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Product tracing or component tracing? Blockchain adoption in a two-echelon supply chain management ☆

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Highlights

- Developing a novel MILP model to design a blockchain-enabled two-echelon supply chain.
- Investigating four real cases of green product traceability and green component tracing.
- Developing an efficient decision-making tool based on B&E algorithm and SDEA.
- Analyzing a benchmark example along with a set of sensitivity analyses.

Abstract

Consumer awareness of product authenticity and carbon footprint tracing are among the most remarkable reasons for adopting blockchain in the supply chain in today's world. However, the research literature has not yet examined specific ways to adopt blockchain in the supply chain. This study aims to develop a decision support tool to deal with the adoption of blockchain technology to design a two-echelon supply chain. In this regard, four specific cases for integrating supply chain and blockchain are developed based on types of tracing and block generation authority. In product tracing, green products are investigated throughout the supply chain, while in component tracing, green products are examined between the components of the supply chain. As it is necessary to record and verify the supply chain information by authorities in the blockchain network, in this work, such authorities are taken into account for both links and members of the supply chain. As far as we know, this is the first attempt to classify the various methods of adopting blockchain in Green Supply Chain Management (GSCM) and propose mathematical optimization models related to them. In this line, four Mixed-Integer Linear Programming (MILP) models with the aim of minimizing the costs related to the physical supply chain and blockchain deployment are developed for the integration of the supply chain with blockchain technology. They are treated by the Branch and Efficiency (B&E) algorithm and Simultaneous Data Envelopment Analysis (SDEA) model considering common (cost and service) and innovative (blockchain) criteria. The results showed that link-based and component tracing models are cost-effective. In addition, the cost objective function of green product tracing is more sensitive to the number of blocks than that of component tracing. Eventually, the study provides great opportunities for decision-makers and managers to understand how to adopt blockchain in terms of supply chain network characteristics, cost, transparency, and service.

Introduction

A supply chain refers to a complex web of interconnected organizations engaged in a range of processes and tasks aimed at creating goods and services ultimately destined for the final consumer. This network includes upstream and downstream linkages (Stadtler, 2014). The management of relationships across the supply chain is known as Supply Chain Management (SCM). SCM enables companies to integrate and manage relationships within and between companies, resulting in synergies (Lambert &

Cooper, 2000). The incorporation of ecological considerations into supply chain management procedures is termed Green Supply Chain Management (GSCM) (Tseng et al., 2019). There are numerous internal and external drivers which can affect the establishment of GSCM and its overall performance. These drivers are mainly of an economic, environmental, social, and technological sort such as the blockchain technology manifestation. It was reported that 80 % of blockchain adoption studies are exclusively concentrated on Bitcoins, representing the notion that blockchain technology is yet to be adopted, particularly in the GSCM research (Elhidaoui et al., 2022). To adopt blockchain technology in the supply chain, it is necessary to first convert the physical flow of the supply chain into a digital flow through the Internet of Things (IoT) tools such as Quick Response (QR) code and Radio-Frequency Identification (RFID) (Farooq et al., 2015). The digital flow is then encrypted based on hash values to create a blockchain counterpart to the physical flow (Kamilaris et al., 2019, van Groesen and Pauwels, 2022).

In the following, Sub-section 1.1 introduces the concept of blockchain. Sub-section 1.2 discusses the necessity of using blockchain in the supply chain. Sub-section 1.3 provides an overview of the research literature on the topic. Sub-section 1.4 highlights our innovations and identifies research gaps.

It should be noted that supply chain firms incur costs, including administrative costs, for being green. Using a QR code, it is possible to reduce some unnecessary costs and thus enhance the economic performance of the firms (Li et al., 2020). Blockchain technology is a decentralized system which puts an end to the application of third-party organizations where no one is involved intermediately, and the blockchain actors make decisions. Blockchain technology is accompanied by its own authenticity to guarantee verified transactions wherein every movement is incorporated into the blockchain wherein each actor represents available data records. Modification and deletion of these data are not possible wherein immutability and transparency are ensured with the help of such a recording approach through blockchain (Khan et al., 2022). Each block in a blockchain contains a timestamp, the hash value of the previous block, a nonce, and transactions. The nonce is a random number that is used to verify the hash, which is a unique identifier for the block. Any attempt to alter the contents of a block would result in a different hash value, making fraud detection and prevention possible (Nofer et al., 2017). The hashing algorithm used is SHA256, which, together with the Proof of Work (PoW) algorithm, enhances the security of transaction-related information (Krishnapriya & Sarath, 2020).

Blockchain is also known as a highly secure technology since it connects any individual to the network. In fact, a unique identity is allocated to each individual. Moreover, a cryptographic hash is another factor that increases blockchain security. A hash value is calculated for any newly-added block which also contains its previous value. The identification information of the block, identification information of the user, block creation time, previous hash value, and the details of all previous transactions are given in terms of the hash value of any block. The hashes are automatically created and it is not possible to modify the hash value. Fig. 1 depicts the blockchain comprising *n* blocks. Every block is composed of the preceding block's hash, transaction information regarding, timestamp, information on the nonce number for excavating process, and any further practically-required characteristics.

The major challenge in the traditional way of working is the existence of multiple ledgers for record-keeping, while blockchain technology involves all the transactions in a single ledger. On the other hand, faster processing is the other advantage of blockchain technology (Li and Liang 2022).

GSCM and Sustainable Supply Chain Management (SSCM) involve activities across all supply chain levels that remarkably influence the environment and social well-being. Due to the digital transformation and its requirements in the era of Industry 4.0, supply chain managers are more concerned about sustainable compliance and green product tracing. A green product is known as a sustainable product designed to reduce negative environmental impacts during its life cycle and even after the end of its useful life. A high priority to guarantee such activities in real practice is blockchain adoption. It should be noted that concerns about pollution and global warming have increased the requests of environmentally-friendly non-profit organizations to reduce carbon footprints in production organizations that are major consumers of natural resources (Birasnav et al., 2022). It is important to use blockchain technology in this field because it can trace and record the carbon footprint in all stages of production (Scott et al., 2021). Supply chains are capacious storages to store large amounts of data under sustainable practices. This can be fulfilled efficiently by means of blockchain technology which also interconnects storages (Kumar et al., 2020). Industrial SCM as an indispensable factor in modernization has also embraced fruitful opportunities for transformation towards this great trend (Xu et al., 2021).

The critical role of organized data in designing a sustainable supply chain is not ignorable, which can be treated according to the decentralized nature of the blockchain along with sharing information in a faster mode. It also helps managers prevent unnecessary establishments in the supply chain. However, blockchain adoption is not yet mature (Zhao et al., 2019). To be more specific, blockchain allows different levels of supply chains such as warehouses, suppliers, manufacturing plants, and distribution centers to connect to each other using a permanent record of every transaction that occurs. Next, all the records are stored and approachable from the network. With such transparency, manufacturers can better manage product origins and traceability as well as potential recalls, towards *smart manufacturing* (Zhang and Ming, 2021). In fact, customer demand can be scrutinized in real time which aids manufacturers to forecast the demand with high accuracy and plan the production along with inventory replenishment.

The traditional inventory management system was based on a reactive model wherein replenishment orders were placed whenever inventory was used up. Moreover, predictive models were applied to estimate the time inventory would run out. With the emergence of blockchain technology, warehouse inventory management is able to accurately forecast demand, and accordingly, always proceed with the right quantity and type of products required to cover expected demand. Blockchain adoption makes a supply chain able to optimize profitability while diminishing the risk of lost sales.

Dutta et al. (2020) examined different supply chain operations which can be improved through blockchain technology. They conducted a review study in order to determine the main challenges and research opportunities related to blockchain adoption in SCM. Technical and non-technical challenges in blockchain adoption for supply chains were analyzed by Jabbar et al. (2021) along with the appropriateness of different consensus algorithms applicable to the supply chain. They also evaluated and illustrated the tools and technological components within the realm of blockchain. Li et al. (2022) by studying the data collected from Chinese firms, found that the adoption of blockchain can improve supply chain resilience due to the emphasis on the importance of transparency process and information symmetry. From this point of view, it is important to adopt blockchain because the operations of firms can continue in the presence of disruptions. In this way, the performance of firms can be improved. Kumar et al. (2022) discussed the trends and future directions towards SSCM with the help of blockchain. They could demonstrate the application of blockchain to design sustainable supply chains, especially for four major sectors; i.e., healthcare, food, manufacturing, and infrastructure.

Shah et al. (2021) performed a comprehensive review of the application of blockchain for the COVID-19 pandemic and stated that storing, managing, and analyzing large amounts of data can be efficiently done through blockchain technology to tackle the pandemic situation. A case study of blockchain-enabled digital vaccine passports was also investigated to find out the complexity. Júnior et al. (2022) discussed the blockchain adoption scenario of the battery SCM allowing an improved regulation of battery performance and its impact on the environment. They carried out a review study to delineate the utilization of blockchain technology to deal with battery traceability and discover the key challenges in the relevant markets which can be handled by this technology. A unified five-layer blockchain and IoT-based smart tracking and tracing platform was offered by Liu et al. (2021) to build up a decentralized traceability workaround for drug SCM. Analyzing a case study revealed that blockchain adoption not only gives useful insights into the optimal configuration of the transaction, but also suggests a feasible solution for drug traceability and visibility. A comprehensive review was conducted by Aoun et al. (2021) to examine the main features as well as technological and sustainability-related barriers of Industry 4.0 considering potential enhancements with the help of blockchain technologies. As was mentioned, the food sector is one of the most applicable areas of the blockchain to not only deal with product traceability, but also guarantee their safety, freshness, and quality within its GSCM. Khan et al. (2022) assessed the benefits and cleaner solutions of blockchain technology for agricultural GSCM during the COVID-19 pandemic through online interviews. An experimental design approach was proposed by Arunmozhi et al. (2022) to prove the efficient application of blockchain technology in autonomous vehicle supply chains. They addressed how Artificial Intelligence (AI) and blockchain-based smart contracts can contribute to the sustainable development of supply chain activities. The results demonstrated that their offered approach provides robust control over costs and energy while ensuring a high transparency level in managing decentralized autonomous vehicles supply chain activities, environmental sustainability, and monetary effects.

On the other hand, scholars have been recently investigating the use of Multi-Criteria Decision-Making (MCDM) techniques to assess the applicability and challenges of blockchain adoption in different supply chains. Yadav and Kumar (2022) expressed that blockchain technology integrated with IoT can make an efficient platform for global vaccine distributions in terms of traceability, trust, transparency, and data management. Their research evaluated the blockchain adoption barriers on the basis of the extant literature and opinions from experts by applying Delphi and fuzzy

Decision-Making Trial and Evaluation Laboratory (DEMATEL) methods. The results indicated that the most significant obstacle is the alteration of organizational structure and policies. An integrated fuzzy MCDM approach was developed by Zhang et al. (2022) to assess the critical success factors of blockchain technology in SSCM. An empirical case study problem was investigated to represent and prioritize these factors as well as prove the superiority of the offered approach. Kumar et al. (2022) suggested a conceptual model to tackle the effect of adoption barriers against blockchain-IoT applications in food supply chains. Thirteen key barriers were found and analyzed using Interpretive structural modeling (ISM) and DEMATEL techniques. Based on the findings, workers' low competency and lack of government regulation highly affect blockchain-IoT adoption.

There are a few papers that investigated blockchain adoption based on mathematical optimization in supply chain network design. De Carvalho et al. (2022) presented a mixed-integer quadratic programming model for a two-level supply chain planning in which the costs related to the IoT are considered. In their model, transportation times between the levels of supply chains could be stored on the blockchain. Babaei et al. (2022) and Babaei et al. (2023a) developed data envelopment analysis models that evaluate the configurations of omni-channel distribution networks based on criteria related to cost, service, environment, and blockchain. The blockchain criterion was measured based on the amount of configuration transparency. They argued that as the number of blockchain participants increases, decision-making becomes more decentralized, and transparency increases throughout the distribution network configuration. In this regard, Maity et al. (2021) offered an optimization model with the aim of minimizing batch dispersion in the five-level supply chain of sausages, in which the suggested model considered blockchain technology from the point of view of transparency. They concluded that raising the number of blocks improves the transparency in the blockchain because the attacker's ability to manipulate the data of the blocks decreases greatly if the number of blocks increases. In order to endorse the transparency, tracing, and non-manipulation of information, Yadav and Singh (2022) applied a Mixed-Integer Linear Programming (MILP) model for procurement problems. The model minimized not only the costs of procurement but also the cost of blockchain technology, which was based on the number of generated blocks during purchasing, ordering, transportation, and holding processes. Babaei et al. (2023b) offered a bi-objective optimization model in order to simultaneously minimize the costs of the three-level supply chain (such as establishment, transportation, and production costs) and maximize the transparency of the blockchain by increasing the number of blocks.

As discussed in the literature review, the majority of the studies tried to review important research works to highlight the trends, challenges and future directions. Furthermore, some studies utilized MCDM methods to extract and assess the main adoption barriers. On the other hand, the research literature indicates that few articles examined the configuration and evaluation of supply chains based on optimization methods such as linear programming and mixed-integer programming. After carefully reviewing these resources, we found that there is no specific research on how blockchain can be adopted to design and evaluate supply chain networks. In other words, there are no specific ways and patterns for adopting blockchain in the supply chain. In this regard, For example, some studies (e.g., Babaei et al., 2022) accounted for nodes (members) of the supply chain to be responsible for block generation and participate in the blockchain, while there are also some research works (e.g., De Carvalho et al., 2022) that consider the transportation links between supply chain members to be responsible for block generation. From a real-world application perspective, Babaei et al. (2022) and Babaei et al. (2023e) discussed how supply chain members are integrated into the blockchain. Specifically, these articles describe how supply chain members are responsible for registering and verifying the specifications of manufactured goods on the blockchain. In other words, in this series of articles, the authenticity of manufactured goods is verified by supply chain members who are also part of the blockchain. In contrast, in the studies conducted by De Carvalho et al., 2022, Babaei et al., 2023f and Babaei et al. (2024), the transport agents are responsible for registering, checking, and confirming the characteristics of the goods. For instance, the transportation time between two members is recorded on the blockchain. For example, the freshness of a flower is recorded on the blockchain by tracking the travel time of the cut flowers between supply chain members.

As Saberi et al. (2019) asserted, the adoption of blockchain in the supply chain is still open to investigation, and it is necessary to conduct research on this issue. For this reason, we aim to examine the adoption of blockchain in the two-echelon supply chain. Research gaps are specifically noted below:

I. Lack of specific optimization models for how to adopt blockchain in supply chain design,

II. Not paying attention to the adoption of blockchain in the supply chain optimization model from the point of view of product tracing or tracing of supply chain components,

III. Neglecting to evaluate solutions obtained from blockchain-enabled supply chain optimization models based on cost, service and blockchain technology aspects,

IV. Lack of analysis and comparison of the results obtained from the ways of adopting blockchain in supply chain optimization models,

V. Lack of sufficient attention to investigate and explain the effects caused by the length of the blockchain, minimal transparency and the costs of adopting the blockchain in supply chain optimization models.

In order to fill the research gaps, the main contributions of this study can be listed as follows:

I. Developing novel MILP models to design a blockchain-enabled two-echelon supply chain,

II. Extending the proposed MILP model according to the four real cases of product traceability and component tracing based on participating in the links and nodes of the supply chain,

III. Proposing an efficient solution approach based on the Branch and Efficiency (B&E) algorithm and Simultaneous Data Envelopment Analysis (SDEA) considering cost, service and blockchain criteria,

IV. Analyzing a benchmark example from the literature in order to validate the applicability of the developed methodology along with a set of sensitivity analyses,

V. Discussing the theoretical and practical implications of the results in order to provide managerial decision aids.

In this research, one main question and two sub-questions are taken into account as well as sub-questions representing the ways to deal with the main question.

Main question

- What are the optimization models that can formulate a two-echelon supply chain with different blockchain adoption classes?

Sub-questions

1. What are the classes of blockchain adoption methods in the supply chain?
2. How is the blockchain-enabled two-echelon supply chain model formulated?

In order to answer the questions, a single objective and two sub-objectives are listed as follows:

Main objective

- Providing two-echelon supply chain optimization models based on the classification of various ways to adopt blockchain in the supply chain.

Sub-objectives

1. Investigating the classes of adopting blockchain technology in the supply chain with regard to product and component tracing,
2. Formulation of the blockchain-enabled two-echelon supply chain mathematical optimization model based on the participation of transportation links or supply chain members in the blockchain network in terms of block generation responsibility.

The specific issue addressed by our research is the lack of optimization models for adopting blockchain technology in supply chain design. Our paper contributes to the existing knowledge by filling the aforementioned research gaps by developing MILP models, discussing the extended models for product traceability and component tracing, proposing a solution approach using the B&E algorithm and SDEA, presenting the analysis of a benchmark example, and finally, discussing the implications of the results for managerial decision-making. Readers can gain a clear understanding of the research problem by examining how our study fills the gaps in existing research and contributes to the field. Our study addresses the research questions and provides valuable insights into the adoption of blockchain in supply chain optimization models.

The first step of our roadmap involves developing various mathematical models. The next step is to develop a novel algorithm that considers transparency in addition to other common criteria. The following step involves analyzing the cost and blockchain structures. The ultimate step involves a deep dive into the managerial implications based on the obtained results.

The rest of the manuscript is organized as follows. Section 2 defines the problem and describes the developed MILP model in detail. Moreover, four different cases and corresponding models are also discussed in this section. Section 3 presents the proposed solution approach. The numerical results and sensitivity analyses are given in Section 4. Finally, Section 5 represents the discussion and main concluding remarks which are then followed by an outlook for future research.

Section snippets

Problem statement

The traditional supply chain that is planned exclusively based on physical flow is inefficient and unreliable. There are several reasons for these claims. Some of the most important reasons are (a) Presence of high risk in the non-transparent exchange of goods between buyers and sellers based on paper-heavy settlement, (b) Vulnerability of transactions to fraud, (c) Involvement of intermediaries, (d) Increase in the cost of transfers, (e) Buyer's lack of knowledge of the goods' origins, and (f) …

Results and analysis

In order to solve our presented mathematical models in fair conditions in terms of the same data, we implemented them on the benchmark example presented in Petridis et al. (2017) (see Appendix B). Since our research focuses on the blockchain-enabled two-echelon supply chain, it is appropriate to use the data of Petridis et al. (2017) regarding the physical supply chain data because the number of echelons was considered two in that article. Furthermore, Babaei et al. (2023b) utilized the data …

Discussion

The lack of transparency in the relationship between the seller and the buyer, the lack of knowledge about the authenticity of the goods, the inability to track the goods regarding environmental issues, and the vulnerability of transactions are among the important reasons that make traditional supply chains inefficient and unreliable. To deal with the mentioned challenges, it is necessary to integrate the supply chains with blockchain technology so that the information of the supply chain is …

Conclusion

Transparency is one of the important emerging factors in better GSCM because transparency can prevent product returns, improve customer satisfaction, make supply chain activities more efficient, and secure the trading environment in the era of Industry 4.0. One of the ways to create transparency in the supply chain is the use of blockchain technology in the supply chain, which many recent research works have focused on. However, few researchers have worked on the design of blockchain-enabled …

CRediT authorship contribution statement

Ardavan Babaei: Writing – original draft, Visualization, Software, Methodology, Conceptualization. **Majid Khedmati:** Writing – review & editing, Project administration, Formal analysis, Data curation. **Mohammad Reza Akbari Jokar:** Writing – review & editing, Supervision, Investigation, Data curation, Conceptualization. **Erfan Babaee Tirkolaee:** Writing – review & editing, Validation, Methodology, Investigation, Formal analysis, Data curation. …

Special issue articles   Recommended articles

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