockchain solutions. Aspects related to business relationship quality, partners' trust, and information transparency are emphasized through promising middle-range theorizing angles.

Among the existing works regarding blockchain through a network theory lens, qualitative approaches are predominant (TAN *et al.*, 2022; PAUL *et al.*, 2021; FERREIRA; PALAZZO; CARVALHO, 2023). Yousefi and Tosarkani (2022) and Treiblmaier (2018) adopt analytical and theoretical approaches, respectively. Therefore, quantitative empirical evidence is suitable to complement these findings and extend the knowledge in the field.

From another perspective, regarding the simulation works involving blockchain, discrete-event and agent-based simulation models were built to investigate the benefits of prefixed supply chain arrangements (MANUPATI *et al.*, 2022; LOHMER; BUGERT; LASCH, 2020). Thus, none of them explored variations on the network structure considered. Alternatively, Saltini and Akkerman (2012) proposed a simulation model to explore a traceability system to analyze production efficiency and recall size without involving blockchain. However, the proposal is anchored on strategies to avoid raw material mixing and does not consider the monitoring of processing transportation parameters.

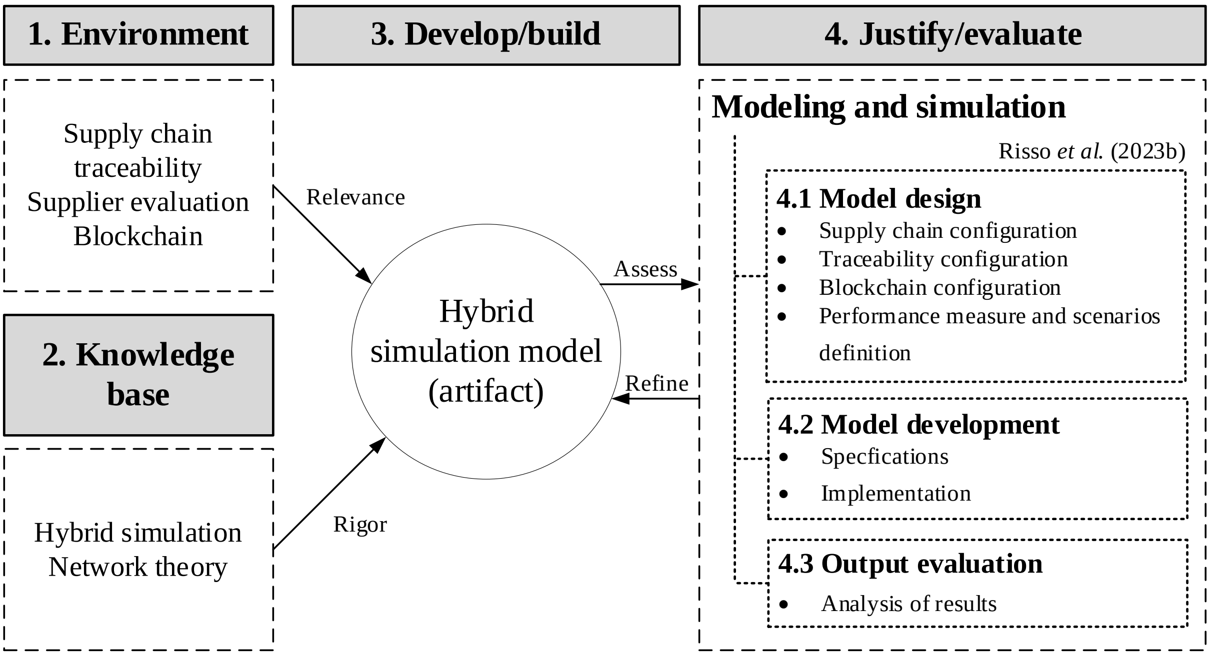
While these papers have made significant contributions, there is a noticeable gap in the literature from a network theory perspective, especially when it comes to the usage of simulation-based methods (HEARNSHAW; WILSON, 2011; TREIBLMAIER, 2018). Among these methods, agent-based simulation stands out for its ability to model complex distributed systems like supply chain networks (OLIVEIRA; LIMA; MONTEVECHI, 2016). This approach offers valuable insights into the intricate interactions between nodes of the supply chain network. More specifically, it can simulate the behavior of individual entities and their social interactions, shedding light on information flows across the network, trust establishment, and the impact of disruptions on the overall network. Integrating the supply chain with another distributed system, such as blockchain, further enhances the relevance of this approach (MANUPATI *et al.*, 2022; LOHMER; BUGERT; LASCH, 2020).

Thus, to contribute to bridging this research gap, this study employs the principles of network theory to examine supplier evaluation when a blockchain-based supply chain traceability system is adopted, using a hybrid simulation model, as explained in the next section.

## 5.3 Research design

This work follows the Design Science Research (DSR) approach, as prescribed by Hevner *et al.* (2004), aiming to establish scientific rigor in a creative proposal related to a context with practical relevance. After emerging in the information system field, DSR has been frequently applied in engineering to guide the building process of new artifacts, which includes systems, algorithms, models, and frameworks (PEFFERS *et al.*, 2007). The DSR cycle of development is synthesized in Figure 23. The modeling approach is detailed in the right-side part. Cycles of verification and validation are performed to ensure the model logic is working as expected.

Figure 23 - Research approach based on the Design Science Research paradigm




**Source:** adapted from Hevner *et al.* (2004).

The creative process is initiated by identifying a problem or a business demand. Alternatives to deal with the situation are listed according to the knowledge found in the literature and technical databases, considering other feasible approaches. Then, an assessment is provided through empirical tests or simulation, and the proposed artifact is improved iteratively. This iterative refinement cycle is usually recommended for future studies (HEVNER *et al.*, 2004).

As depicted in Figure 23, the environment elements (1) stress the relevance of the interplay between supply chain traceability, supplier evaluation, and blockchain, while the knowledge base (2) attests to the topics adopted to provide rigor to the approach, namely hybrid simulation and network theory. At the heart of the DSR cycle is the artifact. In our case, it stands for the development (3) of a novel hybrid simulation model anchored on the agent-based paradigm employing discrete-event mechanisms for assessing the impact of information sharing on performance evaluation considering supplier ranking updates.

The development of this simulation model follows the methodological framework proposed by Risso *et al.* (2023b), which also provides support for justifying and evaluating modeling choices (4). This framework aims to guide modelers to create and test blockchain-based traceability systems using hybrid simulation models. The advantage of using this approach is the integration of concepts from foundational references for scholars and practitioners, such as the Supply Chain Operations Reference (SCOR) (APICS, 2017) model and the Global Traceability Standard (GTS) (GS1, 2017). In addition, it is anchored on the ADACOR holonic architecture (LEITÃO; RESTIVO, 2006) for the agentification process. In a nutshell, the sequence proposed in the framework presented by Risso *et al.* (2023b) supports both the assessment and the refinement of the artifact under development, as the framework assists modelers in identifying the main aspects of the supply chain under analysis, as well as it addresses the blockchain working logic, the traceability elements to be included, and the characteristics of the agents to be represented.

In addition, to better capture the complexity of the agent's cognition, we have integrated a multicriteria method to enrich the agents' decision-making ability, using the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Since each agent needs to make their own decisions, the TOPSIS multicriteria method is used to allow agents to function as decision-makers based on the elaboration of rankings of alternatives (i.e., suppliers according to their performance). This method is particularly useful when dealing with complex problems where trade-offs between conflicting criteria need to be made. By providing a systematic and objective way to compare alternatives, TOPSIS helps ensure that the chosen solution is the most balanced and optimal one according to the defined criteria (BEHZADIAN *et al.*, 2012).

Next, following the DSR protocol, the artifact is instantiated as a proof-of-concept application, employing real-scale data from a live lobster supply chain from Canada. The selection of the application case considered the economic relevance of the seafood supply chain and the recent interest in adopting technologies to enhance traceability practices using data-sharing alternatives (CHIKHI *et al.*, 2022). Through the development of industrial partnerships, the research team has had access to real data about the supply chain investigated, including transaction database files, field observation during visits in loco, and interviews with experts who are members of companies from different supply chain tiers. These data are essential to set the supply chain dynamics and the interactions in the hybrid simulation model.

Finally, the conceptual model was at first validated with the assistance of domain experts, aiming to obtain consistency about information and material flows, number of network parties, and performance indicators adopted. The computational model was verified and validated through both degenerated tests and extreme conditions tests (SARGENT, 2013), including experiments. Agents' performance was examined through a careful examination of results and the comparison with input data.

## 5.4 Modeling and scenarios

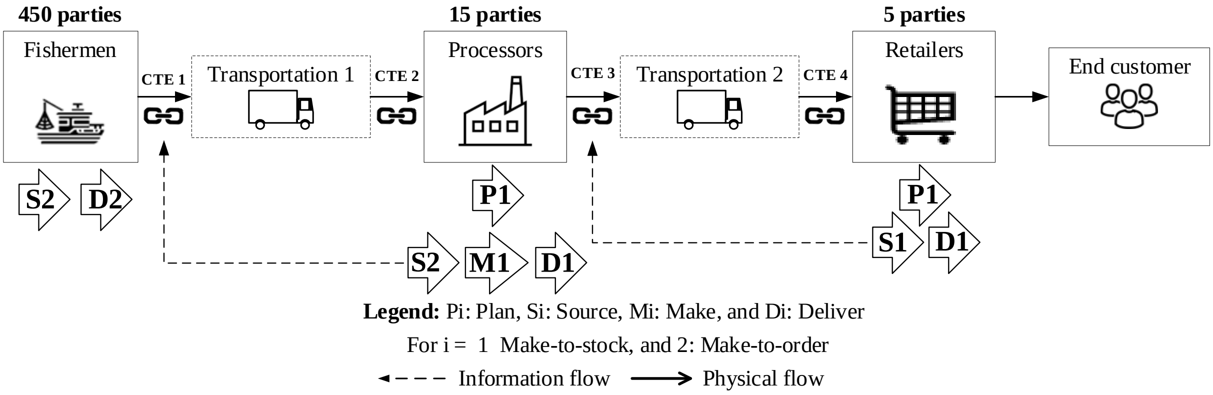
This section contains four parts. The first part describes the live lobster supply chain, based on a real case from Canada. In the second part, we give details about the characteristics of the hybrid simulation model, including its working logic and the descriptions of the agents' interactions. In the third part, we present the definition of criteria used to evaluate suppliers' performance. Finally, in the fourth part, we specify the scenarios considered for analysis and the output obtained from the simulation runs.

### *5.4.1 Supply chain context*

Our scope encompasses the first three tiers of a four-tier live lobster supply chain. End customers are not part of the scope, as we are interested in organizational supply. We consider the possibility of interaction between four hundred and fifty fishermen teams, fifteen processors, and five retailers. All these entities are modeled as autonomous agents.

Figure 24 shows the physical flow of goods and the virtual flow of information alongside a representation following the SCOR model (APICS, 2017). The connections between the parties are designated after the transactions are established, which optionally considers the traceability data shared in a blockchain representation. The letters inside the arrows indicate the SCOR processes, and the number refers to the type of production strategy adopted.

Figure 24 - Live lobster supply chain representation




The business scenario modeled in this study involves the negotiation of contracts for the upcoming annual fishing season, which takes place at the end of each season. In this process, processor agents assess the performance of fishermen agents, while retailer agents evaluate the performance of processor agents. Within this context, suppliers may disclose past performance information to buyers, who then decide with whom they will sign a new annual contract looking to optimize their performance for the next season. The decision-making process is influenced by the type and availability of data, highlighting the role of a traceability system in this process. This logic is integrated into the simulation model, which will be detailed in the following subsection.

*5.4.2 Simulation model characteristics: supplier evaluation and contract negotiation*

Figure 25 synthesizes the simulation model's working structure. The supply chain's informational and physical flows are mutually associated, allowing the suppliers to be ranked yearly based on traceability data stored in a blockchain representation, which influences the transactions established in the sequence.

At the end of each year, all the processors and retailers reevaluate their suppliers before signing new contracts for the next annual fishing season. A ranking based on the TOPSIS method indicates that the last one-third with low performance will possibly be replaced. To optimize performance, agents prefer to keep the first two-thirds for the next season. These proportions are also adopted for cases where the blockchain is not adopted. Still, the connections to be reviewed are randomly assigned, and thereby, agents have less access to performance data.

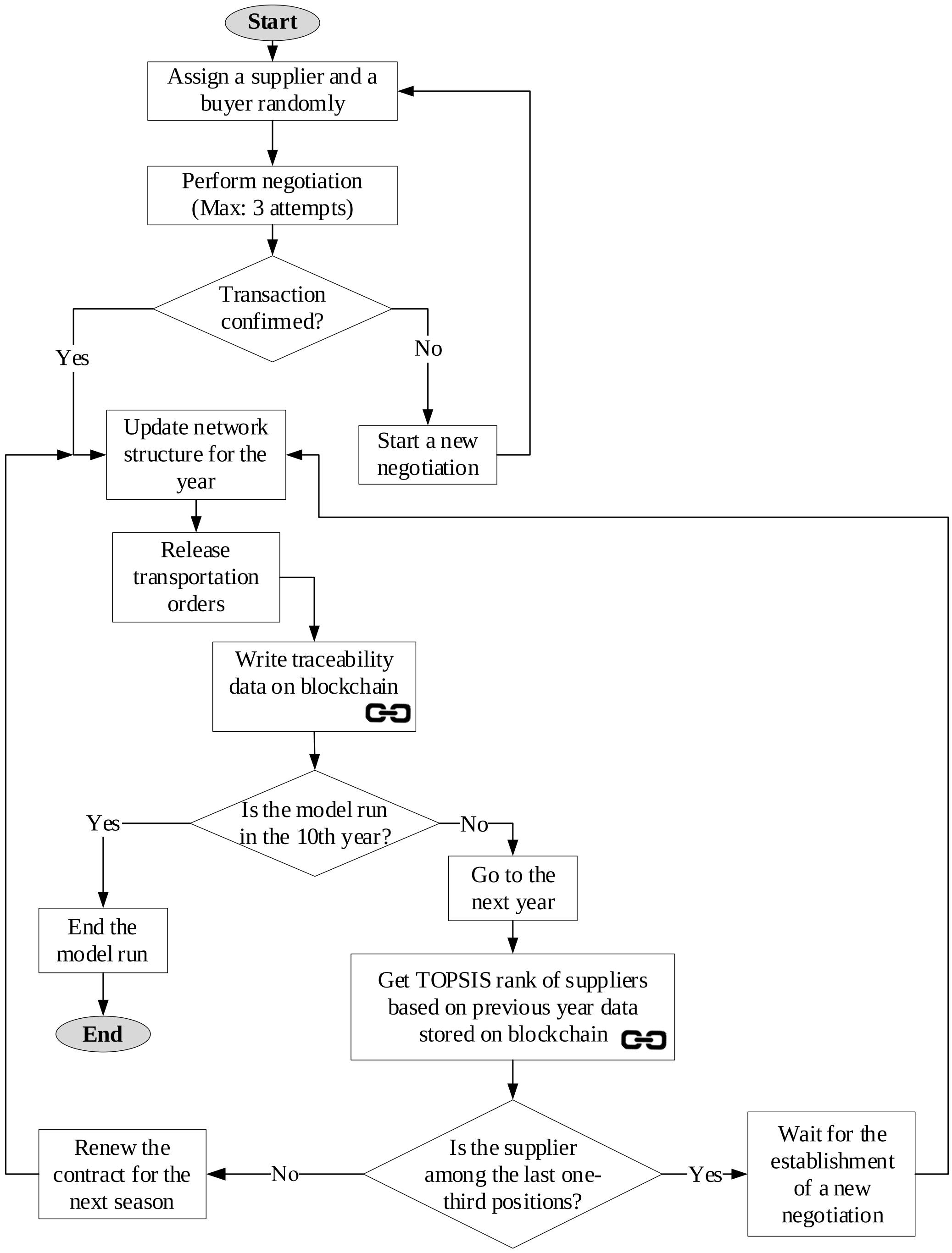
After landing with boxes filled with live lobsters, the fishermen prepare loads into trucks. The demand is larger than the supply capacity, so it is supposed that all products are sold out or destined for other markets. According to the transactions established, the connections are updated, and the respective numbers of deliveries are assigned. This latter part also occurs between processors (tier 2) and retailers (tier 3).

Regarding supplier management, all the data accumulated on the blockchain about a supply chain party's performance during an annual season is used to run the TOPSIS method and then reset for the next season. Regular updates are performed to update the suppliers' ranking for each supplier. In the baseline scenario (i.e., the status quo), the supplier evaluation considers a single criterion, namely "on-time in-full" (OTIF), which encapsulates the customers' preferences. Before closing the deal, to represent a negotiation, each buyer has three chances to beat the price proposed by the supplier.

This open, dynamic, and ranked scheme of supplier selection allows "continuous rewiring" between dyads (XIE; ZHOU; WANG, 2008), thus permitting the emergence of network variations between seasons. In addition, how transaction rules are configured promotes a balance between the possibility of changes and the network's overall stability.

The model is run for a finite horizon of ten years; each year corresponds to a season with ten weeks of fishing, modeling the current reality in Canada. As discussed later, results showcase the impact of different traceability schemes, including the role of blockchain communication for information sharing, considering supplier ranking based on traceability data.

Figure 25 - Model overview




*5.4.3 Criteria definition*

Table 16 presents the criteria assigned to the TOPSIS method, indicating whether they are used for fishermen or processor evaluation. In addition to logistics indicators, technical parameters related to live lobster handling are specified in line with the information obtained through expert interviews.

Table 16 - Description of criteria adopted

| Criteria | Approach | Tier selection | |
|---|---|---|---|
| | | Fish. | Proc. |
| Legal fishing | $LF = \%\ of\ appropriate\ fishing\ practices$ | ✓ (1.1) | |
| On-time in-full (OTIF) | $OTIF_i = \%\ of\ complete\ deliveries\ on\ promised\ time$ | ✓ (1.2) | ✓ (2.1) |
| Transport conditions | $TC_i = \frac{Temp_{T_i} + Hum_{T_i}}{2}, where:$ | ✓ (1.3) | ✓(2.2) |
| *Temperature* | $Temp_{T_i} = \%\ of\ time\ inside\ indicated\ range$ | | |
| *Humidity level* | $Hum_{T_i} = \%\ of\ time\ inside\ indicated\ range$ | | |
| In-facility conditions | $FC = \frac{Am_{\%} + Ox_{\%} + Temp_{\%}}{3}, where:$ | | ✓ (2.3) |
| *Ammoniac level* | $Am_{\%} = \%\ of\ time\ inside\ indicated\ range$ | | |
| *Oxygen level* | $Ox_{\%} = \%\ of\ time\ inside\ indicated\ range$ | | |
| *Temperature* | $Temp_{\%} = \%\ of\ time\ inside\ indicated\ range$ | | |

All these criteria are based on accumulated data registered yearly to provide a dynamic and comprehensive representation of the supply chain party performance during the simulation run. “Legal fishing” refers to the catching practices that follow the quantity limit and avoid catching female and baby fish, embracing sustainability aspects. The well-known performance indicator “On-time in-full” is measured by getting the accomplishment rate of the promised transportation time with complete quantities. “Transport conditions” and “In-facility conditions” are obtained from the average of the fraction of time that respective parameters are inside the recommended range. In addition, the simulation model is built on top of the assumptions described next:

1) Trucks full of boxes containing live lobsters correspond to the level of granularity adopted for the flowing entities throughout the supply chain.
2) Weights used to run TOPSIS are assumed as constant values for the entire run and all the ranking updates of all scenarios.
3) Weights for TOPSIS are considered the same for all the selecting parties in the same tier.
4) The individual performance is reset by the end of each season.
5) The number of players is kept constant. No party is removed from or added to any tier of the supply chain.

6) Enough supply is provided, as we are not interested in exploring the quantitative balance.
7) The parties of the same tiers are all equal in terms of capacity and demand volume.
8) The excess amount not sold is supposed to be sent to alternative markets, including exportation, non-live commercialization, and parties of other supply chain networks.
9) The blockchain configuration adopted is classified as private and permissionless since authorized members have unrestricted access to read and write data (ZHENG *et al.*, 2017).

Table 17 contains the parameters input to set the simulation model. Those are organized into two categories. "Supply chain structure and flow" gives the number and the characteristics of the parties involved in the transactions. "Suppliers ranking through TOPSIS" brings part of the multicriteria method specifications. The parameters' type is also informed in the right column.

Table 17 - Parameters for the simulation model

| Description | Value or range of values | | Type |
|---|---|---|---|
| *Supply chain structure and flow* | | | |
| Fishermen agents | 450 | | C |
| Deliveries to processors | 60/fishermen/season | | R |
| Processors agents | 15 | | C |
| Negotiations with fishermen | 30/processor/season | | R |
| Deliveries to retailers | 15/processor/season | | R |
| Retailers agents | 5 | | C |
| Negotiations with processor | 90/retailer/season | | R |
| *Supplier ranking through TOPSIS* | | | |
| Criteria for Fishermen Evaluation | 3 | | P |
| Criteria for Processor Evaluation | 3 | | P |
| Type of distance considered | Euclidean | | P |
| Weights from Fishermen to Processor | Sc. II | Sc. III | |
| Legal fishing | - | 5% | P |
| On-time in-full | - | 10% | P |
| Transport conditions | - | 10% | P |

| Description | Value or range of values | | Type |
|---|---|---|---|
| Weights from Processor to Retailer | | | |
| On-time in-full | 20% | 22,5 | P |
| Transport conditions | 40% | 26,25% | P |
| Facility conditions | 40% | 26,25% | P |
| Frequency of update | Once a season | | P |

Where: C: constant, P: predetermined, and R: random parameter.

Table 18 presents the parameters input to represent the performance of fishermen. Two levels of randomness are assigned. First, the range is defined by percentage; then, inside the range, the performance is determined by a statistical distribution. The triangular numbers have equal values for mode and maximum. Table 19 gives the data input predetermined to represent processors' performance according to a five-level linguistic scale, whose values are specified in Table 20.

Table 18 - Parameters for fishermen agents' performance

| Criteria | Percentage | Range | Distribution |
|---|---|---|---|
| Legal fishing | | | |
| | 60 | 0,90-095 | Triangular |
| | 35 | 0,96-0,98 | Uniform |
| | 5 | 0,98-1,00 | Uniform |
| On-time in-full (OTIF) | | | |
| | 80 | 0,85-0,90 | Triangular |
| | 10 | 0,90-0,95 | Triangular |
| | 10 | 0,95-1,00 | Uniform |
| Transportation condition | | | |
| Temperature | | | |
| | 60 | 0,70-0,75 | Triangular |
| | 20 | 0,75-0,90 | Triangular |
| | 15 | 0,90-0,97 | Triangular |
| | 5 | 0,97-1,00 | Uniform |
| Humidity level | | | |
| | 70 | 0,70-0,80 | Triangular |

| Criteria | Percentage | Range | Distribution |
|---|---|---|---|
| | 15 | 0,80-0,90 | Triangular |
| | 10 | 0,90-0,95 | Triangular |
| | 5 | 0,95-1,00 | Uniform |

Table 19 - Categories of performance input for each processor

| Processor | On-time in-full ($C_{21}$) | Transport conditions ($C_{22}$) | Facility conditions ($C_{23}$) |
|---|---|---|---|
| P1 | Very good | Good | Very poor |
| P2 | Regular | Regular | Poor |
| P3 | Very good | Very poor | Regular |
| P4 | Good | Very good | Very good |
| P5 | Poor | Regular | Good |
| P6 | Regular | Good | Regular |
| P7 | Very poor | Poor | Poor |
| P8 | Good | Very good | Very good |
| P9 | Good | Poor | Regular |
| P10 | Very good | Good | Very good |
| P11 | Poor | Very poor | Poor |
| P12 | Regular | Very good | Good |
| P13 | Very good | Regular | Very poor |
| P14 | Very poor | Poor | Good |
| P15 | Poor | Very good | Very good |

Table 20 - Parameters and distribution assigned to each category of performance

| Category | Range | Distribution |
|---|---|---|
| Very good | 0,80-0,90 | Uniform |
| Good | 0,75-0,85 | Uniform |
| Regular | 0,70-0,80 | Uniform |
| Poor | 0,65-0,75 | Uniform |
| Very poor | 0,60-0,70 | Uniform |

*5.4.4 Scenarios and output*

Based on traceability aspects regarding supplier ranking, the scenarios are derived following a best-guess approach, focused mainly on processors representing tier 2. Table 21 exhibits the characteristics of scenarios considered through different combinations of blockchain adoption, traceability practices, and criteria used for supplier evaluation.

In Scenario I, processors are ranked based only on the performance of OTIF, since no traceability data has been collected so far. In Scenarios II and III, each retailer agent is equipped to run its own TOPSIS ranking, which characterizes a one-to-one information-sharing scheme. In Scenario II, processors are evaluated based on their performance, considering the indicators “On-time in-full”, “Transport conditions”, and “Facility conditions”.

In an extended approach, in Scenario III, a two-step-back traceability practice is taken, as the TOPSIS also embraces the performance of the processors’ suppliers. By considering the performance between tiers 1 and 2, visibility is enhanced, and the indicators of “Legal fishing”, “On-time in-full”, and “Transport conditions” are included in the evaluation process. We assume that all the supply chain parties are blockchain members in Scenarios II and III, in which the technology is included.

Including beyond one-step-back traceability allows capturing the data in the previous supply chain stage (subsupplier), from fishing to the processor, which impacts the remaining shelf life of the live lobsters bought by a retailer and enriches the approach adopted.

Table 21 - Scenarios’ deployment

| Sc. | Traceability from retailer perspective | Blockchain technology | Criteria used for supplier evaluation | |
|---|---|---|---|---|
| | | | Fishermen | Processor |
| I | None (OTIF-based) | Not included | - | 2.1 |
| II | One-step-back | Included | - | 2.1 to 2.3 |
| III | Two-step-back | Included | 1.1 to 1.3 | 2.1 to 2.3 |

We analyze the interactions between processors (tier 2) and retailers (tier 3) for the analysis. The simulation aims to explore two main aspects related to the ranking of processors’ performance, described as follows:

1) Ability to find the best suppliers: through replication runs, we get the simulation model robustness in terms of the probability of classifying the best suppliers, according to the data input.
2) Position variation: we provide a consolidated comparison of processors' ranking positions due to the access to different criteria for performance evaluation.

These two aspects enable us to address the research's main points, which seek to understand how information sharing through a blockchain-based traceability system impacts supplier evaluation and thereby assists supplier selection, ultimately influencing the supply chain network structure.

**5.5 Results**

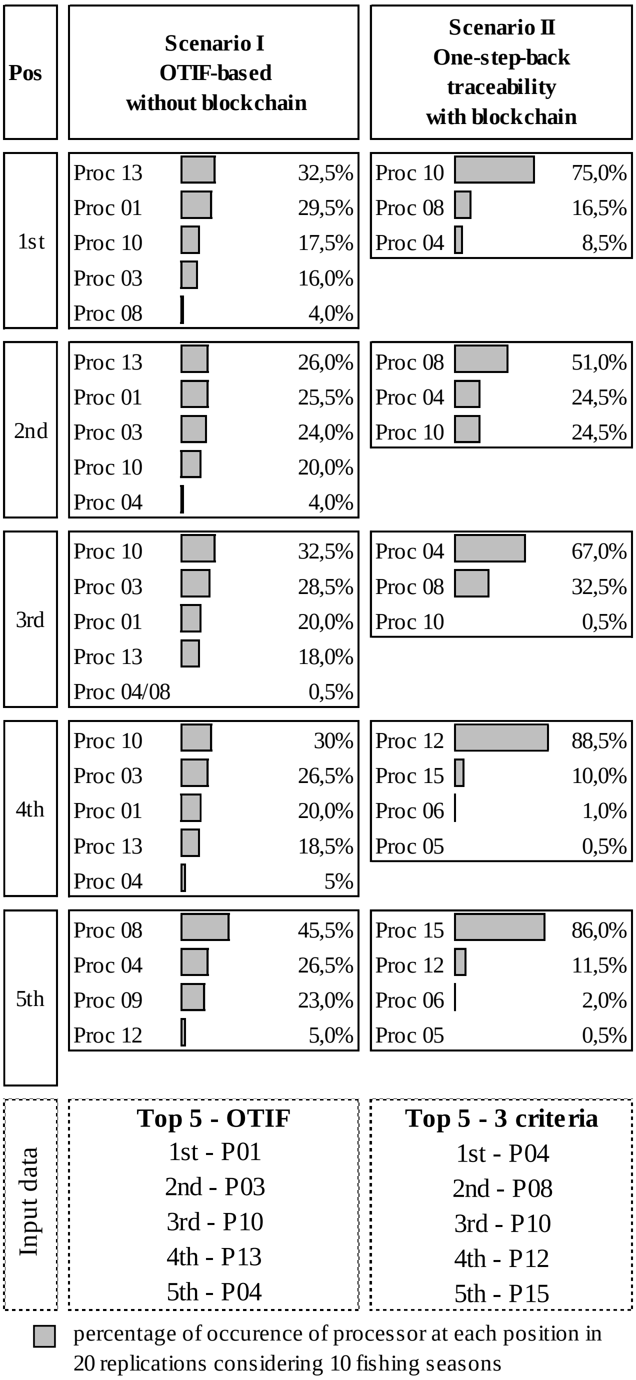
Results exhibited in this section focus on the perspective of dyads between processors and retailers. The number presented refers to the mode of 20 replications.

*5.5.1 Single-level supplier evaluation process*

Figure 26 presents results regarding the first five positions of rankings registered by a single supplier during ten annual fishing seasons. According to the performance classes given in the bottom part, as expected, for the OTIF-based classification, Scenario I, Processors P01, P03, P10, and P13, alternate between each other and dominate the top four positions.

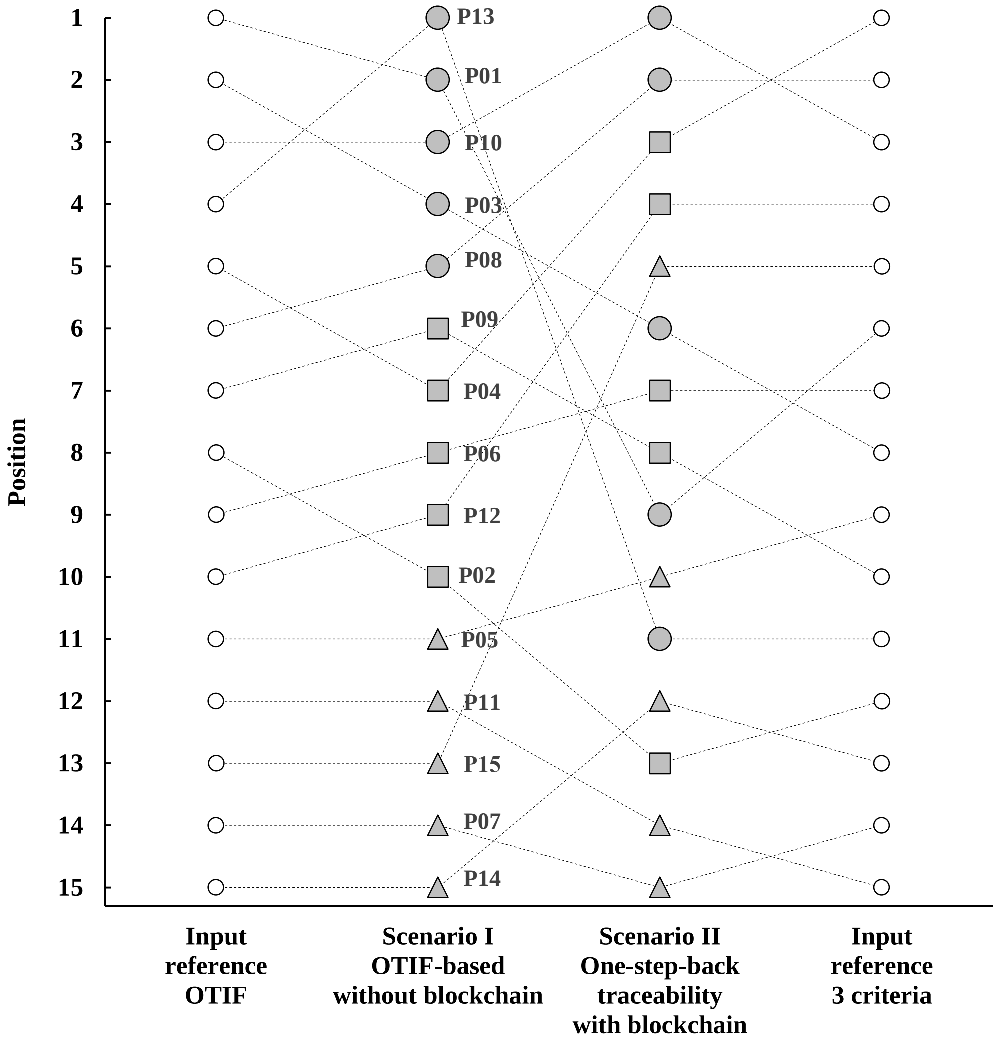
For Scenario II, with traceability information shared through blockchain, we notice that processors P04, P08, and P10 assume the first three positions since their performance is classified as "very good" in two criteria and as "good" in the remaining one. Another interesting fact is that three parties (P04, P08, and P10) respond for 100% of the replications for the first three positions. This suggests that blockchain-based traceability offers a more stable and predictable behavior when higher transparency is provided. In the bottom right part, we notice that Processors P05, P06, P12, and P15 alternate in the $4^{th}$ and $5^{th}$ positions, as they present a satisfactory overall performance. Similarly, the $4^{th}$ and $5^{th}$ positions are occupied by only four processors, as a natural result of the interactions of the simulation model.

Figure 26 - Comparison of position occurrence between Scenarios I and II




To gain a deeper understanding of potential alterations in the supply chain structure, Figure 27 shows the changes of position experimented by each processor for Scenarios I and II. The white symbols in the columns on the right and left sides refer to the input data considered for Scenarios I and II, respectively. The variations between the input data and their respective scenarios are useful to observe the changes in positions due to output variability, mainly for processors with the same initial levels of performance. In addition, in the middle part, it is possible to compare Scenarios I and II. Representative changes are seen, even from the first to the third tercile of positions, between Scenarios I and II, for example, concerning processors P01 and P13, which go down in the ranking, and processor P15, which goes up in the ranking.

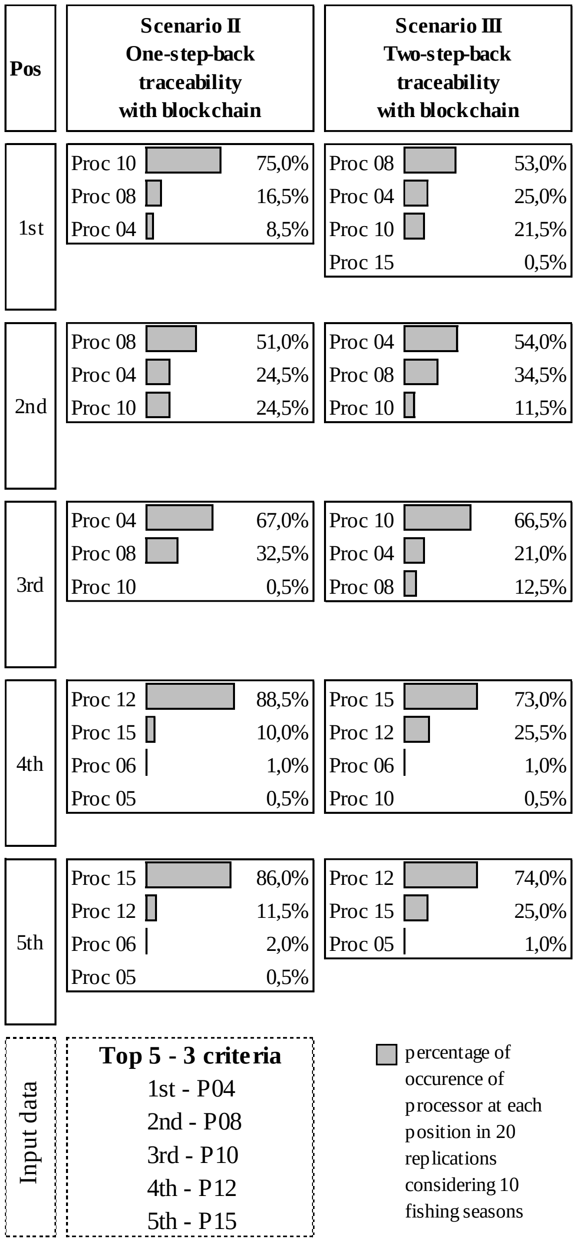
Figure 27 - Variation of processors' position in the Scenario I and II




*5.5.2 Multi-level supplier evaluation process*

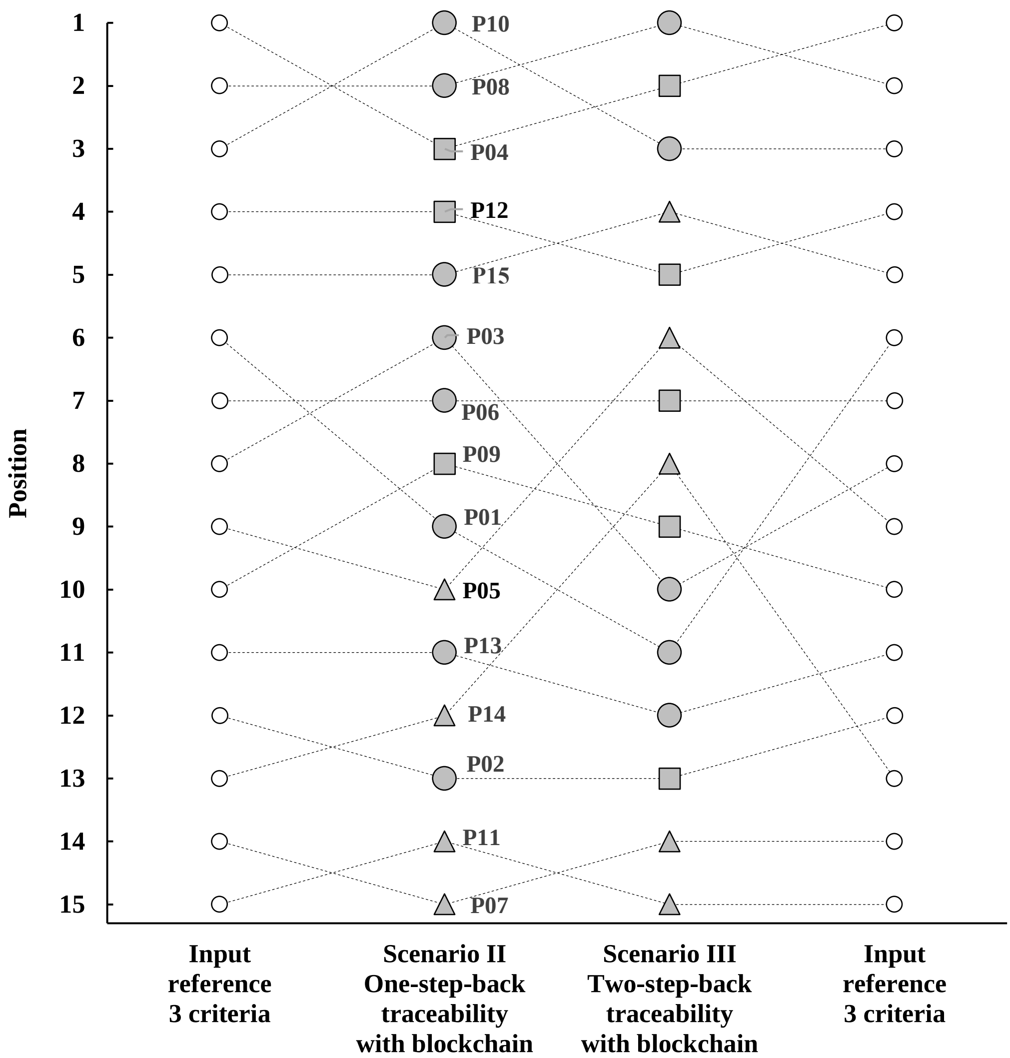
Figure 28 shows a comparison between Scenarios II and III, again concerning the first five positions of rankings registered by a single supplier during ten annual fishing seasons. We can notice some changes in the top 3 positions and mainly in the percentages registered. However, once again, these positions are dominated by a restricted number of processors, namely processors P04, P08, and P10, while P15 has just a small appearance in the first position. The $4^{th}$ and $5^{th}$ positions are almost entirely dominated by processors P12 and P15, as processors P05, P06, and P10 have small percentages.

Figure 28 - Comparison of position occurrence between Scenarios II and III




In Figure 29, another comparison between Scenarios II and III is exhibited. The white symbols in the columns on the right and the left sides refer to the input data considered for Scenarios II and III, which are the same. For Scenario III, after including the performance of the immediate suppliers, we observe some changes in the ranking positions. For example, the high performance of processor P10 experiences a clear negative impact, as its appearance in the 1$^{st}$ position goes down to the 3$^{rd}$ position. A similar effect happens for processor P12, which goes down from the 4$^{th}$ to the 5$^{th}$ position. Once again, we find more convergence among the processors that occupy the first five positions. In practical terms, Scenario III suggests the benefit of blockchain technology in providing transparency through the visibility of a fully informed traceability system that covers beyond one-step-back transactions. In contrast, as an example, comparing Scenarios II and III reveals that P03 moves four positions down, while processors P02 and P06 maintain the same positions.

Figure 29 - Variation of processors' position in the Scenarios II and III




## 5.6 Discussion

The main points regarding our research are discussed in the following sections.

### *5.6.1 Single-level supplier evaluation process*

When the buyer company relies exclusively on shortsighted information for supplier evaluation, based on only one indicator (OTIF, in Scenario I), it tends to keep suppliers excelling only in this performance criteria. In contrast, the integration of blockchain-based traceability data enriches the supplier evaluation process, enabling the use of a diversified set of performance indicators. This refinement in precision improves the supplier evaluation process and leads to a more robust and effective supply chain by supporting future decisions related to contract establishment and supplier selection.

Providing access to refined traceability data highlights the disruptive impact that blockchain-based traceability might have in terms of transforming supplier evaluation processes. Traditional supplier evaluation and selection methods often rely on limited data for this supply chain, taking an oversimplified view of supplier performance. The literature highlights that a shortsighted approach can result in non-coherent exclusions of suppliers that perform well in other critical performance criteria (JUM'A, 2023; HO; XU; DEY, 2010).

In this context, introducing blockchain-based traceability appears to be a game changer for supplier evaluation processes. By providing a comprehensive and real-time view of supplier performance in multiple relevant dimensions, blockchain supports buyer companies to make more precise supplier evaluation processes. In the case of the live lobster supply chain under consideration, this broader perspective allows the coherent consideration of suppliers that might be outstanding in legal fishing and transportation conditions, among other key factors (BISWAS *et al.*, 2023, KAMBLE *et al.*, 2023; GIMENEZ; TACHIZAWA, 2011).

This refined precision creates a more efficient supply chain network, due to the access to complete information, leading to a more robust decision-making process. Suppliers aware of being evaluated based on a broader set of performance indicators are more likely to contribute positively to the overall supply chain network. This refinement improves operational efficiency and promotes innovation and competition among suppliers, bringing tangible and non-tangible benefits to the entire supply chain (JUM'A, 2023; KAFETZOPOULOS *et al.*, 2022; ASIOLI; BOECKER; CANAVARI, 2014).

In contrast, it is essential to recap that supplier evaluation is a critical component of supply chain management, and it is far from being a straightforward or unequivocal process (HO; XU; DEY, 2010). Buyers must consider many performance criteria when choosing their suppliers, and the complexity of this task cannot be underestimated, as it is a non-trivial procedure.

One key challenge lies in the lack of comprehensive data available for supplier evaluation. In many supply chains, supplier evaluation has traditionally relied upon easily measurable metrics such as on-time in-full (OTIF) performance. This simplification is not due to a lack of ambition but is often a result of historical practices, resource constraints, and technological limitations (HO; XU; DEY, 2010, MGONJA; LUNING; VAN DER VORST, 2013). In this context, our first result gains relevance.

Introducing blockchain-based traceability data is a relatively recent and evolving technological advancement in supply chain management. While its potential may seem apparent firsthand, its practical application and implications are still being developed and explored (RISSO *et al.*, 2023a). In general, using of blockchain technology enriches the supplier evaluation process as it puts forward a more comprehensive perspective for supply chain communication.

Moreover, the competitive advantage gained through advanced supplier evaluation methods is not immediately apparent to all supply chain parties. Despite the non-obvious characteristics of the benefits obtained, those are implicit in the transactions established in the supply chain network. Also, according to the relevance given to logistics and processing traceability, the proposed application encompasses criteria that address both internal (in-facility conditions) and external traceability (transport conditions) (MGONJA; LUNING; VAN DER VORST, 2013).

From an extended perspective, introducing higher transparency through blockchain traceability stresses the potential for integrating sustainability and ethical considerations into supplier evaluation processes. In the context of our study, this involves the evaluation of suppliers based on their performance in terms of legal fishing and transportation conditions, moving beyond traditional OTIF metrics focused only on logistics issues. Regarding a live lobster supply chain, this result highlights how blockchain technology may be an impeller for promoting sustainable and ethical initiatives in seafood supply chains. This integrated approach aligns with ethical and sustainable objectives and contributes to a responsible and conscious supplier evaluation process.

This transformation aligns with the increasing global emphasis on responsible and sustainable supply chain practices, which can be associated with sustainable development goals (SDG) (HUGHES *et al.*, 2019). It demonstrates how blockchain technology can leverage environmental conservation, ethical fishing practices, and consumer safety and awareness (RODRIGUEZ-SALVADOR; DOPICO, 2020). The supply chain's ethical dimension is reinforced, emphasizing responsible sourcing and compliance with legal regulations. In addition, these elements also bring improvements to the informal processes taken of fishing and landing steps (TOKKOZHINA; MARTINS; FERREIRA, 2023, ASIOLI; BOECKER; CANAVARI, 2014, KAFETZOPOULOS *et al.*, 2022).

Furthermore, integrating sustainability and ethics into supplier evaluation may lead to far-reaching implications. It can enhance the reputation and brand value of the primary company, attending to concerns of consumers related to transparency and social responsibility (GOVINDAN; KHODAVERDI; JAFARIAN, 2013, LUTHRA *et al.*, 2017).

From a theoretical perspective, exploring a single supplier evaluation process contributes to network theory by emphasizing the depth and complexity of relationships in supply chain networks. Network theory traditionally focuses on the structure and dynamics of relationships among network nodes (BORGATTI; HALGIN, 2011; TREIBLMAIER, 2018). In this context, our research stresses the importance of studying the existence of these connections and embraces the quality and diversity of relationships through an ex post facto perspective. Our results suggest that networks are about the number of connections and the strength and versatility of these connections, as indicated by Hearnshaw and Wilson (2011). For this purpose, in the simulation model, we rely on continuous monitoring of supply chain traceable object agents' behavior.

In the face of that, the enhanced supplier evaluation precision highlights the concept of "tie strength" – defined as the degree of closeness and influence among connected nodes (HEARNSHAW; WILSON, 2011). Supplier evaluation becomes more refined when based on several performance indicators. Network theory includes the notion that not all ties are equal, and some ties, particularly those with strong multi-dimensional connections, substantially impact the overall network behavior (HALLDÓRSSON; HSUAN; KOTZAB, 2015). Therefore, the continuous monitoring of supply chain agents' performance impacts the relation between dyads of previously connected nodes.

In addition, integrating higher transparency enhances network theory by highlighting the role of networks in promoting ethical and sustainable practices in supply chains. Traditionally, network theory examines the diffusion of information or innovations in networks (BORGATTI; HALGIN, 2011). However, our result expands the theory's scope to encompass the dissemination of ethical and sustainable behavior as a competitive factor. Our results suggest that supply chain networks are channels for information, financial, and physical flows as well as disseminators for the propagation of ethical principles and sustainable practices. According to network theory, a node's performance influences its dyads through its connections, leading to the diffusion of practices or principles (HALLDÓRSSON; HSUAN; KOTZAB, 2015). This result demonstrates that the supply chain network can facilitate the spread of ethical and sustainable behaviors, making network theory a valuable framework for understanding and analyzing supply chain dynamics beyond typical operational, informational, and financial aspects.

*5.6.2 Multi-level supplier evaluation process*

Simulation results show that multi-level supplier performance evaluation through blockchain-based traceability offers interesting prospects. This approach brings a refined level of precision and gives a more transparent portrait regarding the set of supplier options, which is coherent with the literature (TOKKOZHINA; MARTINS; FERREIRA, 2023; SHAMSUZZORA; MARTTILA; HELO, 2023, HOWSON, 2020).

By considering the performance of both immediate and second-tier suppliers, companies can make more informed decisions, by perceiving suppliers that perform well on indicators from different perspectives (TOKKOZHINA; MARTINS; FERREIRA, 2023; SHAMSUZZOHA; MARTTILA; HELO, 2023). In the literature, this is referred to as subsupplier evaluation (GRIMM; HOFSTETTER; SARKIS, 2016, GRIMM; HOFSTETTER; SARKIS, 2014).

A multi-level, or subsupplier evaluation, brings benefits to the overall quality and reliability of both supply chain transactions and relations. Moreover, the use of blockchain-based traceability expands the horizons for potential supplier choices in terms of continuation for the next purchases. In the position of buyers, companies are no longer restricted to accessing only their immediate, i.e., first-tier suppliers; instead, they can explore a more extensive set of suppliers in the supply chain network. This expansion is a purposeful approach, mainly in supply chains in which suppliers' performance evaluation affects first-tier capabilities, unveiling hidden suppliers of suppliers'(subsuppliers) potential.

The enhanced precision ensures that companies evaluate suppliers without overestimating those that only meet basic performance criteria. In addition, the proposed approach brings to light suppliers that perform well in criteria from additional perspectives, contributing to the supply chain's overall levels of reliability and performance. The transparency provided by blockchain technology justifies the adoption of enhanced precision, making it a game-changer alternative to assist decision-makers in addressing supplier evaluation processes. Moreover, the impact of this high level of precision will probably also affect trust issues in the supply chain network, as considered by Cole, Stevenson, and Aitken (2019).

In parallel, the expanded horizons of performance evaluation provide buyers with a higher level of flexibility to explore suppliers beyond their immediate dyads. In this case, by considering second-tier suppliers or even further, buyer companies may discover previously unnoticed distinguished suppliers, benefiting the performance of the supply chain network (GRIMM; HOFSTETTER; SARKIS, 2016, GRIMM; HOFSTETTER; SARKIS, 2014).

Going beyond the one-step-back traceability for supplier evaluation contributes to network theory by showcasing how blockchain-based traceability and multi-level performance evaluation expand the depth and breadth of supply chain networks. Network theory typically examines the structure and connections existing in networks and emphasizes that the structure can be multi-layered and multi-dimensional (HALLDÓRSSON; HSUAN; KOTZAB., 2015). Although the concept of a multi-level network is not novel in network theory, our results still highlight the significant role of obtaining multi-level performance data in enhancing the overall efficiency of a supply chain network.

In addition, the extended evaluation horizon allows for a more comprehensive exploration of potential suppliers in multiple tiers, creating a more extensive network structure (GRIMM; HOFSTETTER; SARKIS, 2016, GRIMM; HOFSTETTER; SARKIS, 2014). This expansion is valuable in network theory, as it reveals how integrating blockchain technology and multi-level performance evaluation uncover previously hidden network nodes and connections with promising potential of performance, which influences the network's overall dynamics. This result aligns with the focus of network theory on understanding the implicit and inherent relationships and interactions in networks, making it a valuable addition to the literature.

Thus, the proposed inclusion of blockchain has an impact on inter-organizational relationships since the focus is driven on performance instead of subjective perceptions, corroborating the statements provided by Treiblmaier (2018) and Ferreira, Palazzo, and Carvalho (2023), which are addressed to dyadic relations.

## 5.7 Conclusions

This work explores the performance evaluation in a supply chain network considering information shared through blockchain technology. Connections are reviewed after a supplier ranking process based on criteria obtained from traceability data. By combining simulation with a novel dynamic multicriteria approach, we were able to go beyond a cross-sectional approach, allowing the deployment of different decision-making scenarios.

The results obtained indicate that the proposed inclusion of blockchain technology for information sharing enables and leverages both single and multi-level supplier evaluation processes. Considering the integration of additional aspects goes beyond a one-step-back traceability approach and brings higher transparency to the supply chain network. Besides achieving gains in performance through a more consistent performance evaluation process, other non-tangible benefits may also be propagated to end customers regarding product awareness.

### *5.7.1 Academic contributions*

This research enriches the supply chain literature by demonstrating the transformative potential of blockchain-based traceability in supplier evaluation and network configuration. It emphasizes the importance of comprehensive supplier evaluation, transcending conventional metrics and single-tier evaluation processes, and broadening academic comprehension of supply chain dynamics.

Furthermore, we offer evidence and an in-depth explanation regarding the practical aspects and advantages of blockchain-based traceability in supplier evaluation. These elements enhance academic discourse on integrating emerging technologies in supply chain management.

The research also contributes to network theory by emphasizing the role of blockchain-based traceability in influencing supply chain network structure and dynamics, as well as aspects related to visibility and collaboration between dyadic partners. It broadens the theoretical understanding of supply chain networks, mainly in the context of multi-tier supplier relationships using a granular traceability system.

Moreover, this research introduces the notion of "extending supplier horizons" through blockchain-based traceability. It deepens the comprehension of network dynamics in supply chains by highlighting the significance of considering multiple performance indicators and multiple tiers for supplier evaluation. The extended perspective adopted here leads to a more thorough exploration of network theory, as it examines the interaction among multiple supply chain parties in terms of performance evaluation.

### *5.7.2 Practical and ethical implications*

Regarding practical implications, managers can benefit from the results presented in this research when deciding about adopting blockchain traceability to achieve more precise and comprehensive supplier evaluation. This can lead to improved supplier quality, reliability, and performance, ultimately strengthening their supply chains network robustness.

In this context, the practical implication of considering second-tier suppliers implies that companies can explore an extended range of suppliers. This allows them to identify and engage with suppliers who may have been previously overlooked, promoting supplier diversity.

From another perspective, ethical implications are also noticed. The integration of blockchain-based traceability leverages sustainable practices in supply chains. By evaluating suppliers based on multiple performance indicators, including those related to ethical and sustainable practices, companies contribute to putting forward Sustainable Development Goals related to responsible sourcing. In this context, companies adopting blockchain-based traceability systems may collaborate to reduce environmental damage, preserve natural ecosystems, and support sustainable fishing practices. Therefore, sustainable supplier choices, particularly in seafood supply chains have a positive environmental impact in terms of longevity.

Moreover, companies that participate in blockchain-based traceability systems can align their actions with expectations of responsible business initiatives. Thus, through the high level of transparency in their transactions, these companies contribute to a more conscious and ethical business environment, which is essential for building trust among consumers and stakeholders. Intentions related to consumer awareness also benefit from the data about the item's origin and processing conditions.

### *5.7.3 Limitations and future directions*

This work contains limitations. First, the performance of supply chain parties is simplified by random distributions, which could be enriched using detailed submodels to represent the behavior. The weights adopted for applying the TOPSIS multicriteria method are the same for all parties involved and are kept constant throughout the simulation horizon. The definition and variations of weights are issues that may be more explored. At last, although a moderate degree of flexibility is assigned to the supply chain structure, the role and number of parties are predetermined, and both demand variation and competition are not addressed, since the focus is on information sharing concerning the level of blockchain adoption. These conditions may also be refined.

For future works, we recommend the exploration of other contexts related to supply chain management, for example involving costs, inventory, and service level issues, and with a higher number of tiers. From the theoretical standpoint, network theory can be explored from different prisms and indicators, and adopting other lenses, such as the principal-agent theory and transaction cost analysis, reinforcing the call from Treiblmaier (2018). Regarding blockchain, possibilities include the study of other configurations such as a multichain or the experimentation of different profiles of access and permission. Alternatively, the effect of the type of information shared can be evaluated, and phenomena related to trust and dispute resolution, even including smart contracts. Finally, apart from the context considered, the simulation approach provided can be useful to explore the effect of weights attributed adopted and employed through TOPSIS and other multicriteria methods, such as the Analytic Hierarchy Process (AHP).

# 6 CONCLUSIONS AND CLOSING REMARKS

This chapter starts with a general overview, synthesizes the contributions of this thesis, and presents both its limitations and the directions recommended for future works.

## 6.1 Thesis general overview

The main objective of this thesis is to propose and test the usability of a framework to model and simulate supply chain traceability systems supported by blockchain technology. This objective was pursued through specific objectives contained in the three papers that are the building blocks of this document and can be consumed as standalone parts.

In Chapter 3, the specific objective was to examine the present and future perspectives of blockchain in supply chain management and identify how simulation has been considered. This study explored eight supply chain general metrics and nine supply chain requirements and highlighted ten blockchain features. In terms of future directions, twelve directions for primary research were discussed, and a comprehensive research agenda with fifteen topics for future literature reviews was proposed. Traceability was the second most discussed feature, just behind smart contracts; but despite the huge interest, the connection of blockchain with supply chain traceability was currently mentioned as limited (GALVEZ; MEJUTO; SIMAL-GANDARA, 2018; FENG *et al.*, 2020). The lack of empirical evidence regarding traceability and the small number of studies that employed simulation modeling helped to set the path for the next parts.

In Chapter 4, the specific objective was to develop a framework to model and simulate supply chain traceability considering blockchain technology. A methodological framework comprising eight steps was proposed, including the phases of model design, model development, and output evaluation. It assists the development of simulation models, the hybrid ones combining agent-based and discrete event paradigms, or solely agent-based models. The approach integrates the concepts and terminologies of the Supply Chain Operations Reference (SCOR) model and the Global Traceability Standard (GTS), which are well-accepted by the business and research communities. Thereby, the structured approach to building hybrid simulation models consists of a novel contribution to the literature.

A proof-of-concept application was exhibited based on a real-scale industrial case of a live lobster supply chain from Canada. The focus of this application was on the reverse flow, embracing the analysis of recall performance, which extends the approach brought by Long (2014), by including the return processes from the SCOR model. The sequence of steps proposed in the framework contributes to helping modelers create realistic hybrid simulation models following an informative, modular, and user-friendly approach. Moreover, the framework is versatile to model traceability from the perspectives of origin, process, movement, and after delivery, from the source of raw materials to the final consumption, encompassing elements of both external and internal traceability. It also allows the consideration of different levels of granularity and information stored to complement key data elements (KDEs). Concerning blockchain, alternatives of configuration can be tested, encompassing different profiles of access and permission, and specific smart contract parameters.

Besides integrating the SCOR model and GTS standard, the multiple levels of granularity indicated also provide customization and versatility for representing both supply chain and traceability flows. Scenarios may also be enriched by developing models mixing members and non-members of a blockchain. The versatility of the proposed approach still allows us to analyze agents as individuals and as collectives. The different topologies for agents' relationships and social interactions, presented in Figure 6, may be adopted according to the context being modeled.

In Chapter 5, the specific objective was to put the framework into practice, test it in a real-scale application, and evaluate its capacity to capture the complexity of traceability systems from both theoretical and practical perspectives. In more specific terms, this application allows us to analyze the evolution of a supply chain after supplier-buyer interactions managed through blockchain communication. Following the steps of the methodological framework, we have developed a hybrid simulation model to evaluate the supply chain network structure and performed an analysis through the lens of network theory. A live lobster supply chain from Canada was investigated, and the model was initiated with a pre-fixed structure.

Moreover, the agents' autonomy was equipped with a dynamic and updatable application of a multicriteria method, namely the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS). Then, consumer agents were allowed to dynamically rank their suppliers based on traceability data stored and shared on a blockchain representation regarding the individual supplier performance during the last season. The analysis was based on the consolidated ranking positions considering single-level and multi-level supplier evaluation schemes. This application has helped to test the framework's adaptability to a situation involving a large volume of traceability data and a flexible network. In terms of novelty, this work complements the literature by applying hybrid simulation to deal with supplier evaluation considering blockchain technology using a theoretical lens.

Furthermore, considering the requirement analysis provided by Dorigatti *et al.* (2016), the five capabilities are found in the framework proposed in this work, as described in the following:

- Reusable components: building blocks of the simulation model can be reused in the development of other models with similar characteristics, to represent either the supply chain processes or the flows of information exchanged through blockchain.
- Dynamic links: a flexible approach is encouraged through the enrichment of agents' abilities and the use of open and adaptable supply chain network structures.
- Business process orientation: the adoption of the SCOR model and GTS standard stresses the focus on integrating business aspects into the model logic.
- Explicit control and decision making: the control may be refined according to the level of granularity adopted while the inclusion of the TOPSIS multicriteria method sophisticates the agents' decision-making ability.
- Message-based interaction protocols: those are used to support the communication and transference of transaction information and traceability data among agents.

Therefore, these aspects reinforce the simulation model's capability of properly representing a blockchain-based supply chain traceability system.

The hybrid simulation model developed for the third part also retains aspects of novelty. In contrast with other research works that have applied simulation models to study blockchain in supply chain, this one brings a flexible and adaptable supply chain network structure. Moreover, different types of traceability information are taken into consideration regarding process and logistics parameters, through an accumulated history of performance, and with the possibility of encompassing traceability beyond one step back. In terms of contextualization through network theory lenses, the links were associated with state-based conditions, and outcomes of success were highlighted, and, instead of a cross-section portrait, a temporal panorama was taken. As a quantitative approach was adopted, this work also contributes by complementing the qualitative ones found in the literature regarding blockchain in supply chain management through network theory lenses.

From another perspective, as proposed in Chapter 5, the inclusion of a multicriteria method also sheds light on another possibility for simulation modeling. Typically, multicriteria methods are used to evaluate the output of simulation experiments in the analysis phase or to define scenarios for experimentation during the planning phase. Setting a multicriteria application with a “continuously update scheme” to guide agents’ decision-making also has a distinguished value as it reveals the relevance of considering additional criteria in a dynamic mechanism. As noted, this alternative feeds back the model during its runs. In addition to empowering agents’ abilities, it can also be used to leverage the application of multicriteria methods on business decisions taken regularly, for example, daily or monthly.

In terms of the multiple contributions provided, scholars can benefit from the guidelines presented in the framework to develop more realistic and refined hybrid simulation models and increase both the rigor and the level of detail of research works. In contrast, decision-makers may explore the possibilities and impacts of different scenarios to support decisions involving technology adoption and configuration, traceability schemes, and business rules in either supply chain or smart contract contexts. Policymakers may use simulation models to assist in the definition of rules and laws, concerning issues of dispute resolutions, sensitive information protection, and fair competition, aiming to assist and encourage blockchain adoption.

Another important aspect to be highlighted is the usability of the hybrid simulation framework presented. The sequence proposed assists the modeler in integrating aspects of supply chain traceability and blockchain configuration. In parallel it enables the customization of agents’ characteristics and the finding of compatible modeling decisions, leading to a versatile approach to dealing with different situations. Overall, the “Model implementation” phase is facilitated and strengthened by the steps taken in a previous robust “Model design” phase.

This work assumes that the performance of blockchain-based traceability can be experimented through hybrid simulation models. This assessment may contribute to dealing with the skepticism of supply chain parties interested in adopting this technology, as the simulation is a powerful tool to test alternatives with reduced time and cost before implementation. The advantages can be extended to other blockchain features beyond traceability, as several combinations of factors are investigated in other works, as listed in Table 6. From an in-depth perspective, among others, the hybrid simulation framework proposed can be used for tests related to the definition of operational schemes regarding information sharing and frequency of updates.

In a nutshell, this thesis focuses on blockchain’s potential to leverage supply chain traceability and provides instruction to apply simulation to analyze traceability systems and comprehend some of the blockchain benefits to supply chain management from a quantitative standpoint.

### 6.2 Thesis contributions

This thesis is centered on supply chain traceability as an application context for blockchain technology, which has been extensively studied in the literature recently. We have explored traceability as one of the several potential features of blockchain, by combining the SCOR model and the GTS standard to structure the development of realistic hybrid simulation models. Following the DSR paradigm, two artifacts are given, a methodological framework for model development, and a hybrid simulation model to analyze supply chain networks' structure.

A review of reviews depicts the first contribution of this research. This study was published in a peer-reviewed journal with a high impact factor, in a special issue entitled "Blockchain-based applications for enhancing cybersecurity in manufacturing and building supply chain resilience".

Secondly, a methodological framework was developed as an artifact under the Design Science Research paradigm, bringing practical contributions for modelers that are going to develop hybrid simulation models to analyze supply chain traceability considering blockchain. A proof-of-concept was developed in a live lobster supply chain in Canada and has employed part of the framework functionalities and properly explored the hierarchical relations in the decomposition of different traceable object agents.

Regarding the contribution of the third part, supplier evaluation is explored in both single and multi-level approaches, indicating the potential of blockchain to enhance the precision and transparency of the process. Moreover, it illustrates the framework's suitability to represent complex phenomena that emerge from the decisions made by multiple agents and the possibility of including business theories. In practical terms, the hybrid simulation model developed may motivate new insights related to supplier selection processes and ways to bring together internal and external traceability particularities. Alternatively, from a theoretical perspective, the inclusion of network theory illustrates the framework's potential to involve theoretical lens.

In a nutshell, this thesis has provided new insights for the comprehension of some contributions of blockchain technology for supply chain management, by highlighting supply chain general metrics and supply chain requirements in its first part. Moreover, a practical contribution is offered to simulation modelers who can utilize the methodological framework to build models following a structured approach. The framework may also be used as a resource to teach classes about hybrid simulation modeling, supply chain operations, and traceability processes. Lastly, in a broader perspective, the usability of data-capturing technologies may be exemplified through the applications herein considered as existing field resources for traceability.

### 6.3 Thesis limitations and future directions

As intrinsic to research, this work has its limitations. The application case used to test both the methodological framework and the hybrid simulation model in parts two and three was the same. Although it was explored from different angles, the analysis of other contexts would be worthy of embracing other particularities. The case adopted has distinctive characteristics as it handles a live product with sufficient demand, which makes the time to consumption shorter. For non-live products, an interesting aspect to be included is inventory issues, according to different demand profiles and supply chain coordination schemes.

In terms of blockchain technology, a limitation of this work is not having integration with a real blockchain platform, as proposed by Longo *et al.* (2019). In addition, we have focused on traceability data, practices, and decisions. Other relevant aspects such as smart contracts and information processing time were not analyzed. However, the proposed framework is suitable to deal with the former in the context of traceability and can be adapted to analyze the latter, revealing promising opportunities for future research. The study of smart contracts regarding parametrization may accelerate the digitalization of processes and the automation of existing flows, bringing lead time reductions to validate transactions. Another possible path is related to analyzing membership aspects and exploring blockchain adoption, according to the profile of supply chain parties in terms of preferences and readiness to upgrade their practices.

From the perspective of supply chain management, the trust paradigm may be addressed through the steps of the framework proposed and included as a component to impact network structure formation. Also, traceability data may be explored for additional applications, such as anticounterfeiting, dispute resolution, product provenance, and supply chain disintermediation. Another possible future direction is taking traceability data of vehicles to assist logistics management through the anticipation of transport-related decisions.

Regarding simulation modeling, the scope of the models presented can be complemented. Submodels may be addressed to dictate the agents' behavior and to set environmental conditions in more sophisticated ways. Other business rules may be added for experimentation, enhancing the interaction between agents, and possibly involving collective impacts. Agents' abilities in decisions may be enriched by the combined implementation of either genetic or machine learning algorithms, even to set the criteria to be adopted or their respective weights in decision-making processes.

From the theoretical standpoint, there are open opportunities concerning network theory. Other measures related to aspects such as segregation, integration, centrality, and resilience (RUBINOV; SPORNS, 2010) may be explored. From this perspective, a longer supply chain network should be assessed. The impact of customer selection may also be addressed in terms of its impact on a network establishment and transition.

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## APPENDIX

Table A1 - Sample information

Subsample of RQ3: 57

| # | Authors | Year | Title | Type of review | Objectives | | | | | | Journal | DOI | Factors listed | Supply chain objectives | | | | | | | | Supply chain improvements | | | | | | | | | Industry / Sector | Blockchain features | | | | | | | | | | Research directions | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | State-of-the-art | Research consolidation | Gaps and directions | Factors listing | Framework | New issues | | | | Cost | Security | Quality | Sustainability | Safety | Speed | Flexibility | Reliability | Transparency | Trust | Anticounterfeit | Disintermediation | Compliance | Decentralization | Provenance | Dispute resolution | Property rights | | Smart Contracts | Traceability | Real-time processing | Immutability | Consensus mechanism | Permanent availability | Verifiability | Peer-to-peer network | Chronological chain | Digital signature | Adoption and contextual factors | Technology integration | Sustainability | Governance | Security | Relationships | Information / Data management | Structural complexity | Costs | Traceability | Theoretical developments | Competitiveness |
| 1 | Ahmad, R. W., Hasan, H., Yaqoob, I., Salah, K., Jayaraman, R., and Omar, M. | 2021 | Blockchain for aerospace and defense: opportunities and open research challenges | Narrative | x | x | x | - | x | - | Computers & Industrial Engineering | 10.1016/j.cie.2020.106982 | - | x | x | - | - | - | - | - | x | x | x | x | - | x | - | x | x | - | Aerospace and defense | x | x | - | x | - | x | - | - | - | x | - | - | - | x | x | - | x | - | - | - | - | - |
| 2 | Al-Farsi, S., Rathore, M. M., and Bakiras, S. | 2021 | Security of blockchain-based supply chain management systems: challenges and opportunities | Systematic | x | x | x | - | - | - | Applied Sciences | 10.3390/app11125585 | - | x | x | - | x | - | - | - | - | x | x | - | - | x | x | x | x | - | - | x | x | x | x | x | - | x | - | - | - | - | - | - | x | x | - | - | x | - | - | - | - |
| 3 | Alkhudary, R., Queiroz, M. M., and Féniès, P. | 2022 | Mitigating the risk of specific supply chain disruptions through blockchain technology | Systematic | - | x | x | x | - | - | Supply Chain Forum: An International Journal | 10.1080/16258312.2022.2090273 | Mitigable risks | - | x | - | - | - | - | - | - | x | - | x | - | - | - | - | x | x | - | - | x | x | - | - | x | - | - | - | - | x | - | - | - | - | - | - | x | - | x | - | - |
| 4 | Antonucci, F., Figorilli, S., Costa, C., Pallottino, F., Raso, L., and Menesatti, P. | 2019 | A review on blockchain applications in the agri-food sector | Narrative | x | x | - | - | - | - | Journal of the Science of Food and Agriculture | 10.1002/jsfa.9912 | - | - | - | x | x | x | - | - | - | x | x | - | - | - | x | - | - | - | Agri-food | x | x | - | x | - | - | - | - | - | - | | | | | | | | | | | | |
| 5 | Asante, M., Epiphaniou, G., Maple, C., Al-Khateeb, H., Bottarelli, M., and Ghafoor, K. Z. | 2021 | Distributed ledger technologies in supply chain security management: a comprehensive survey. | Systematic | x | x | x | - | - | - | IEEE Transactions on Engineering Management | 10.1109/TEM.2021.3053655 | - | x | x | x | - | - | x | - | - | x | x | x | x | x | x | x | - | x | - | x | x | x | x | x | x | - | - | - | x | x | - | - | - | x | - | - | - | - | - | - | x |
| 6 | Astarita, V., Giofrè, V. P., Mirabelli, G., and Solina, V. | 2020 | A review of blockchain-based systems in transportation | Systematic | x | x | x | - | - | - | Information | 10.3390/info11010021 | - | - | - | - | - | - | - | - | - | x | x | x | - | x | x | - | - | - | Transportation | x | x | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | x | x | - | - |
| 7 | Astill, J., Dara, R. A., Campbell, M., Farber, J. M., Fraser, E. D. G., Sharif, S., and Yada, R. Y. | 2019 | Transparency in food supply chains: a review of enabling technology solutions | Narrative | x | - | - | x | - | - | Trends in Food Science & Technology | 10.1016/j.tifs.2019.07.024 | Challenges | x | x | x | x | - | - | - | - | x | - | - | - | x | - | - | - | - | Food | x | x | - | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 8 | Bamakan, S. M. H., Moghaddam, S. G., and Manshadi, S. D. | 2021 | Blockchain-enabled pharmaceutical cold chain: applications, key challenges, and future trends | Narrative | x | x | x | x | - | - | Journal of Cleaner Production | 10.1016/j.jclepro.2021.127021 | Challenges and opportunit | x | x | x | - | x | x | - | - | x | - | x | x | x | - | x | - | - | Pharmaceutical | x | x | - | - | - | - | - | x | - | - | x | x | - | - | - | x | x | x | - | - | - | - |
| 9 | Bekrar, A., Ait El Cadi, A., Todosijevic, R., and Sarkis, J. | 2021 | Digitalizing the closing-of-the-loop for supply chains: a transportation and blockchain perspective | Narrative | x | x | x | - | - | - | Sustainability | 10.3390/su13052895 | - | x | x | x | x | - | x | - | - | x | x | - | - | - | - | - | - | - | - | x | x | x | x | - | - | - | - | - | - | - | x | - | - | - | - | - | - | x | x | - | - |
| 10 | Berneis, M., Bartsch, D., and Winkler, H. | 2021 | Applications of blockchain technology in logistics and supply chain management—Insights from a systematic literature review | Systematic | - | x | - | - | - | - | Logistics | 10.3390/logistics5030043 | - | - | x | - | - | - | - | - | - | x | x | - | - | - | - | - | - | - | Multiple | x | x | - | x | - | x | - | - | - | - | | | | | | | | | | | | |
| 11 | Casino, F., Dasaklis, T. K., and Patsakis, C. | 2019 | A systematic literature review of blockchain-based applications: current status, classification and open issues | Systematic | x | x | x | - | - | - | Telematics and Informatics | 10.1016/j.tele.2018.11.006 | - | - | x | - | x | - | - | x | - | x | x | x | x | - | x | - | - | - | Multiple | - | x | - | - | - | - | - | - | - | - | x | x | x | - | x | - | x | - | - | - | - | - |
| 12 | Chang, S. E. and Chen, Y. | 2020 | When blockchain meets supply chain: a systematic literature review on current development and potential applications | Systematic | x | x | x | - | - | - | IEEE Access | 10.1109/ACCESS.2020.2983601 | - | x | x | - | - | - | - | - | - | x | x | - | x | - | - | x | x | x | Multiple | x | x | - | - | - | - | - | - | - | x | x | x | - | x | x | - | - | - | - | - | - | - |
| 13 | Chang, Y., Iakovou, E., and Shi, W. | 2019 | Blockchain in global supply chains and cross border trade: a critical synthesis of the state-of-the-art, challenges and opportunities | Narrative | x | x | x | x | - | - | International Journal of Production Research | 10.1080/00207543.2019.1651946 | Challenges and opportunit | x | x | x | - | - | - | - | - | x | x | x | - | x | - | - | x | x | Global trade | x | x | x | x | x | - | x | - | - | - | - | - | - | - | x | - | x | - | - | - | - | - |
| 14 | Chen, S., Liu, X., Yan, J., Hu, G., and Shi, Y. | 2020 | Processes, benefits, and challenges for adoption of blockchain technologies in food supply chains: a thematic analysis | Systematic | x | x | - | x | x | - | Information Systems and e-Business Management | 10.1007/s10257-020-00467-3 | Benefits and challenges | x | - | x | - | x | - | - | - | x | x | - | x | - | x | x | - | - | Food | - | x | x | - | - | x | - | - | - | - | | | | | | | | | | | | |
| 15 | Cole, R., Stevenson, M. and Aitken, J. | 2019 | Blockchain technology: implications for operations and supply chain management | Narrative | x | - | x | x | - | - | Supply Chain Management: An International Journal | 10.1108/SCM-09-2018-0309 | Potential uses | x | x | x | x | x | - | - | - | x | x | x | x | - | x | - | - | - | - | x | x | x | x | - | - | - | - | x | - | x | - | - | - | - | x | - | - | - | - | x | - |
| 16 | Dasaklis, T. K., Voutsinas, T. G., Tsoulfas, G. T., and Casino, F. | 2022 | A systematic literature review of blockchain-enabled supply chain traceability implementations | Systematic | x | x | x | - | - | - | Sustainability | 10.3390/su14042439 | - | x | x | x | x | x | - | - | - | x | x | x | - | - | - | x | - | x | Multiple | x | x | x | - | - | x | - | - | - | - | - | - | x | x | - | - | x | x | x | x | - | - |
| 17 | Demestichas, K., Peppes, N., Alexakis, T.,and Adamopoulou, E. | 2020 | Blockchain in agriculture traceability systems: a review | Narrative | x | x | x | - | - | - | Applied Sciences | 10.3390/app10124113 | - | x | - | - | - | - | - | - | - | x | - | - | - | - | - | - | - | - | Agriculture | x | x | - | - | - | - | - | - | - | - | - | x | - | - | - | - | - | - | - | - | - | - |
| 18 | Di Vaio, A. and Varriale, L. | 2020 | Blockchain technology in supply chain management for sustainable performance: evidence from the airport industry | Systematic | x | x | - | - | - | x | International Journal of Information Management | 10.1016/j.ijinfomgt.2019.09.010 | - | x | - | - | x | - | - | - | - | - | x | - | - | - | - | - | - | - | Airport | - | - | - | - | x | - | - | - | - | - | | | | | | | | | | | | |
| 19 | Dobrovnik, M., Herold, D. M., Fürst, E., and Kummer, S. | 2018 | Blockchain for and in logistics: what to adopt and where to start | Systematic | x | x | - | x | x | - | Logistics | 10.3390/logistics2030018 | Applications | x | - | - | x | - | - | - | - | x | - | x | - | - | - | - | - | - | Logistics | x | - | - | - | - | - | - | - | x | - | | | | | | | | | | | | |
| 20 | Duan, J., Zhang, C., Gong, Y., Brown, S., and Li, Z. | 2020 | A content-analysis based literature review in blockchain adoption within food supply chain | Systematic | x | x | - | x | - | - | International Journal of Environmental Research and Public Health | 10.3390/ijerph17051784 | Benefits and challenges | - | - | x | x | - | - | - | - | x | x | - | - | - | x | - | - | - | Food | x | x | x | x | - | - | - | - | - | - | | | | | | | | | | | | |
| 21 | Dutta, P., Choi, T. M., Somani, S., and Butala, R. | 2020 | Blockchain technology in supply chain operations: applications, challenges and research opportunities | Systematic | x | x | x | x | - | - | Transportation Research Part E | 10.1016/j.tre.2020.102067 | Applications, benefits, and | x | x | - | x | x | x | - | - | x | x | x | - | x | x | - | - | - | Multiple | x | x | x | - | x | - | - | - | - | - | x | - | x | - | - | x | - | - | - | - | - | - |
| 22 | Esmaeilian, B., Sarkis, J., Lewis, K., and Behdad, S. | 2020 | Blockchain for the future of sustainable supply chain management in Industry 4.0 | Narrative | x | - | x | - | - | - | Resources, Conservation & Recycling | 10.1016/j.resconrec.2020.105064 | - | x | - | - | x | x | - | - | - | x | - | x | - | - | x | - | - | - | - | x | x | x | x | x | - | x | - | - | x | - | x | - | - | - | - | - | - | - | - | - | - |
| 23 | Etemadi, N., Borbon-Galvez, Y., Strozzi, F., and Etemadi, T. | 2021 | Supply chain disruption risk management with blockchain: a dynamic literature review | Systematic | x | x | x | - | - | - | Information | 10.3390/info12020070 | - | x | x | x | - | x | - | x | x | x | x | x | - | - | - | x | - | - | - | x | x | x | - | - | - | - | - | - | - | x | x | - | - | x | - | x | - | - | x | - | - |
| 24 | Feng, H., Wang, X., Duan, Y., Zhang, J., and Zhang, X. | 2020 | Applying blockchain technology to improve agri-food traceability: a review of development methods, benefits and challenges | Systematic | x | - | - | x | x | - | Journal of Cleaner Production | 10.1016/j.jclepro.2020.121031 | Methods, benefits, and ch | - | x | x | x | x | - | - | x | x | x | x | - | x | x | - | - | - | Agri-food | x | x | - | x | x | - | - | - | - | x | | | | | | | | | | | | |
| 25 | Filimonau, V. and Naumova, E. | 2020 | The blockchain technology and the scope of its application in hospitality operations | Narrative | x | x | - | - | x | x | International Journal of Hospitality Management | 10.1016/j.ijhm.2019.102383 | - | x | x | - | x | - | x | - | - | x | x | - | - | - | - | - | - | - | Hospitality | x | - | - | - | - | - | - | x | - | - | | | | | | | | | | | | |
| 26 | Fosso Wamba, S., Kala Kamdjoug, J. R., Epie Bawack, R., and Keogh, J. G. | 2020 | Bitcoin, blockchain, and fintech: a systematic review and case studies in the supply chain | Systematic | x | x | - | x | x | - | Production Planning & Control | 10.1080/09537287.2019.1631460 | Benefits and challenges | x | x | - | x | - | x | - | x | x | x | x | x | x | x | - | - | - | Multiple | - | - | x | x | - | x | x | - | - | - | | | | | | | | | | | | |
| 27 | Fosso Wamba, S. and Queiroz, M. M. | 2020 | Blockchain in the operations and supply chain management: benefits, challenges and future research opportunities | Systematic | - | x | x | - | - | - | International Journal of Information Management | 10.1016/j.ijinfomgt.2019.102064 | - | - | - | - | - | - | - | - | - | x | x | x | x | - | x | - | - | - | - | x | x | - | - | - | - | - | - | - | - | - | x | - | - | - | - | - | - | x | x | - | - |
| 28 | Galvez, J. F., Mejuto, J. C., and Simal-Gandara, J. | 2018 | Future challenges on the use of blockchain for food traceability analysis | Narrative | x | x | - | x | - | - | Trends in Analytical Chemistry | 10.1016/j.trac.2018.08.011 | Challenges | x | x | x | - | x | - | - | - | x | x | x | - | - | - | x | - | - | Food | x | x | x | - | - | - | x | - | - | - | | | | | | | | | | | | |
| 29 | Gonczol, P., Katsikouli, P., Herskind, L., and Dragoni, N. | 2020 | Blockchain implementations and use cases for supply chains-A survey | Systematic | x | x | x | x | - | - | IEEE Access | 10.1109/ACCESS.2020.2964880 | Benefits and challenges | x | - | x | - | - | x | - | - | x | x | x | - | x | - | - | - | - | Multiple | - | x | x | - | - | - | - | - | - | - | x | x | - | - | - | - | - | - | - | x | - | - |
| 30 | Gurtu, A. and Johny, J. | 2019 | Potential of blockchain technology in supply chain management: a literature review | Systematic | x | x | - | - | - | - | International Journal of Physical Distribution & Logistics Management | 10.1108/IJPDLM-11-2018-0371 | - | x | - | - | - | - | x | - | x | - | x | - | - | - | - | - | - | - | - | x | - | - | - | - | - | x | - | - | - | | | | | | | | | | | | |
| 31 | Hald, K. S. and Kinra, A. | 2019 | How the blockchain enables and constrains supply chain performance | Systematic | x | - | x | x | - | - | International Journal of Physical Distribution & Logistics Management | 10.1108/IJPDLM-02-2019-0063 | Enablers and constraints | - | - | x | x | - | - | x | - | x | x | - | x | x | x | - | - | - | - | x | x | x | - | x | x | - | - | - | - | - | - | x | x | - | - | x | x | - | x | - | - |
| 32 | Hastig, G. M. and Sodhi, M. S. | 2020 | Blockchain for supply chain traceability: business requirements and critical success factors | Systematic | x | x | - | x | - | - | Production and Operations Management | 10.1111/poms.13147 | Business requirements and | x | x | x | x | - | x | - | - | x | x | x | - | x | x | x | x | - | - | - | x | x | x | - | - | - | - | - | - | | | | | | | | | | | | |
| 33 | Hughes, L., Dwivedi, Y. K., Misra, S. K., Rana, N. P., Raghavan, V., and Akella, V. | 2019 | Blockchain research, practice and policy: applications, benefits, limitations, emerging research themes and research agenda | Narrative | x | - | x | x | x | x | International Journal of Information Management | 10.1016/j.ijinfomgt.2019.02.005 | Applications, benefits, and | x | x | - | x | - | - | x | - | x | x | - | x | - | - | - | - | - | - | x | - | - | x | - | - | x | - | - | - | x | - | - | x | x | - | - | - | x | - | - | - |
| 34 | Juma, H., Shaalan, K., and Kamel, I. | 2019 | A survey on using blockchain in trade supply chain solutions | Systematic | x | x | - | - | - | - | IEEE Access | 10.1109/ACCESS.2019.2960542 | - | - | x | - | - | x | x | - | - | - | - | x | - | - | - | - | - | - | International trade | x | x | - | - | x | - | x | - | - | - | | | | | | | | | | | | |
| 35 | Kamilaris, A., Fonts, A., and Prenafeta-Boldύ, F. X. | 2019 | The rise of blockchain technology in agriculture and food supply chains | Systematic | x | x | - | x | - | - | Trends in Food Science & Technology | 10.1016/j.tifs.2019.07.034 | Challenges and opportunit | - | x | x | x | x | - | x | - | x | x | - | x | - | - | - | x | - | Agriculture | x | x | - | - | - | x | - | - | - | - | | | | | | | | | | | | |
| 36 | Karakas, S., Acar, A. Z., and Kucukaltan, B. | 2021 | Blockchain adoption in logistics and supply chain: a literature review and research agenda | Systematic | x | - | x | x | x | - | International Journal of Production Research | 10.1080/00207543.2021.2012613 | Enablers, risks, and challe | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | x | - | - | x | x | x | x | x | - | - | - | - | - | x | - | x | x | - | - | - | x | - | x | x | x |
| 37 | Kassab, M., DeFranco, J., Malas, T., Laplante, P., Giuseppe, D., and Graciano Neto, V. V. | 2021 | Exploring research in blockchain for healthcare and a roadmap for the future | Systematic | x | x | - | - | - | - | IEEE Transactions on Emerging Topics in Computing | 10.1109/TETC.2019.2936881 | - | - | - | - | - | x | - | - | - | x | - | x | - | - | - | x | - | - | Healthcare | x | - | - | - | - | - | - | - | x | - | | | | | | | | | | | | |
| 38 | Kayikci, Y., Subramanian, N., Dora, M., and Bhatia, M. S. | 2022 | Food supply chain in the era of Industry 4.0: blockchain technology implementation opportunities and impediments from the perspective of people, process, performance, and technology | Systematic | x | x | - | - | x | - | Production Planning & Control | 10.1080/09537287.2020.1810757 | - | x | x | x | x | x | - | - | - | x | x | - | - | - | - | x | - | - | Food | x | x | - | - | x | - | - | - | x | - | | | | | | | | | | | | |
| 39 | Kayikci, Y., Usar, D. D., and Aylak, B. L. | 2021 | Using blockchain technology to drive operational excellence in perishable food supply chains during outbreaks | Systematic | x | x | - | x | - | - | International Journal of Logistics Management | 10.1108/IJLM-01-2021-0027 | Enablers | x | x | x | - | x | x | x | - | x | - | - | x | - | x | x | - | x | Food | x | x | - | x | x | - | - | - | - | - | | | | | | | | | | | | |
| 40 | Khanfar, A. A., Iranmanesh, M., Ghobakhloo, M., Senali, M. G., and Fathi, M. | 2021 | Applications of blockchain technology in sustainable manufacturing and supply chain management: a systematic review | Systematic | x | x | x | x | - | - | Sustainability | 10.3390/su13147870 | Contributions | x | x | x | x | x | x | x | x | x | x | - | - | x | x | - | - | - | Manufacturing | x | x | x | - | - | - | x | - | - | - | x | - | x | - | - | - | - | - | - | - | - | - |
| 41 | Kiu, M. S., Chia, F. C., and Wong, P. F. | 2020 | Exploring the potentials of Blockchain application in construction industry: a systematic review | Systematic | x | x | x | - | - | - | International Journal of Construction Management | 10.1080/15623599.2020.1833436 | - | - | x | - | - | - | - | - | - | x | - | - | - | - | - | - | x | - | Construction | x | x | - | - | - | - | - | - | x | - | x | - | x | - | - | - | x | - | - | - | - | - |
| 42 | Kouhizadeh, M. and Sarkis, J. | 2018 | Blockchain practices, potentials, and perspectives in greening supply chains | Narrative | x | - | x | x | x | - | Sustainability | 10.3390/su10103652 | Practices, potentials, and p | - | - | x | x | - | - | - | - | x | x | x | x | x | - | - | - | - | - | x | x | - | - | - | - | x | - | x | - | x | x | x | - | - | x | - | - | - | - | x | - |
| 43 | Kramer, M. P., Bitsch, L., and Hanf, J. | 2021 | Blockchain and its impacts on agri-food supply chain network management | Systematic | x | x | - | - | - | - | Sustainability | 10.3390/su13042168 | - | x | - | x | x | x | - | - | - | x | x | - | x | - | x | x | - | - | Agri-food | x | x | - | x | x | - | - | x | - | - | | | | | | | | | | | | |
| 44 | Kummer, S., Herold, D. M., Dobrovnik, M., Mikl, J., and Schäfer, N. | 2020 | A systematic review of blockchain literature in logistics and supply chain management: identifying research questions and future directions | Systematic | x | x | x | - | - | - | Future Internet | 10.3390/fi12030060 | - | x | - | - | - | - | - | - | - | x | x | - | x | - | - | - | - | - | - | x | - | - | - | - | - | - | - | - | - | x | - | - | - | - | x | - | - | x | - | - | x |
| 45 | Lambourdiere, E. and Corbin, E. | 2020 | Blockchain and maritime supply-chain performance: dynamic capabilities perspective | Narrative | - | x | x | - | x | - | Worldwide Hospitality and Tourism Themes | 10.1108/WHATT-10-2019-0069 | - | x | - | - | - | - | - | - | - | x | x | - | x | - | x | - | - | - | Maritime | - | - | x | - | - | x | - | - | x | - | - | - | - | - | - | - | - | x | - | - | - | - |
| 46 | Lezoche, M., Hernandez, J. E., Díaz, M. D. M. E. A., Panetto, H., and Kacprzyk, J. | 2020 | Agri-food 4.0: a survey of the supply chains and technologies for the future agriculture | Narrative | x | - | - | x | - | - | Computers in Industry | 10.1016/j.compind.2020.103187 | Impact and challenges | x | - | x | - | - | - | - | x | - | x | - | x | - | x | - | - | - | Agri-food | - | - | x | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 47 | Li, J., Maiti, A., Springer, M., and Gray, T. | 2020 | Blockchain for supply chain quality management: challenges and opportunities in context of open manufacturing and industrial internet of things | Narrative | x | - | - | x | x | - | International Journal of Computer Integrated Manufacturing | 10.1080/0951192X.2020.1815853 | Advantages and challenges | x | x | x | - | - | - | x | x | x | x | - | - | x | - | - | - | - | - | x | x | x | x | - | - | x | - | - | - | | | | | | | | | | | | |
| 48 | Li, K., Lee, J. Y., and Gharehgozli, A. | 2021 | Blockchain in food supply chains: a literature review and synthesis analysis of platforms, benefits and challenges | Systematic | x | x | - | x | - | - | International Journal of Production Research | 10.1080/00207543.2021.1970849 | Enablers, benefits, and cha | x | x | x | x | x | x | - | - | x | x | x | - | - | - | - | - | - | Food | x | x | x | x | - | - | - | - | x | - | | | | | | | | | | | | |
| 49 | Li, L. and Zhou, H. | 2021 | A survey of Blockchain with applications in maritime and shipping industry | Narrative | x | x | - | - | - | - | Information Systems and e-Business Management | 10.1007/s10257-020-00480-6 | - | x | x | - | - | x | x | - | x | x | - | - | - | x | - | - | - | - | Maritime and shipping | x | x | x | - | - | x | - | - | - | x | | | | | | | | | | | | |
| 50 | Li, Z., Zhong, R. Y., Tian, Z. G., Dai, H. N., Barenji, A. V., and Huang, G. Q. | 2021 | Industrial blockchain: a state-of-the-art survey | Systematic | x | x | - | - | - | - | Robotics and Computer-Integrated Manufacturing | 10.1016/j.rcim.2021.102124 | - | x | x | - | x | - | - | - | - | - | - | x | - | - | - | - | - | - | Multiple | x | - | - | - | x | - | - | - | - | x | | | | | | | | | | | | |
| 51 | Lim, M. K., Li, Y., Wang, C., and Tseng, M. L. | 2021 | A literature review of blockchain technology applications in supply chains: a comprehensive analysis of themes, methodologies and industries | Systematic | x | x | x | - | - | - | Computers & Industrial Engineering | 10.1016/j.cie.2021.107133 | - | x | x | - | x | x | - | - | - | x | x | - | - | - | - | - | - | - | - | x | x | x | - | x | - | - | x | - | - | x | x | x | - | x | x | x | x | - | - | x | - |
| 52 | Liu, J., Zhang, H., and Zhen, L. | 2021 | Blockchain technology in maritime supply chains: applications, architecture and challenges | Narrative | x | x | x | x | - | - | International Journal of Production Research | 10.1080/00207543.2021.1930239 | Applications and challeng | x | x | x | x | - | x | - | - | x | x | x | - | x | x | - | - | - | Maritime | x | x | x | x | - | - | x | - | - | - | - | x | - | x | - | - | - | x | - | - | - | - |
| 53 | Lohmer, J., Ribeiro da Silva, E., and Lasch, R. | 2022 | Blockchain technology in operations & supply chain management: a content analysis | Systematic | x | x | x | x | - | - | Sustainability | 10.3390/su14106192 | Potentials and barriers | x | x | - | x | - | - | - | - | x | x | - | x | - | x | - | - | x | - | x | x | x | x | x | - | - | - | - | - | x | x | x | x | - | - | - | - | - | - | - | - |
| 54 | Longo, F., Nicoletti, L., and Padovano, A. | 2020 | Estimating the Impact of blockchain adoption in the food processing industry and supply chain | Systematic | - | x | - | - | - | - | International Journal of Food Engineering | 10.1515/ijfe-2019-0109 | - | x | - | x | - | - | - | - | - | - | - | - | - | - | - | x | - | - | Food | - | x | - | - | - | x | x | - | - | - | | | | | | | | | | | | |
| 55 | Mackey, T. K. and Nayyar, G. | 2017 | A review of existing and emerging digital technologies to combat the global trade in fake medicines | Systematic | x | x | - | - | - | - | Expert Opinion on Drug Safety | 10.1080/14740338.2017.1313227 | - | - | x | x | - | - | - | - | - | x | - | x | - | - | - | - | - | - | Pharmaceutical | - | - | - | - | - | - | x | - | - | - | | | | | | | | | | | | |
| 56 | Maesa, D. D. F. and Mori, P. | 2020 | Blockchain 3.0 applications survey | Narrative | x | x | - | - | - | - | Journal of Parallel and Distributed Computing | 10.1016/j.jpdc.2019.12.019 | - | x | x | - | - | - | x | - | - | x | x | x | x | x | - | - | x | - | Multiple | x | x | x | x | - | x | - | - | x | - | | | | | | | | | | | | |
| 57 | Mahyuni, L. P., Adrian, R., Darma, G. S., Krisnawijaya, N. N. K., Dewi, I. G. A. A. P., and Permana, G. P. L. | 2020 | Mapping the potentials of blockchain in improving supply chain performance | Systematic | x | x | - | - | - | - | Cogent Business & Management | 10.1080/23311975.2020.1788329 | - | x | - | - | x | - | - | - | - | x | x | - | - | - | - | - | - | - | - | x | x | - | - | - | - | - | - | - | - | | | | | | | | | | | | |

| # | Authors | Year | Title | Type of review | Objectives: State-of-the-art | Research consolidation | Gaps and directions | Factors listing | Framework | New issues | Journal | DOI | Factors listed |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 58 | Menon, S. and Jain, K. | 2021 | Blockchain technology for transparency in agri-food supply chain: use cases, limitations, and future directions | Systematic | x | x | x | - | - | - | IEEE Transactions on Engineering Management | 10.1109/TEM.2021.3110903 | - |
| 59 | Min, H. | 2019 | Blockchain technology for enhancing supply chain resilience | Narrative | x | x | - | - | - | - | Business Horizons | 10.1016/j.bushor.2018.08.012 | - |
| 60 | Mistry, I., Tanwar, S., Tyagi, S., and Kumar, N. | 2020 | Blockchain for 5G-enabled IoT for industrial automation: a systematic review, solutions, and challenges | Narrative | x | x | - | - | - | - | Mechanical Systems and Signal Processing | 10.1016/j.ymssp.2019.106382 | - |
| 61 | Müßigmann, B., von der Gracht, H., and Hartmann, E. | 2020 | Blockchain technology in logistics and supply chain management-A bibliometric literature review from 2016 to january 2020 | Narrative | x | x | - | - | - | - | IEEE Transactions on Engineering Management | 10.1109/TEM.2020.2980733 | - |
| 62 | Nabipour, M. and Ülkü, M. A. | 2021 | On deploying blockchain technologies in supply chain strategies and the COVID-19 pandemic: a systematic literature review and research outlook | Systematic | x | - | x | - | - | x | Sustainability | 10.3390/su131910566 | - |
| 63 | Nandi, M.L., Nandi, S., Moya, H., and Kaynak, H. | 2020 | Blockchain technology-enabled supply chain systems and supply chain performance: a resource-based view | Systematic | x | x | x | x | x | - | Supply Chain Management: An International Journal | 10.1108/SCM-12-2019-0444 | Capabilities |
| 64 | Nurgazina, J., Pakdeetrakulwong, U., Moser, T., and Reiner, G. | 2021 | Distributed ledger technology applications in food supply chains: a review of challenges and future research directions | Systematic | x | x | x | x | - | - | Sustainability | 10.3390/su13084206 | Challenges |
| 65 | Paliwal, V., Chandra, S., and Sharma, S. | 2020 | Blockchain technology for sustainable supply chain management: a systematic literature review and a classification framework | Systematic | x | x | x | x | x | - | Sustainability | 10.3390/su12187638 | Barriers |
| 66 | Pandey, V., Pant, M., and Snasel, V. | 2022 | Blockchain technology in food supply chains: review and bibliometric analysis | Systematic | x | x | - | - | - | - | Technology in Society | 10.1016/j.techsoc.2022.101954 | - |
| 67 | Park, A. and Li, H. | 2021 | The effect of blockchain technology on supply chain sustainability performances | Systematic | x | x | - | - | - | - | Sustainability | 10.3390/su13041726 | - |
| 68 | Pournader, M., Shi, Y., Seuring, S., and Koh, S. C. L. | 2020 | Blockchain applications in supply chains, transport and logistics: a systematic review of the literature | Systematic | x | x | x | - | x | - | International Journal of Production Research | 10.1080/00207543.2019.1650976 | - |
| 69 | Queiroz, M. M., Telles, R., and Bonilla, S.H. | 2019 | Blockchain and supply chain management integration: a systematic review of the literature | Systematic | x | x | x | x | - | - | Supply Chain Management: An International Journal | 10.1108/SCM-03-2018-0143 | Disruptions and challenges |
| 70 | Rana, R. L., Tricase, C., and De Cesare, L. | 2021 | Blockchain technology for a sustainable agri-food supply chain | Systematic | x | x | - | - | - | - | British Food Journal | 10.1108/BFJ-09-2020-0832 | - |
| 71 | Reddy, K. R. K., Gunasekaran, A., Kalpana, P., Sreedharan, V. R., and Kumar, S. A. | 2021 | Developing a blockchain framework for the automotive supply chain: a systematic review | Systematic | x | x | x | x | x | - | Computers & Industrial Engineering | 10.1016/j.cie.2021.107334 | Challenges |
| 72 | Rejeb, A., Keogh, J. G., Simske, S. J., Stafford, T., and Treiblmaier, H. | 2021 | Potentials of blockchain technologies for supply chain collaboration: a conceptual framework | Narrative | - | - | x | - | x | - | The International Journal of Logistics Management | 10.1108/IJLM-02-2020-0098 | - |
| 73 | Rejeb, A., Keogh, J. G., and Treiblmaier, H. | 2019 | Leveraging the internet of things and blockchain technology in supply chain management | Narrative | x | x | x | - | - | - | Future Internet | 10.3390/fi11070161 | - |
| 74 | Rejeb, A., Keogh, J. G., Zailani, S., Treiblmaier, H., and Rejeb, K. | 2020 | Blockchain technology in the food industry: a review of potentials, challenges and future research directions | Systematic | x | x | x | x | x | - | Logistics | 10.3390/logistics4040027 | Potential and challenges |
| 75 | Rejeb, A., Rejeb, K., Simske, S., and Treiblmaier, H. | 2021 | Blockchain technologies in logistics and supply chain management: a bibliometric review | Systematic | x | x | x | - | - | - | Logistics | 10.3390/logistics5040072 | - |
| 76 | Rufino Júnior, C. A., Sanseverino, E. R., Gallo, P., Koch, D., Schweiger, H. G., and Zanin, H. | 2022 | Blockchain review for battery supply chain monitoring and battery trading | Systematic | x | x | - | x | - | - | Renewable and Sustainable Energy Reviews | 10.1016/j.rser.2022.112078 | Benefits |
| 77 | Saberi, S., Kouhizadeh, M., Sarkis, J., and Shen, L. | 2019 | Blockchain technology and its relationships to sustainable supply chain management | Narrative | x | - | x | x | x | - | International Journal of Production Research | 10.1080/00207543.2018.1533261 | Barriers |
| 78 | Santhi, A. R. and Muthuswamy, P. | 2022 | Influence of blockchain technology in manufacturing supply chain and logistics | Narrative | - | x | x | - | - | - | Logistics | 10.3390/logistics6010015 | - |
| 79 | Schmidt, C. G. and Wagner, S. M. | 2019 | Blockchain and supply chain relations: a transaction cost theory perspective | Narrative | x | - | x | - | x | - | Journal of Purchasing and Supply Management | 10.1016/j.pursup.2019.100552 | - |
| 80 | Schuetz, S. and Venkatesh, V. | 2020 | Blockchain, adoption, and financial inclusion in India: research opportunities | Narrative | x | - | x | - | - | x | International Journal of Information Management | 10.1016/j.ijinfomgt.2019.04.009 | - |
| 81 | Scott, D. J., Broyd, T., and Ma, L. | 2021 | Exploratory literature review of blockchain in the construction industry | Systematic | x | x | - | - | - | - | Automation in Construction | 10.1016/j.autcon.2021.103914 | - |
| 82 | Shoaib, M., Lim, M. K. and Wang, C. | 2020 | An integrated framework to prioritize blockchain-based supply chain success factors | Systematic | x | - | - | x | x | - | Industrial Management & Data Systems | 10.1108/IMDS-04-2020-0194 | Success factors |
| 83 | Srivastava, A. and Dashora, K. | 2022 | Application of blockchain technology for agrifood supply chain management: a systematic literature review on benefits and challenges | Systematic | x | x | - | x | - | - | Benchmarking: An International Journal | 10.1108/BIJ-08-2021-0495 | Benefits and challenges |
| 84 | Sun, Z. H., Chen, Z., Cao, S., and Ming, X. | 2021 | Potential requirements and opportunities of blockchain-based industrial IoT in supply chain: A survey | Systematic | x | x | - | - | - | - | IEEE Transactions on Computational Social Systems | 10.1109/TCSS.2021.3129259 | - |
| 85 | Sunny, J., Undralla, N., and Pillai, V. M. | 2020 | Supply chain transparency through blockchain-based traceability: an overview with demonstration | Narrative | x | x | - | - | - | - | Computers & Industrial Engineering | 10.1016/j.cie.2020.106895 | - |
| 86 | Tanwar, S., Parmar, A., Kumari, A., Jadav, N. K., Hong, W. C., and Sharma, R. | 2022 | Blockchain adoption to secure the food industry: opportunities and challenges | Systematic | x | x | x | - | - | - | Sustainability | 10.3390/su14127036 | - |
| 87 | Thakker, U., Patel, R., Tanwar, S., Kumar, N., and Song, H. | 2021 | Blockchain for diamond industry:opportunities and challenges | Systematic | x | x | x | - | - | - | IEEE Internet of Things Journal | 10.1109/JIOT.2020.3047550 | - |
| 88 | Tharatipyakul, A. and Pongnumkul, S. | 2021 | User interface of blockchain-based agri-food traceability applications: a review | Systematic | x | x | - | x | - | - | IEEE Access | 10.1109/ACCESS.2021.3085982 | Benefits and challenges |
| 89 | Tijan, E., Aksentijević, S., Ivanić, K., and Jardas, M. | 2019 | Blockchain technology implementation in logistics | Narrative | x | x | - | x | - | - | Sustainability | 10.3390/su11041185 | Benefits and challenges |
| 90 | Tokkozhina, U., Martins, A. L., and Ferreira, J. C. | 2022 | Uncovering dimensions of the impact of blockchain technology in supply chain management | Systematic | x | x | x | x | - | - | Operations Management Research | 10.1007/s12063-022-00273-9 | Advantages, disadvantages |
| 91 | Treiblmaier, H. | 2018 | The impact of the blockchain on the supply chain: a theory-based research framework and a call for action | Narrative | x | - | x | - | x | - | Supply Chain Management: An International Journal | 10.1108/SCM-01-2018-0029 | - |
| 92 | Tsiulin, S., Reinau, K. H., Hilmola, O.-P., Goryaev, N., and Karam, A. | 2020 | Blockchain-based applications in shipping and port management: a literature review towards defining key conceptual frameworks | Systematic | x | x | - | - | - | - | Review of International Business and Strategy | 10.1108/RIBS-04-2019-0051 | - |
| 93 | Upadhyay, A., Ayodele, J. O., Kumar, A., and Garza-Reyes, J. A. | 2021 | A reviewof challenges and opportunities of blockchain adoption for operational excellence in the UK automotive industry | Systematic | x | x | x | x | - | - | Journal of Global Operations and Strategic Sourcing | 10.1108/JGOSS-05-2020-0024 | Challenges and opportunit |
| 94 | Varriale, V., Cammarano, A., Michelino, F., and Caputo, M. | 2020 | The unknown potential of blockchain for sustainable supply chains | Systematic | x | x | - | x | - | - | Sustainability | 10.3390/su12229400 | Sustainable and unsustain |
| 95 | Varriale, V., Cammarano, A., Michelino, F., and Caputo, M. | 2021 | New organizational changes with blockchain: a focus on the supply chain | Systematic | x | x | x | x | - | - | Journal of Organizational Change Management | 10.1108/JOCM-08-2020-0249 | Benefits and challenges |
| 96 | Vivaldini, M. | 2020 | Blockchain platforms in supply chains | Systematic | x | x | x | x | - | - | Journal of Enterprise Information Management | 10.1108/JEIM-12-2019-0416 | Solutions and applications |
| 97 | Vivaldini, M. and de Sousa, P. R. | 2021 | Blockchain connectivity inhibitors: weaknesses affecting supply chain interaction and resilience | Systematic | x | x | x | x | - | - | Benchmarking: An International Journal | 10.1108/BIJ-10-2020-0510 | Connectivity inhibitors and |
| 98 | Vu, N., Ghadge, A., and Bourlakis, M. | 2021 | Blockchain adoption in food supply chains: a review and implementation framework | Systematic | x | - | x | x | x | - | Production Planning & Control | 10.1080/09537287.2021.1939902 | Drivers, barriers, and appl |
| 99 | Wan, P. K., Huang, L., and Holtskog, H. | 2020 | Blockchain-enabled information sharing within a supply chain: a systematic literature review | Systematic | x | x | - | - | - | - | IEEE Access | 10.1109/ACCESS.2020.2980142 | - |
| 100 | Wang, Y., Han, J. H. and Beynon-Davies, P. | 2019 | Understanding blockchain technology for future supply chains: a systematic literature review and research agenda | Systematic | x | x | x | x | - | - | Supply Chain Management: An International Journal | 10.1108/SCM-03-2018-0148 | Drivers, challenges, and b |
| 101 | Yin, W. and Ran, W. | 2021 | Theoretical exploration of supply chain viability utilizing blockchain technology | Systematic | x | x | - | - | - | - | Sustainability | 10.3390/su13158231 | - |
| 102 | Zhao, G., Liu, S., Lopez, C., Lu, H., Elgueta, S., Chen, H., and Boshkoska, B. M. | 2019 | Blockchain technology in agri-food value chain management: a synthesis of applications, challenges and future research directions | Systematic | x | x | x | x | - | - | Computers in Industry | 10.1016/j.compind.2019.04.002 | Applications and challenge |
| 103 | Zhu, Q., Bai, C., and Sarkis, J. | 2022 | Blockchain technology and supply chains: the paradox of the atheoretical research discourse | Systematic | x | x | x | - | - | - | Transportation Research Part E | 10.1016/j.tre.2022.102824 | - |
| | | | Sample size: | Total | 96 | 85 | 57 | 47 | 23 | 5 | | | Total.: |
| | | | 103 | Percentage | 93% | 83% | 55% | 46% | 22% | 5% | | | |

| # | Supply chain objectives | | | | | | | | Supply chain improvements | | | | | | | | | Industry / Sector | Blockchain features | | | | | | | | | | Research directions | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Cost | Security | Quality | Sustainability | Safety | Speed | Flexibility | Reliability | Transparency | Trust | Anticounterfeit | Disintermediation | Compliance | Decentralization | Provenance | Dispute resolution | Property rights | | Smart Contracts | Traceability | Real-time processing | Immutability | Consensus mechanism | Permanent availability | Verifiability | Peer-to-peer network | Chronological chain | Digital signature | Adoption and contextual factors | Technology integration | Sustainability | Governance | Security | Relationships | Information / Data management | Structural complexity | Costs | Traceability | Theoretical developments | Competitiveness |
| 58 | x | x | x | - | x | - | - | - | x | - | - | - | x | - | x | x | - | Agri-food | x | x | - | x | - | - | - | - | - | - | - | x | x | x | x | - | - | - | - | - | - | - |
| 59 | - | x | - | - | - | - | x | - | x | x | - | - | - | - | - | - | - | - | x | - | - | x | x | x | - | - | - | - | | | | | | | | | | | | |
| 60 | x | x | x | - | x | - | - | - | - | - | - | x | - | - | - | x | - | Multiple | x | x | x | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 61 | - | x | - | x | x | - | - | - | x | - | - | - | - | - | - | - | - | - | x | x | - | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 62 | - | - | - | x | - | - | - | - | x | - | - | - | - | - | - | - | - | - | x | - | x | - | - | - | - | - | - | - | - | - | x | - | - | - | - | - | - | - | - | - |
| 63 | x | x | x | - | x | x | x | - | x | - | - | x | x | - | - | - | - | Multiple | x | x | x | - | - | - | x | - | - | - | x | - | - | - | - | - | - | - | - | - | - | x |
| 64 | x | x | x | x | x | - | - | x | x | x | x | - | x | - | - | - | - | Food | x | x | x | x | x | x | x | - | - | - | - | x | - | - | x | - | x | - | - | - | - | - |
| 65 | x | x | - | x | - | - | x | - | x | x | x | - | - | - | x | - | - | - | x | x | x | - | - | - | x | - | - | - | x | x | x | x | - | - | - | - | - | - | x | - |
| 66 | x | x | x | x | x | - | - | - | x | x | x | - | - | - | x | - | - | Food | x | x | - | x | x | x | - | - | - | - | | | | | | | | | | | | |
| 67 | - | - | - | x | - | - | - | - | x | - | - | - | x | - | - | - | - | - | - | x | - | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 68 | x | x | - | x | - | - | - | - | x | x | x | - | - | - | - | x | - | - | x | x | - | x | - | - | - | - | - | - | - | - | - | - | - | x | - | x | - | - | - | - |
| 69 | x | x | - | - | - | - | - | - | x | x | x | x | - | x | x | - | - | - | x | x | x | - | - | - | - | x | - | - | - | x | x | x | x | x | - | - | x | - | - | x |
| 70 | x | x | x | x | x | - | - | - | x | - | x | x | - | - | - | - | - | Agri-food | x | x | - | x | - | x | - | - | - | - | | | | | | | | | | | | |
| 71 | x | - | x | x | - | - | - | - | x | x | x | x | - | - | - | - | - | Automotive | x | x | x | x | x | - | x | - | - | - | - | x | x | x | - | - | - | - | x | x | - | - |
| 72 | x | x | - | - | - | - | x | - | x | x | - | x | x | x | - | x | - | - | x | x | x | - | - | - | x | x | - | - | - | x | - | - | x | x | x | - | - | - | x | - |
| 73 | - | x | x | - | - | x | - | x | x | x | x | - | - | x | x | - | - | - | x | x | x | x | x | - | - | x | - | - | - | x | - | - | x | - | x | - | - | x | - | - |
| 74 | x | x | x | x | x | - | x | - | x | x | x | x | - | - | x | x | - | Food | - | x | x | - | - | - | - | - | - | - | - | - | x | - | - | - | - | x | - | - | - | - |
| 75 | x | x | x | x | x | - | x | - | x | x | - | - | x | - | x | - | x | - | x | x | x | - | - | - | - | - | - | - | - | x | - | - | x | x | - | - | - | x | - | x |
| 76 | x | - | x | x | x | - | - | - | x | x | x | - | x | x | x | x | - | Battery | x | x | x | x | - | - | - | - | - | x | | | | | | | | | | | | |
| 77 | x | x | - | x | - | - | - | - | x | x | - | x | - | - | - | - | - | - | x | - | x | x | x | - | x | x | - | - | - | - | x | x | - | x | - | - | - | - | x | - |
| 78 | - | x | - | - | - | - | x | - | x | x | x | - | x | x | - | - | x | Manufacturing | x | x | x | - | - | - | - | - | - | - | x | x | - | x | - | x | - | - | - | - | - | - |
| 79 | x | - | x | x | - | - | - | - | x | x | x | - | x | - | x | - | - | - | x | x | - | x | x | x | - | - | - | - | x | - | x | x | - | - | x | - | - | - | x | - |
| 80 | x | x | - | x | - | - | x | - | - | x | - | x | - | - | - | x | - | - | x | - | - | x | - | - | - | x | - | - | x | - | - | - | - | - | - | - | - | - | - | - |
| 81 | x | - | - | x | - | - | - | x | x | x | - | x | x | x | - | x | x | Construction | x | x | x | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 82 | x | x | x | x | - | - | x | x | x | x | - | x | - | x | - | - | - | - | x | x | - | x | x | x | - | - | - | - | | | | | | | | | | | | |
| 83 | x | x | - | - | x | - | - | - | x | x | - | x | - | - | - | - | - | Agri-food | - | x | - | x | - | x | - | x | - | - | | | | | | | | | | | | |
| 84 | x | - | x | - | - | - | - | - | x | x | x | - | - | - | - | x | x | - | x | x | - | - | - | x | - | - | - | - | | | | | | | | | | | | |
| 85 | - | x | x | x | x | - | - | - | x | - | x | - | x | - | - | - | - | Multiple | x | x | - | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 86 | - | x | x | - | - | - | - | - | x | x | - | - | - | - | - | - | - | Food | - | x | - | - | - | - | - | - | - | - | - | - | - | - | x | - | - | - | x | - | - | - |
| 87 | x | x | x | - | x | x | - | x | x | x | x | x | x | - | x | - | x | Diamond | x | x | x | x | x | x | x | - | - | - | - | - | - | x | x | - | x | x | x | - | - | - |
| 88 | x | x | x | x | x | - | - | x | x | - | - | - | - | - | - | x | - | Agri-food | x | x | x | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 89 | x | x | - | - | - | - | - | x | x | x | x | - | - | x | - | - | - | Logistics | x | x | - | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 90 | x | x | x | x | x | x | - | x | x | x | x | x | - | x | x | - | - | - | x | x | x | x | - | - | - | - | - | - | x | - | - | - | - | - | - | x | - | - | - | - |
| 91 | x | - | x | - | - | - | - | - | x | x | - | - | - | - | - | - | - | - | x | - | - | x | - | - | - | - | - | - | x | - | - | - | - | x | - | - | x | - | x | x |
| 92 | x | - | x | - | - | x | x | - | x | x | - | - | - | - | - | x | - | Shipping and port management | x | - | x | x | - | - | - | - | x | x | | | | | | | | | | | | |
| 93 | x | x | x | x | - | x | - | - | x | x | - | x | - | x | - | - | - | Automotive | x | x | - | - | - | - | - | x | - | - | x | - | - | - | - | - | - | - | - | - | - | - |
| 94 | x | - | - | x | - | - | - | - | x | - | - | - | - | - | - | x | - | - | x | - | - | x | - | x | x | - | - | - | | | | | | | | | | | | |
| 95 | x | x | - | x | - | x | - | x | x | x | - | x | x | x | - | - | - | - | x | x | - | x | - | - | - | - | x | x | x | x | x | x | x | - | - | x | - | - | - | - |
| 96 | - | x | x | - | - | - | - | - | x | - | - | - | x | - | x | - | - | - | x | x | x | - | - | x | - | - | - | - | - | x | - | - | - | - | - | - | x | - | - | - |
| 97 | x | x | x | - | - | x | x | - | - | x | x | - | - | - | x | x | x | - | x | x | x | - | - | - | - | - | - | - | x | x | - | - | - | x | - | x | - | - | - | - |
| 98 | x | x | x | x | x | x | - | x | x | x | x | - | x | - | x | x | - | Food | x | x | x | - | - | - | - | - | - | - | x | - | x | x | - | x | x | x | - | - | - | - |
| 99 | - | - | - | - | - | - | - | - | x | x | - | - | - | x | x | - | - | - | x | x | x | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 100 | x | x | x | x | x | - | - | x | x | x | x | x | x | x | x | x | - | - | x | x | x | - | - | - | - | x | x | - | - | - | - | x | - | x | - | - | - | - | - | - |
| 101 | x | - | - | - | - | - | x | - | x | x | - | x | - | - | - | - | - | - | - | - | x | - | - | - | - | - | - | - | | | | | | | | | | | | |
| 102 | x | x | x | x | - | x | - | - | x | x | - | x | x | x | x | x | - | Agri-food | x | x | x | x | - | - | - | x | - | - | x | x | x | - | x | - | x | - | - | x | - | - |
| 103 | x | - | x | x | - | - | x | - | x | x | - | x | - | - | - | x | x | - | - | x | - | - | - | - | - | - | - | - | x | - | x | x | - | x | - | - | x | - | x | x |
| Total.: | 78 | 70 | 57 | 57 | 38 | 27 | 22 | 21 | 94 | 78 | 48 | 40 | 37 | 37 | 33 | 27 | 14 | | 86 | 83 | 54 | 43 | 25 | 24 | 22 | 13 | 12 | 10 | 30 | 26 | 22 | 21 | 19 | 17 | 16 | 16 | 13 | 13 | 10 | 8 |
| | 76% | 68% | 55% | 55% | 37% | 26% | 21% | 20% | 91% | 76% | 47% | 39% | 36% | 36% | 32% | 26% | 14% | | 83% | 81% | 52% | 42% | 24% | 23% | 21% | 13% | 12% | 10% | 53% | 46% | 39% | 37% | 33% | 30% | 28% | 28% | 23% | 23% | 18% | 14% |