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

Ardavan Babaei [a,b], Majid Khedmati [c], Mohammad Reza Akbari Jokar [c,*], Erfan Babaee Tirkolaee [b,d,e]

[a] Faculty of Industrial Engineering, K. N. Toosi University of Technology, Tehran, Iran
[b] Department of Industrial Engineering, Istinye University, Istanbul, Turkey
[c] Department of Industrial Engineering, Sharif University of Technology, Tehran, Iran
[d] Department of Industrial Engineering and Management, Yuan Ze University, Taoyuan, Taiwan
[e] Department of Mechanics and Mathematics, Western Caspian University, Baku, Azerbaijan

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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.

1. 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,

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* Corresponding author.
E-mail addresses: ardavan.babaei@kntu.ac.ir, ardvan.babaei@istinye.edu.tr (A. Babaei), Khedmati@sharif.edu (M. Khedmati), Reza.Akbari@sharif.edu (M.R. Akbari Jokar), erfan.babaee@istinye.edu.tr (E.B. Tirkolaee).

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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 & 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.

1.1. Blockchain technology

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).

1.2. Blockchain and supply chain integration

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

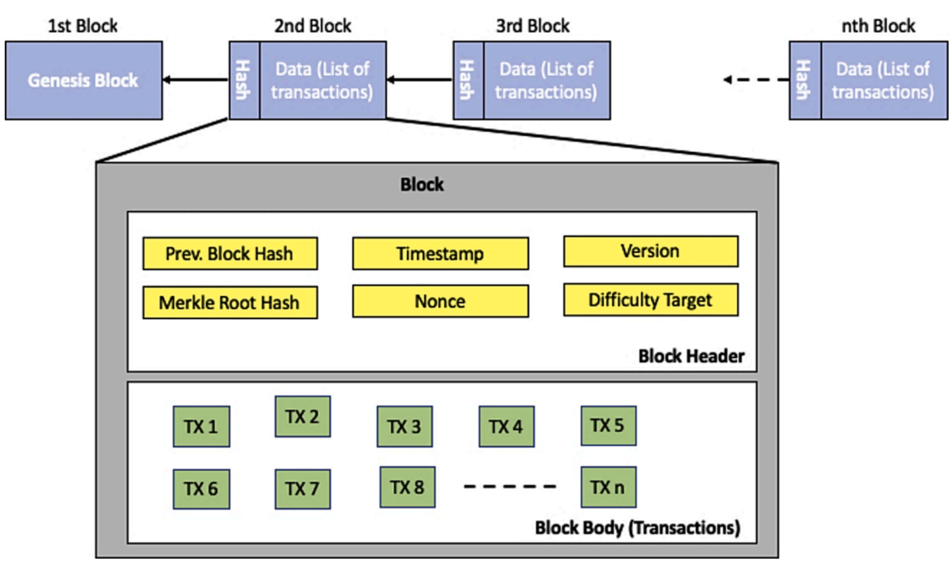


Fig. 1. An example of the blockchain network (Kamilaris et al., 2019).

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.

1.3. Literature review

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.

1.4. Research gaps and our contributions

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.

2. 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) Inability to trace the carbon footprint of production (Kamilaris et al., 2019). To deal with the mentioned challenges, the information related to the physical flow of the supply chain should be recorded in the blockchain through digital technology tools (such as quick response code, digital signatures, near-field communication, and radio-frequency identification). Therefore, an immutable device is responsible for recording information agreed upon by business participants (i.e., members of the supply chain). In short, the physical flow is transformed into a digital flow through IoT tools. A transparent, traceable, and secure counterpart of the physical flow (i.e. the blockchain network) can be then obtained based on the digital flow (Kamilaris et al., 2019; Bhat et al., 2021). An important point that is very challenging is which components of the supply chain are the participants in the blockchain. Some articles accounted for the members of the supply chain as participants in the blockchain to have the responsibility and authority to record information and generate blocks (Babaei et al., 2022). While others consider supply chain transport links as blockchain participants (De Carvalho et al., 2022).

This work aims to investigate the abovementioned challenges in the literature and provide appropriate solutions to deal with them. To this end, we develop different perspectives for the integration between supply chain planning and blockchain technology. In this way, the origin of supply chain goods can be traced. Such traceability is especially important for green goods, which today are of concern to non-profit organizations, governments, and people in terms of environmental requirements and carbon footprint.

In this study, the application of blockchain technology in the two-echelon supply chain is examined from two perspectives. Almost no research literature has discussed these two perspectives. One perspective focuses on tracing supply chain components, and the other focuses on tracing green products throughout the supply chain. When in the supply chain, two components need to use blockchain technology to enhance the transparency of their interactions, the component tracing approach is created. On the other hand, when there is a need, product information from the beginning of the chain to the end is transparently recorded, stored and accessible to everyone (from the producer to the consumer), the green product tracing is created. It is necessary to identify the authorities to register, store, review and verify product and component information in the supply chain in order to use blockchain in the supply chain. For this purpose, we investigated two cases in this work; where supply chain members are authoritative or where links between members are authoritative. Therefore, we present four distinct views on the general conditions for adopting blockchain technology in the supply chain. These views include product tracing throughout the supply chain, tracing of supply chain members (components) participating in the blockchain network, and the responsibility of members or links for records and information. These four cases can serve as a general representation of the adoption of blockchain in the supply chain, which aligns with the main goal of the article to provide optimization models for various viewpoints on adopting blockchain in the supply chain network.

Briefly, blockchain technology is applied to a two-echelon supply chain from two distinct perspectives: product tracing and component tracing. Table 1 presents the aspects of focus, process, and purpose for both product and component tracing.

Accordingly, there are 4 cases for using blockchain in the supply chain, as illustrated in Fig. 2. In Fig. 2(a) and 1(c), the members of the supply chain have the authority to register, record, and confirm information, while in Fig. 2(b) and 2(d), the links have such authority. In Fig. 2(a) and 2(b), the product information can be followed throughout the supply chain, but in Fig. 2(c) and 2(d), the information between the two components of the supply chain becomes transparent. Limited papers have worked on the use of blockchain in supply chain design. In these studies, supply chain members are authorized (Liu et al., 2021) or supply chain links are authorized (De Carvalho et al., 2022). It is worth noting that such a classification as presented in Fig. 2 does not exist in the research literature.

Table 1
Component tracing vs. product tracing.

Aspects	Product Tracing	Component Tracing
Focus	Tracing the entire lifecycle of green products from the start to the end of the supply chain	Tracing the interactions and movements of individual supply chain components
Purpose	To ensure transparency by recording, storing, and making accessible all product information from producers to consumers	To enhance transparency in the interactions between different components within the supply chain using blockchain technology
Process	All relevant product data, such as origin, handling, and environmental impact, is stored on the blockchain. This allows for comprehensive transparency and traceability, enabling stakeholders to verify product authenticity and sustainability throughout its lifecycle	The blockchain records detailed information about each component's interactions, movements, and status updates within the supply chain. This ensures that every step of a component's journey is transparent and verifiable, thereby increasing accountability and operational efficiency

Here, mathematical models are developed based on the above cases to design the two-echelon supply chain, shown in Fig. 3, capable of adopting blockchain (Petridis et al., 2017). This supply chain includes plants, warehouses, and demand areas. Products are produced in plants according to production capacity, then they are transported to warehouses with limited capacity. Finally, the products are transported from warehouses to customers. It should be noted that all customer demands may not be satisfied. The locations of customers and plants are already known, but warehouses need to be located. In addition to location, supply chain managers must also make decisions about the quantity transported at each stage. The costs of installing warehouses, production and transportation are among the costs related to the physical supply chain that supply chain managers are aiming to minimize.

The cost of applying blockchain based on the authority of links or members is one of the costs associated with the virtual counterpart of the physical supply chain, which affects the goal of supply chain managers in reducing costs. For instance, the deployment of blockchain relies on the cost of equipment associated with the IoT. Factors such as the initial cost of establishment (e.g., the size of the warehouse) can significantly impact the size of the fleet of IoT equipment. By incurring such a cost, installed warehouses can become a member of the blockchain network or not. Each member that adds to the blockchain, as a block generator, can enhance the transparency of information flowing in the supply chain. In this regard, we present 4 single-objective optimization models under deterministic conditions based on link/member authority and component/product tracing. The notation related to the models is given in Table 2. In this regard, we present different viewpoints introduced in Fig. 2. We formulate product tracing through Formulas (1)-(24), where the responsibility of recording information in the blockchain lies with the members of the supply chain. This formulation considers both the cost of participation of supply chain members in the blockchain and the cost of links related to participants (Objective Function (25)). Using Constraint (26), the formulated model can be upgraded to the component tracing case, where the responsibility of participating in the blockchain lies with the members of the supply chain. To formulate product tracing, where the responsibility of participating in the blockchain network lies with the links, we apply Constraint (27)-(33). By removing Constraints (29) and (31) from Formulas (27)-(33), the model for tracing components based on the responsibility of links emerges. The specifics of the equations are provided in the remaining sub-sections. It's important to note that our mathematical model aims to establish a warehouse and integrate it with blockchain technology. Moreover, this model can be readily expanded.

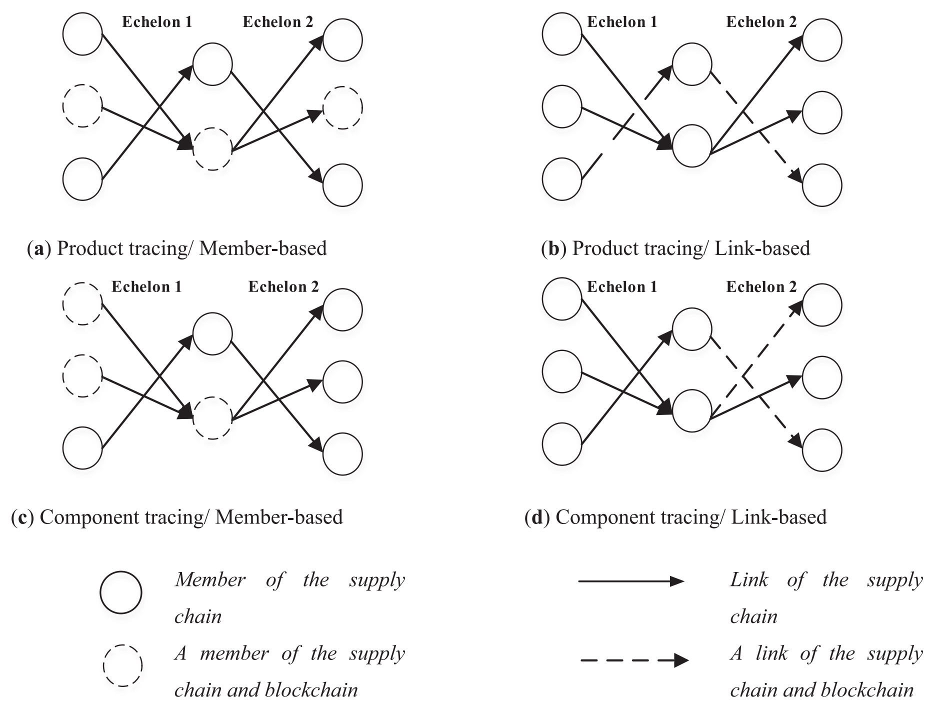


Fig. 2. Various applications of blockchain in the supply chain.

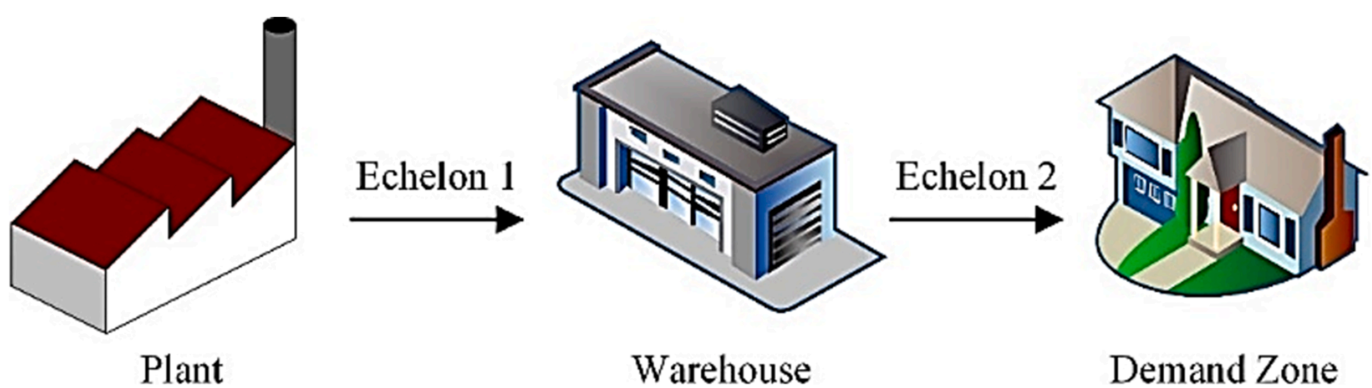


Fig. 3. Examined two-echelon supply chain network.

2.1. Case 1: Product tracing/ member-based

This case is classified into two Sub-cases 1-a and 1-b. In Sub-case 1-a, the cost is not considered for the links of the blockchain, while in Sub-case 1-b, such a cost is taken into account.

2.1.1. Sub-case 1-a: Member fee

In this sub-case, the members of the second level (warehouses) can become members of the blockchain when they are deployed in the supply chain. Each member of the blockchain is connected to at least one member from the previous level (plants) and at least one member from the next level (customers) to create the blockchain. In this sub-case, it is assumed that the membership fee of each member in the blockchain is proportional to the cost of installing that member in the supply chain. As shown in Fig. 3, the supply chain under our investigation has two echelons. It is worth mentioning that for the convenience of the reader, we used the numbers 1, 2, and 3 as representatives of the levels of plants, warehouses, and customers, respectively, in the superscript of the variables so that the flow direction between the levels is more specific and clear. The formulation of this sub-case is given by Formulas (1)-(24):

$$\text{minimize} \sum_{j\in J}\theta f_j^c z_j^{BA} + \sum_{i\in I} c_i^p p_i + \sum_{i\in I}\sum_{j\in J} c_{ij}^v q_{ij}^{12} + \sum_{i\in I}\sum_{j\in J} c_{ij}^f x_{ij}^{12} + \sum_{j\in J}\sum_{k\in K} c_{jk}^v q_{jk}^{23} + \sum_{j\in J}\sum_{k\in K} c_{jk}^f x_{jk}^{23} + \sum_{j\in J} f_j^c y_j \tag{1}$$

subject to

$$p_i = \sum_{j\in J} q_{ij}^{12} \qquad \forall i \in I, \tag{2}$$

Table 2
Indices, parameters, and variables.

Indices	Descriptions
$i \in I$	Index of manufacturing plants
$j \in J$	Index of warehouses
$k \in K$	Index of customers
Parameters	**Descriptions**
p_i^u	Maximum limit of quantities produced in plant i
p_i^l	Minimum limit of quantities produced in plant i
q_{ij}^u	Maximum limit of quantities transported from plant i to warehouse j
q_{jk}^u	Maximum limit of quantities transported from warehouse j to customer k
w_j^u	Maximum capacity of warehouse j
β_j	A coefficient that converts the number of goods into capacity (for example, goods can be stacked in a warehouse, meaning the number of goods does not directly correspond to the occupied area. This coefficient allows us to determine the warehouse's capacity accurately. In other words, this coefficient helps account for the effective use of the warehouse space, beyond just the area.
I_j^0	Amount of inventory stored in warehouse j (the initial inventory prior to planning)
c_i^p	Production cost in plant i
c_{ij}^v	Unit transportation cost of products sent from plant i to warehouse j
c_{ij}^f	Route transportation cost of products sent from plant i to warehouse j
c_{jk}^v	Unit transportation cost of products sent from warehouse j to customer k
c_{jk}^f	Route transportation cost of products sent from warehouse j to customer k
f_j^c	Installation cost of warehouse j
d_k^R	Demand of customer k
η	Service level
s_j^{BA}	Blockchain adoption score in warehouse j
$\underline{z}, \overline{z}$	Minimum and maximum levels of transparency
z^{BA}	Minimum required blocks in the blockchain
θ	Conversion coefficient of the installation cost to the blockchain implementation cost (expressing the impact of deployment costs on the physical supply chain when estimating the deployment cost of its blockchain counterpart)
π	Conversion coefficient of the variable transportation cost to blockchain adoption cost (expressing the impact of transportation costs on the physical supply chain when estimating the transfer cost of its blockchain counterpart)
Variables	**Descriptions**
p_i	Amount of production in plant i
q_{ij}^{12}	Amount of products sent from plant i to warehouse j
q_{jk}^{23}	Amount of products sent from warehouse j to customer k
w_j	Capacity of warehouse j
g_k	Unmet demand of customer k
x_{ij}^{12}	1 if there is a connection between plant i and warehouse j, 0 otherwise
x_{jk}^{23}	1 if there is a connection between warehouse j and customer k, 0 otherwise
y_j	1 if warehouse j is installed, 0 otherwise
z_j^{BA}	1 if warehouse j exists in the blockchain, 0 otherwise.
z_{ij}^{12}	1 if warehouse j and plant i exist in the blockchain, 0 otherwise.
z_{jk}^{23}	1 if warehouse j and customer k exist in the blockchain, 0 otherwise.

$$p_i \le p_i^u \qquad \forall i \in I, \tag{3}$$

$$p_i^l \le p_i \qquad \forall i \in I, \tag{4}$$

$$\sum_{i \in I} q_{ij}^{12} = \sum_{k \in K} q_{jk}^{23} \qquad \forall j \in J, \tag{5}$$

$$q_{ij}^{12} \le q_{ij}^u x_{ij}^{12} \qquad \forall i \in I, j \in J, \tag{6}$$

$$q_{jk}^{23} \le q_{jk}^u x_{jk}^{23} \qquad \forall j \in J, k \in K, \tag{7}$$

$$x_{ij}^{12} \le y_j \qquad \forall i \in I, j \in J, \tag{8}$$

$$x_{jk}^{23} \le y_j \qquad \forall k \in K, j \in J, \tag{9}$$

$$w_j \ge \beta_j \left(\sum_{i \in I} q_{ij}^{12} + I_j^0 \right) \qquad \forall j \in J, \tag{10}$$

$$w_j \le w_j^u y_j \qquad \forall j \in J, \tag{11}$$

$$g_k = d_k^R - \sum_{j \in J} q_{jk}^{23} \qquad \forall k \in K, \tag{12}$$

$$\sum_{k \in K} g_k \le (1 - \eta) \sum_{k \in K} d_k^R, \tag{13}$$

$$z_j^{BA} \le y_j \qquad \forall j \in J, \tag{14}$$

$$z_j^{BA} \le \sum_{i \in I} z_{ij}^{12} \qquad \forall j \in J, \tag{15}$$

$$z_{ij}^{12} \le x_{ij}^{12} \qquad \forall i \in I, j \in J, \tag{16}$$

$$z_{ij}^{12} \le z_j^{BA} \qquad \forall i \in I, j \in J, \tag{17}$$

$$z_j^{BA} \le \sum_{k \in K} z_{jk}^{23} \qquad \forall j \in J, \tag{18}$$

$$z_{jk}^{23} \le x_{jk}^{23} \qquad \forall j \in J, k \in K, \tag{19}$$

$$z_{jk}^{23} \le z_j^{BA} \qquad \forall j \in J, k \in K, \tag{20}$$

$$\underline{z} \le \sum_{j \in J} s_j^{BA} z_j^{BA} \le \overline{z}, \tag{21}$$

$$\sum_{j \in J} z_j^{BA} \ge z^{BA}, \tag{22}$$

$$p_i, q_{ij}^{12}, q_{jk}^{23}, w_j, g_k \geq 0 \qquad \forall i \in I, j \in J, k \in K, \tag{23}$$

$$x_{ij}^{12}, x_{jk}^{23}, y_j, z_{ij}^{12}, z_{jk}^{23}, z_j^{BA} \in \{0, 1\} \qquad \forall i \in I, j \in J, k \in K. \tag{24}$$

The cost of blockchain adoption[1] (including the use of IoT equipment in the members and links), production cost per plant, transportation cost between the stages of the supply chain, and warehouse installation cost are minimized by the objective function which is represented in Equation (1). It should be noted that two types of transportation costs are included in the objective function. The first type of transportation cost is for establishing a relationship between two members of the supply chain. The second type is related to the number of goods transported between these members. To clarify, our model accounts for the cost of the initial contract and the creation of a communication channel between two supply chain members. Additionally, it considers the transportation cost based on the intensity of transactions between these members. Constraint (2) indicates the number of products produced in the plants. Constraints (3) and (4) indicate the thresholds of production. Equation (5) is a balance constraint; i.e., it shows that the number of products that are received by warehouses is equal to the number of products that are shipped from warehouses. Constraints (6) and (7) guarantee that products are shipped at each level of the supply chain with respect to each link capacity. Constraints (8) and (9) ensure a connection exists at each stage if a warehouse has already been installed. Constraints (10) and (11) indicate the capacity of each warehouse. Constraints (12) and (13) specify unsatisfied demand and the allowable threshold of the unmet demand. Constraints (14)-(22) express how to adopt blockchain technology in the supply chain. Constraint (14) states that the warehouse has the authority to join the blockchain. Constraints (15)-(17) are related to the first stage. Constraint (15) indicates that for each warehouse that joins the blockchain, there is at least one link in the first level. Constraint (16) ensures that there is a blockchain link if there is a physical counterpart for that blockchain link. Constraint (17) guarantees that there is a blockchain link if the blockchain member has already been installed. Constraints (18)-(20) are similar to Constraints (15)-(17), for stage two. Constraints (21) and (22) specify the thresholds of blockchain transparency and the minimum required number of blocks. To provide greater clarity, Constraint (14) analyzes the activation of blockchain technology among supply chain members, specifically warehouses, which represent the middle layer of the supply chain. Constraints (15)-(17) focus on the participants in the blockchain with respect to the first level of the physical supply chain, which includes the plant and warehouse. Constraints (18)-(20) are similar to Constraints (15)-(17), but they pertain to warehouse-customer pairs. Constraints (21) and (22) reveal transparency factors, such as the quantity and impact of blocks in generating transparency. Constraints (23) and (24) display the decision variables of the mathematical model.

2.1.2. Sub-case 1-b: Member and link fees

In this sub-case study, the member equipped with blockchain assumes a portion of the transaction costs between the members of the supply chain to which this blockchain-equipped member is connected. Here, the objective function not only considers blockchain costs based on supply chain members, but also accounts for link costs. In this way, the costs of the links that connect to the blockchain are taken into account. For this purpose, Objective Function (1) is changed to Objective Function (25). It is worth mentioning that both in 1–1 and 1–2, supply chain members are responsible for the generation of blocks. It should be noted that in this model, the blockchain fee for members is based on their establishment cost. Conversely, the blockchain fee for links is based on the number of goods transferred between two members. Additionally, this model is comprehensive, allowing the decision maker to adjust the cost coefficients according to their specific supply chain system.

$$\text{minimize } \pi\left(\sum_{i\in I}\sum_{j\in J} c_{ij}^{v} z_{ij}^{12} + \sum_{j\in J}\sum_{k\in K} c_{jk}^{v} z_{jk}^{23}\right) + \sum_{j\in J}\theta f_j^c z_j^{BA} + \sum_{i\in I} c_i^p p_i + \sum_{i\in I}\sum_{j\in J} c_{ij}^{v} q_{ij}^{12} + \sum_{i\in I}\sum_{j\in J} c_{ij}^{f} x_{ij}^{12} + \sum_{j\in J}\sum_{k\in K} c_{jk}^{v} q_{jk}^{23} + \sum_{j\in J}\sum_{k\in K} c_{jk}^{f} x_{jk}^{23} + \sum_{j\in J} f_j^c y_j \\ \text{subject to Constraints } (2) - (24). \tag{25}$$

The main difference between the two recent subcases is their focus on different types of fees within the blockchain integration:

Sub-case 1-a: This subcase emphasizes the membership fee required for members of the second level (warehouses) to join the blockchain network.

Sub-case 1-b: This subcase focuses on transaction fees associated with blockchain operations between two supply chain members and the membership fee. These fees can be based on the frequency and complexity of transactions within the blockchain network and the installation cost.

It is evident that if π is set to 0, sub-case 1-b reduces to sub-case 1-a. Therefore, sub-case 1-b represents a general form of sub-case 1-a.

2.2. Case 2: Component tracing/ member-based

In this case, each blockchain member does not need to have at least one link to the next level (customer) and at least one link to the previous level (plant). Therefore, each stage can be independent of the other level of the supply chain in terms of joining the blockchain. For this purpose, Constraints (15) and (18) are merged into Constraint (26):

$$z_j^{BA} \leq \sum_{i\in I} z_{ij}^{12} + \sum_{k\in K} z_{jk}^{23} \qquad \forall j \in J. \tag{26}$$

To maintain the general form, Case 2 employs Objective Function (25) subject to Constraints (2)-(14), (16), (17), (19)-(24), and (26).

2.3. Case 3: Product tracing/ link-based

In this case, the links in each level of the supply chain can join the blockchain and generate blocks. It is assumed that the membership fee of the joining links is calculated based on a proportion of the variable costs of transportation. For this purpose, Objective Function (1) is updated to Equation (27):

[1] To implement blockchain technology, organizations must invest in hardware, software, and network infrastructure. By estimating the cost of blockchain adoption based on physical supply chain costs, organizations can accurately predict expenses associated with integrating blockchain into their existing infrastructure. We use constant parameters that consider the effectiveness of supply chain costs on blockchain adoption costs.

$$\text{minimize } \pi\left(\sum_{i\in I}\sum_{j\in J}c_{ij}^{v}z_{ij}^{12}+\sum_{j\in J}\sum_{k\in K}c_{jk}^{v}z_{jk}^{23}\right)+\sum_{i\in I}c_i^{p}p_i+\sum_{i\in I}\sum_{j\in J}c_{ij}^{v}q_{ij}^{12}+\sum_{i\in I}\sum_{j\in J}c_{ij}^{f}x_{ij}^{12}+\sum_{j\in J}\sum_{k\in K}c_{jk}^{v}q_{jk}^{23}+\sum_{j\in J}\sum_{k\in K}c_{jk}^{f}x_{jk}^{23}+\sum_{j\in J}f_j^{c}y_j \quad \text{subject to Constraints } (2)-(13),\ (23),\ \text{and } (24). \tag{27}$$

In order to model product tracing/link-based, it is necessary to make changes in the constraints of product tracing/ member-based. Constraints (14)-(22) are changed to Constraints (28)-(33). Constraints (28) and (29) belong to the supply chain levels. Constraint (28) guarantees that a blockchain link can exist if its physical counterpart is installed. Constraint (29) ensures that if the blockchain link exists, at least one link in the next stage must be installed. Constraints (30) and (31) are the same as Constraints (28) and (29), for the second stage. Blockchain adoption in terms of transparency and the minimum required number of blocks are given in Constraints (32) and (33):

$$z_{ij}^{12}\le x_{ij}^{12} \qquad \forall i\in I, j\in J, \tag{28}$$

$$\sum_{i\in I}z_{ij}^{12}\le M\sum_{k\in K}z_{jk}^{23} \qquad \forall j\in J, \tag{29}$$

$$z_{jk}^{23}\le x_{jk}^{23} \qquad \forall j\in J, k\in K, \tag{30}$$

$$\sum_{k\in K}z_{jk}^{23}\le M\sum_{i\in I}z_{ij}^{12} \qquad \forall j\in J, \tag{31}$$

$$\underline{z}\le\sum_{i\in I}\sum_{j\in J}s_j^{BA}z_{ij}^{12}+\sum_{j\in J}\sum_{k\in K}s_j^{BA}z_{jk}^{23}\le\overline{z}, \tag{32}$$

$$\sum_{i\in I}\sum_{j\in J}z_{ij}^{12}+\sum_{j\in J}\sum_{k\in K}z_{jk}^{23}\ge z^{BA}. \tag{33}$$

2.4. Case 4: Component tracing/ link-based

In the previous case, it is assumed that the links that exist in the first and second stages are connected to each other, based on Constraints (29) and (31), while in this case, this assumption is relaxed and these two constraints are removed.

2.5. Solution method

The mathematical models developed in this study are single-objective MILP models. Due to this, all models are treated with the help of CPLEX solver/GAMS optimization software. On the other hand, we use the Branch and Efficiency (B&E) algorithm as the solution method. This method was introduced by Grigoroudis et al. (2014) which comprises an iterative nature to optimize the supply chain design problem in the first iteration. Its results are evaluated by a powerful performance evaluation optimization model under the name of Data Envelopment Analysis (DEA). The efficient solutions resulting from the DEA are added to the supply chain optimization model by constraints called efficiency cuts. In this way, the supply chain design optimization model is updated. In the second iteration, the updated model is solved, and accordingly, the iterations continue. The termination conditions of this algorithm are based on the opinion of the decision-maker. The specific number of iterations and lack of improvement in the solutions of the objective functions in two consecutive iterations can be among the termination conditions in this algorithm. This algorithm is commonly utilized in the research literature for supply chain design (Babaei et al., 2023c; Babaei et al, 2023d). The schematic of the B&E algorithm is presented in Fig. 4. The algorithm consists of the following steps:

- ***Step* 1**: Solve each of the models developed in this paper (such as Formulas (1)-(24)).
- ***Step* 2**: Evaluate the solutions obtained in Step 1 (optimal solutions) using DEA, according to the criteria outlined in Table 3, to identify the most efficient solutions.
- ***Step* 3**: Add the efficient solutions obtained in Step 2 to the model from Step 1 using an efficiency cut (i.e., limit the feasible space to the efficient solutions obtained in Step 2). Then, solve the updated model (i.e., the model from Step 1 that has been updated by the efficiency cut).
- ***Step* 4**: If the termination condition is satisfied, the algorithm will terminate. Otherwise, the algorithm will return to Step 2 for the next iteration. Since this algorithm is related to the decision-maker, various termination conditions can be used. Examples include reaching a certain number of iterations, lack of significant improvement in the objective function of the updated model (with efficiency cut) in two consecutive iterations, or reaching the number of solutions required by the decision-maker.

The algorithm above determines optimal and efficient solutions in each iteration, enabling decision-makers to plan an efficient and optimal supply chain. However, subsequent iterations have a smaller feasible space compared to previous iterations due to efficiency cuts. As a result, costs in subsequent iterations are lower than those in previous iterations, demonstrating the cost-effectiveness of the presented algorithm. One advantage of this algorithm is its ability to interact with the decision-maker. If the decision-maker needs to establish a specific number of facilities (such as warehouses), they can set this as a termination condition. Similarly, if there is a limited amount of time available, the decision-maker can set a maximum number of iterations as the termination condition. Additionally, if cost is a crucial factor for the decision-maker, they can terminate the algorithm when the costs do not show significant improvement in successive iterations.

To improve this algorithm, the DEA model is modified to consider an innovative criterion. The SDEA model was introduced by Klimberg and Ratick (2008). This model, unlike the traditional models of DEA, can evaluate and score all the solutions through a single run. Therefore, the use of a loop to evaluate the solutions is prevented, and thus the number of runs of the evaluation model is reduced from the total number of solutions to one run. The traditional model of DEA operates on the principle of maximizing the weighted sum of output criteria, where the weighted sum of input criteria is contractually equal to one. In this model, outputs are considered as the results of inputs. However, the traditional DEA model must be solved separately for each decision-making unit. On the other hand, the SDEA model can evaluate all decision-making units simultaneously, making the evaluation process fairer and more efficient. The SDEA model transforms the objective function of the traditional DEA model into a series of constraints, which are determined by the number of decision-making units. It optimizes the efficiency of all decision-making units by identifying inefficiencies resulting from a series of constraints. This means that all decision-making units are evaluated in a single run. In our article, we have utilized the advantages of the SDEA model and included an innovative output measure that represents transparency, in addition to the common criteria of cost and services. This criterion is measured based on

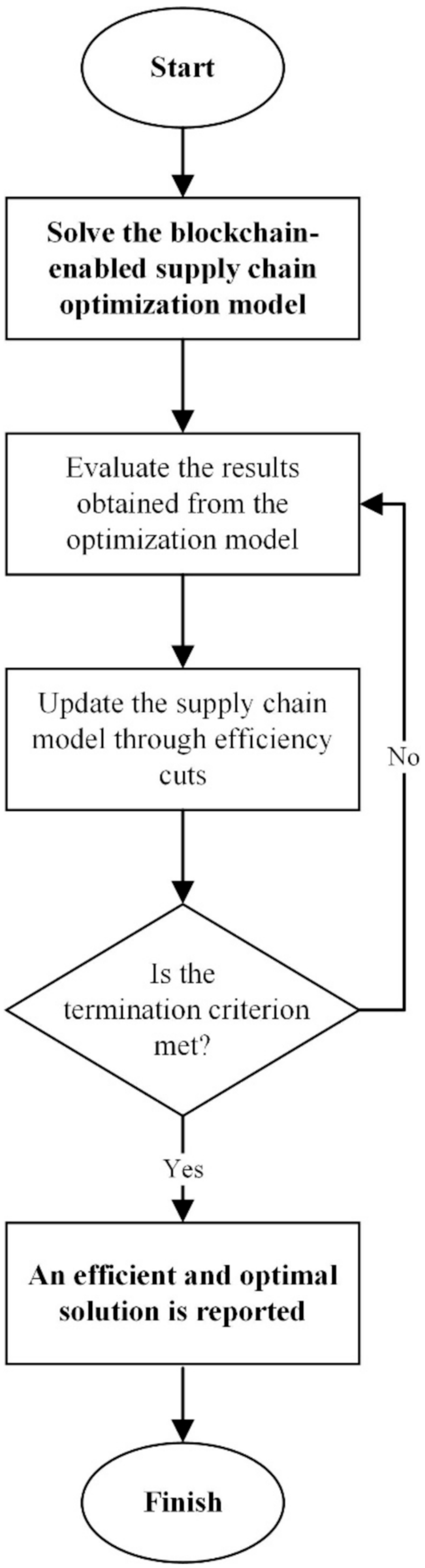


Fig. 4. Flowchart of the suggested B&E algorithm.

Table 3
Evaluation criteria of the study.

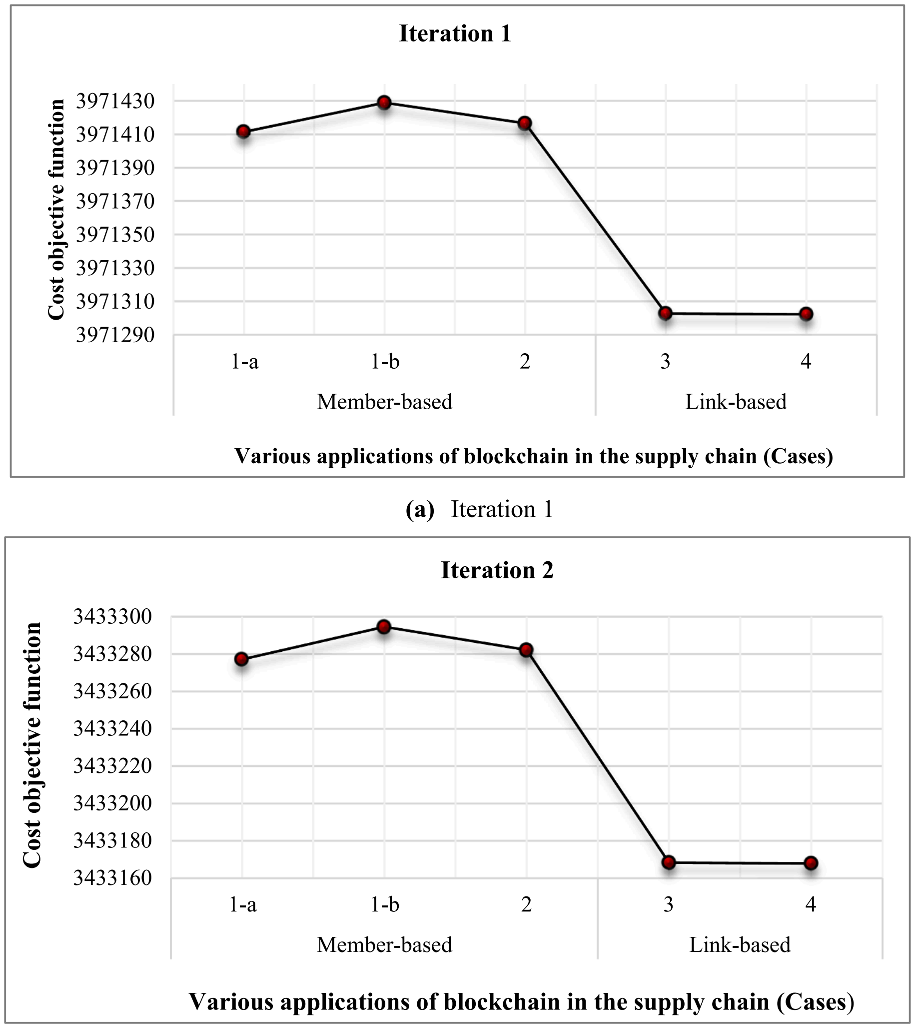
Assessment Aspects	Criteria	Common/ Innovative Criteria
Cost	Variable transportation cost (Stage 1) Variable transportation cost (Stage 2) Fixed transportation cost (Stage 1) Fixed transportation cost (Stage 2) Installation cost	Common
Service	Total quantity that a warehouse sends to customers Total number of customers satisfied by each warehouse	Common
Blockchain Technology	Transparency resulted from adopting blockchain technology in the supply chain	Innovative

Constraint (21) and Table 3. It is noteworthy that Superscripts 1–2 and 2–3 given in Table 2 correspond to Stages 1 and 2 outlined in Table 3, respectively.

Generally, studies such as Grigoroudis et al. (2014) and Petridis et al. (2017), use common criteria related to cost and service to evaluate solutions. The transparency resulting from the use of blockchain in the supply chain is also taken into account. The transparency criterion is determined based on the number of blocks generated by supply chain members/links who participate in the blockchain network. The evaluation criteria of our study are given in Table 3. Our proposed algorithm evaluates warehouses to be established through the criteria introduced in Table 3. Through this algorithm, the efficiency of the solutions increases as the iterations progress. On the other hand, the solutions are optimal because they are obtained from mathematical optimization models. Therefore, in our proposed algorithm, attention is paid to both the optimality and the efficiency of the solutions. It is worth mentioning that our proposed algorithm has capabilities regarding the application of the DEA method and evaluation criteria. Our proposed algorithm uses SDEA to evaluate the solutions, which makes all warehouses to be evaluated at once (in one repetition), under fair conditions and avoiding multiple repetitions. In addition, our proposed algorithm is able to consider the blockchain-related criterion to evaluate all four cases introduced. As previously mentioned, our proposed algorithm involves solving the presented model in the first step. This determines which warehouses will be established to serve customers (note that the locations of customers and plants are already known). By solving the model, we can also determine:

i. The cost of establishing each warehouse and the transportation cost (fixed and variable) for the pairs of plant-warehouse and warehouse-customer,
ii. Which customers each warehouse serves and how many products are provided to satisfy customer demand,
iii. The impact of each warehouse on the blockchain network based on its participation in transparency.

These three criteria demonstrate that the costs associated with a warehouse are related to its success in serving customers and creating transparency. The deployment costs of the blockchain are estimated based on the physical costs of the supply chain (establishment and transportation), so the nature of the cost is consistent with the input criteria of the SDEA model. Similarly, the nature of services and transparency is consistent with the output criteria of the SDEA model. Suppose that the cost, service, and transparency criterion values for Warehouse 1 are 10, 20, and 30, respectively. For Warehouse 2, the same values are 10, 20, and 40, respectively. It is clear that Warehouse 2 has been able to provide services at the same level as Warehouse 1 with the same cost, but with more transparency. Therefore, Warehouse 2 is more efficient than Warehouse 1. The SDEA model can provide such



(a) Iteration 1

(b) Iteration 2

Fig. 5. Comparing the cost objective function of the proposed models.

comparisons, even more complex ones, in an optimal way based on linear programming for the evaluation of warehouses. Our models are based on a two-stage supply chain, which includes (*i*) plant-warehouse stage and (*ii*) warehouse-demand zone stage, as illustrated in Fig. 3. The connections between the components of our supply chain network are shown in Table 2, with Stages 1–2 (plant-warehouse) and 2–3 (warehouse-demand zone) clearly outlined. These components can vary in each two-stage supply chain network, as our model is designed to be general.

Costs can be reduced by using this algorithm. The following proposition expresses and proves such a claim.

Proposition. If S^1 represents the solution space of the supply chain optimization model in iteration 1, and S^t denotes the solution spaces of the following iterations, which include efficiency cuts, then we have $f^1 \geq f^2 \geq \cdots \geq f^T$, where $f^t(t = 0, 1, \cdots, T)$ displays the cost objective function in each iteration.

The proof is given in Appendix A.

3. 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 employed by Petridis et al. (2017) regarding the integration of supply chain and blockchain. As a consequence, it is assumed the suggested two-echelon supply chain consists of 5 factories, 20 warehouses, and 5 customers. The transparency score extracted from adopting blockchain in the two-echelon supply chain was generated on a Likert scale by a random integer number in the interval [1–5]. The cost of joining the supply chain link to the blockchain is assumed to be 2 based on the transportation cost, and the cost of joining the supply chain member to the blockchain is assumed to be 0.0001 based on installation cost. These conversion factors are related to θ and π, respectively. Since joining the supply chain transport link into the blockchain as a blockchain participant (i.e., an entity responsible for generating a block) involves information about transactions between two members of the supply chain, therefore, the joining cost is considered a function of the transport cost. On the other hand, joining the supply chain member into the blockchain as a blockchain participant involves information about transactions within that member (if that supply chain member was established), so the cost of joining a supply chain member on the blockchain is taken into account a function of installation cost. There is also such a view to account for the cost in Babaei et al. (2023b) and De Carvalho et al. (2022). In addition, a detailed sensitivity analysis of these

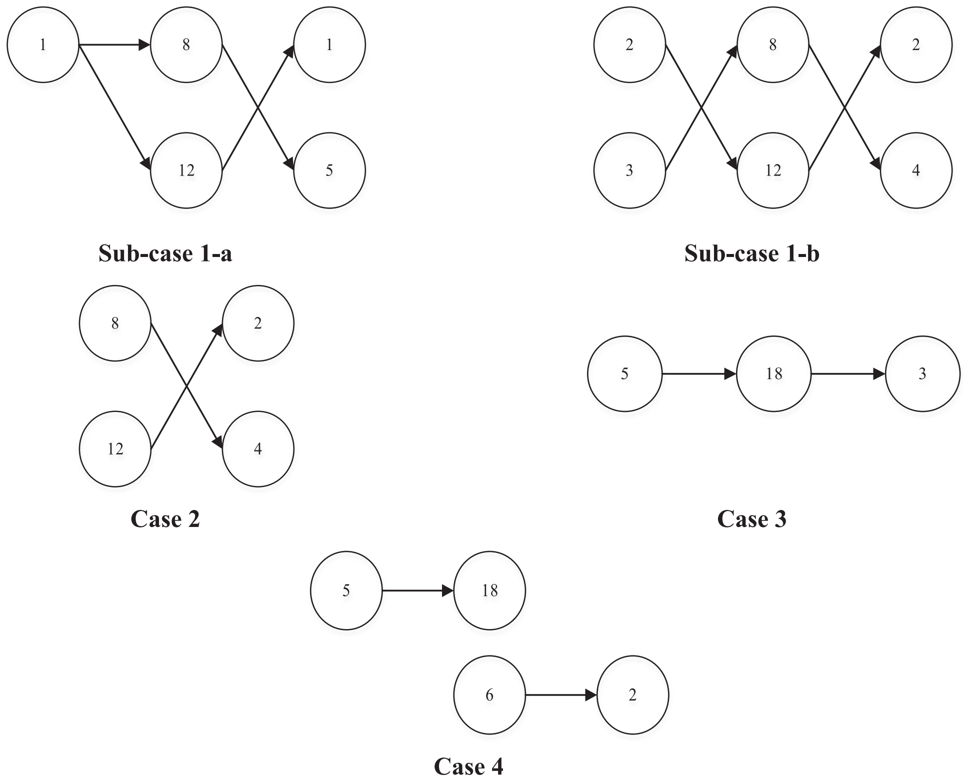
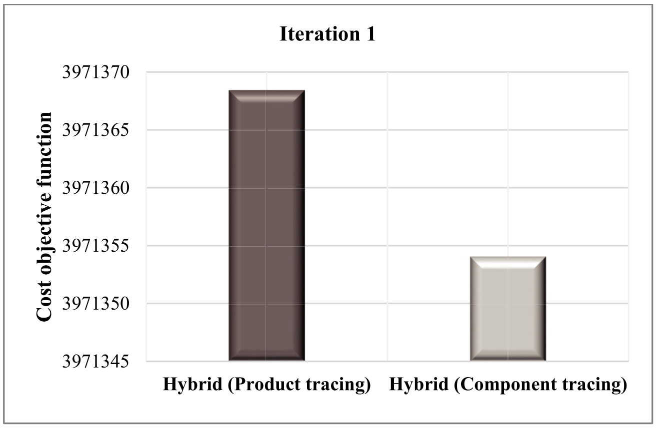


Fig. 6. Blockchain networks resulted from the developed models.

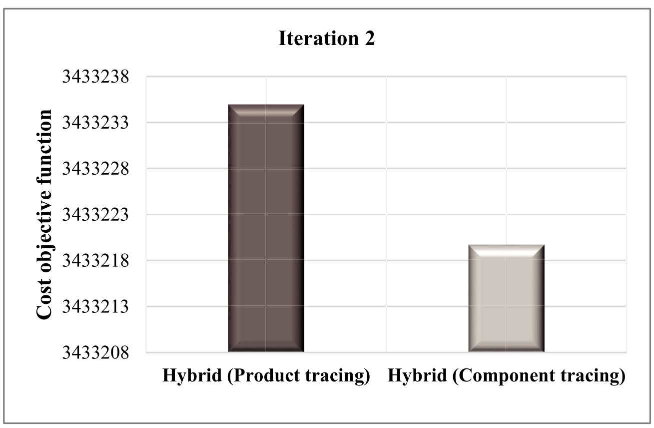
costs is carried out in the rest of this section. The minimum and maximum transparency scores are assumed to be 5 and 20, respectively, and the minimum required number of blocks in the blockchain is set to 2. It is worth mentioning that sensitivity analysis is done on the considered parameters related to the blockchain (such as transparency and the minimum number of blocks) in the rest of this section.

Similar to Petridis et al. (2017), the termination condition is set equal to 2. In other words, the number of iterations explored is equivalent to 2 iterations. Although increasing the number of iterations might reduce costs, according to the proposition and Figure A1, more iterations can lead to a reduction in the feasible space, which may adversely affect the quality of solutions and the number of warehouses, potentially making the problem infeasible. Two iterations offer a balanced condition for a fair comparison. In other words, all our models remained feasible with two iterations. Additionally, Petridis et al. (2017) and Babaei et al. (2023b) demonstrated that two iterations are applicable to a supply chain structure similar to ours, which can also accommodate blockchain technology. Fig. 5 depicts the costs of the developed mathematical models. As expected, the second iteration led to a reduction in costs due to the property of removing inefficient solutions in the branch and efficiency algorithm. Therefore, the results support Proposition 1. Emphasis on cost, which is also significantly addressed in this work, is vital in supply chain planning and management. For this reason, our proposed algorithm was developed, hoping it could lead to cost reduction through solution iterations. Almost all research works conducted in the field of supply chain consider cost minimization in their objective functions. Because cost is an important and influential factor in the decisions of supply chain managers and decision-makers. In this regard, This cost reduction can be attractive for supply chain managers whose strategy is focused on cost minimization (either for the physical costs of the supply chain or for virtual costs such as the cost of adopting Blockchain). Warehouses 1, 6, 8, 10, 11, 12, 14, 15, 16, 17, 18 and 19 are detected as efficient warehouses by the improved B&E algorithm. Costs are lower where the blockchain is defined on the links in each level of the supply chain than where the blockchain is defined on the members of the supply chain. The reason is that the costs of blockchain in terms of links are focused on the flow of information, and these links are not involved in the costs of establishing IoT devices on the scale of a warehouse or a factory. On the other hand, considering Sub-case 1-b vs. Case 2 and Case 3 vs. Case 4, it is concluded that component tracing imposes a lower cost on the supply chain compared to product tracing. It should be noted that this cost is more evident in the member-based mode. It should be noted that the reason for the lower cost in Sub-case 1-a in the member-based cases is that the cost of connecting the links to the blockchain member is ignored in this sub-case. Fig. 5 shows that component tracing is generally more cost-effective than product tracing, as it doesn't require tracing the entire chain. However, if blockchain costs are derived from physical supply chain costs, a link-based blockchain deployment is more cost-effective than a member-based deployment. This is because transportation costs are lower than establishment costs in supply chain decision-making. Fig. 5 provides supply chain managers with an understanding of the costs associated with various types of blockchain implementations. It also highlights the cost differences, allowing managers to plan blockchain use based on the nature of their supply chain and the insights gained from using blockchain. Therefore, the results presented in this figure do not imply that certain types of blockchain deployments are inherently costly and should always be ignored.

In Fig. 6, the blockchain networks resulting from the proposed mathematical models adopted in the two-echelon supply chain are reported. In terms of density, that is, the number of existing links over the number of possible links, link-based blockchain networks are denser than member-based networks. Dense networks should be regarded more in terms of accuracy and control because the density of transactions between the three levels of the supply chain is high. The number of blockchain members (supply chain members and links) in member-based blockchain networks is more than in link-based blockchain networks, which indicates that member-based blockchain networks are more decentralized than link-based blockchain networks. In the member-based cases, component tracing is more centralized than

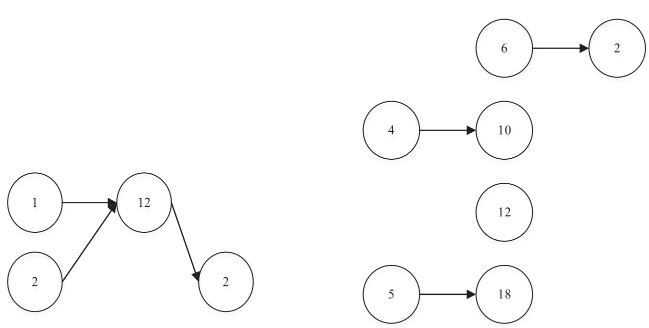


(a) Iteration 1



(b) Iteration 2

Fig. 7. Results of the hybrid models in terms of cost.



(a) Product tracing (b) Component tracing

Fig. 8. Hybrid blockchain network.

product tracing, while in the link-based cases, product tracing is more centralized than component tracing. It is worth noting that in more centralized situations because the information is validated and approved by fewer members, transparency becomes less than the decentralized situations. In contrast, data manipulation is difficult where the number of members who generate blocks is large. Each block contains unique hash values. In this regard, each block also contains its own hash values and its previous block. Therefore, as the number of blocks generated by members increases, it is very difficult to manipulate any data in each block that also contains its own and previous hash values. For this reason, transparency increases with the increase of members. Based on Fig. 5, it appears that the cost of implementing blockchain technology for member-based systems is higher than for link-based systems. However, Fig. 6 shows that the level of transparency achieved by member-based systems is equal to or greater than that of link-based systems. Specifically, when the member-based approach is used to track a product throughout the supply chain, more members are involved, which increases transparency.

One of the merits of the models presented in this study is that they can be used to create hybrid blockchain networks. Hybrid networks are meant to be both link-based and member-based. For this purpose, it is enough to merge Constraints (21) and (32) and merge Constraints (22) and (33) in the model presented in Formulas (1)-(24). In addition, instead of Objective Function (1), Objective Function (25) is used to include both link cost and member cost. Therefore, using Formulas (34) and (35), a hybrid product tracing model is built up.

$$\underline{z} \leq \sum_{i\in I}\sum_{j\in J} s_j^{BA} z_{ij}^{12} + \sum_{j\in J}\sum_{k\in K} s_j^{BA} z_{jk}^{23} + \sum_{j\in J} s_j^{BA} z_j^{BA} \leq \overline{z}, \tag{34}$$

$$\sum_{j\in J} z_j^{BA} + \sum_{i\in I}\sum_{j\in J} z_{ij}^{12} + \sum_{j\in J}\sum_{k\in K} z_{jk}^{23} \geq z^{BA}. \tag{35}$$

To obtain the hybrid component tracing model, Constraints (15) and (17) for levels one and two of the supply chain and Constraints (18) and (20) for levels two and three of the supply chain are removed. The following two constraints are added to the model wherein there should be at least one member of each type (member or link) in the blockchain:

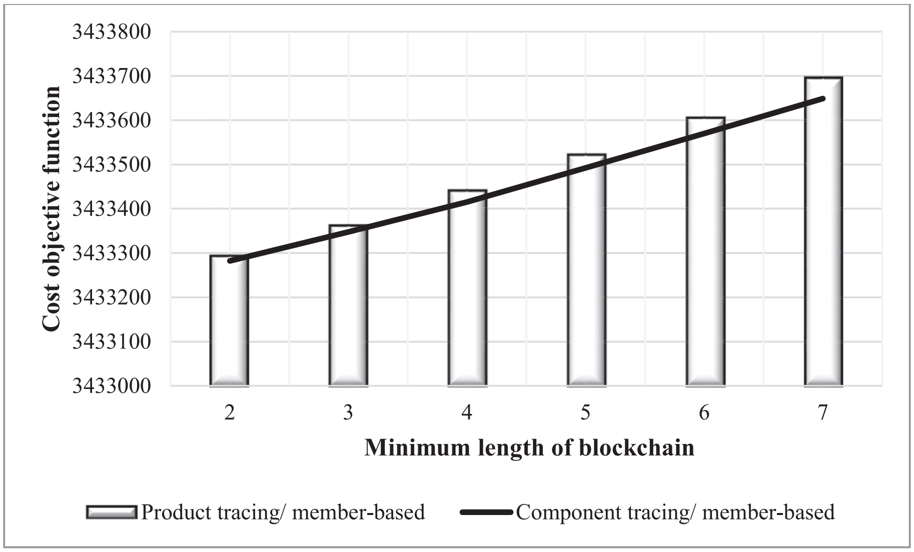
$$\sum_{j\in J} z_j^{BA} \geq 1, \tag{36}$$

$$\sum_{i\in I}\sum_{j\in J} z_{ij}^{12} + \sum_{j\in J}\sum_{k\in K} z_{jk}^{23} \geq 1. \tag{37}$$

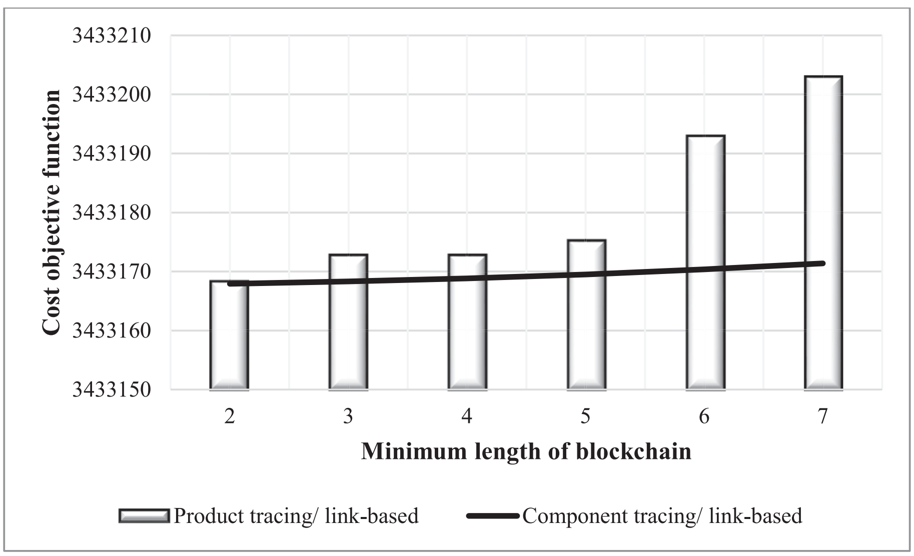
Considering that both links and members of the supply chain are supposed to be members of the blockchain, we assume the parameter of the minimum number of members of the blockchain to be 4. Based on this, we implement the improved B&E algorithm on the product tracing hybrid model and the component tracing hybrid model. The results of the first iteration and the second iteration are illustrated in Fig. 7. It is revealed that the second iteration reduces costs and component tracing is cheaper than the product tracing one. As previously mentioned, component tracing involves fewer constraints compared to product tracing. Therefore, it is expected that the cost associated with component tracing will be lower.

As shown in Fig. 8, component tracing has the ability to be more transparent because more members of the supply chain are present on the blockchain, while this type of tracing may not be able to support origin to destination across the entire supply chain on the blockchain. Hybrid component tracing is more decentralized than hybrid product tracing. It should be noted that by increasing the number of participants in the blockchain, decisions become more decentralized, and more participants are present in validating transactions. Hence, the possibility of fraud in exchanges and transactions between the buyer and the seller is reduced. In general, it should be noted that the four cases described earlier are primary examples of using blockchain in supply chain design. Hybrid models are derived from these primary cases by integrating links and members based on different types of tracing. Various other combinations of the four cases are possible. The presentation of hybrid models demonstrates that the primary models can generate a variety of hybrid configurations.

Since the minimum number of blocks produced can indicate the level of transparency in terms of the attacker's inability to manipulate blockchain data in the supply chain, the parameter related to the minimum number of blocks required in Fig. 9 is subjected to sensitivity analysis. Fig. 9 includes all primary cases, including **Case 1:** Product tracing/member-based, **Case 2:** Component tracing/member-based, **Case 3:** Product tracing/link-based, and **Case 4:** Component tracing/link-based. Given that the choice between a member-based or link-



(a) Member-based



(b) Link-based

Fig. 9. Analysis of the minimum required length of the blockchain (z^{BA}).

based approach is a fundamental decision for supply chain managers regarding blockchain use, Fig. 9 is organized accordingly. Fig. 9(a) represents that by increasing the minimum required number of blocks, the cost objective functions increase in the member-based approach where product tracing cost growth is greater than component tracing cost growth.

In this regard, Fig. 9(b), similar to Fig. 9(a), demonstrates that by raising the minimum required number of blocks, the cost objective function increases in the link-based approach. In general, the cost of product tracing is more influenced by the number of blocks than the cost of component tracing. This influence is more evident in link-based than member-based. It is worth noting that the cost of transparency in the member-based approach is higher than in the link-based approach. This is because the member-based approach relies on strategic costs, such as establishment costs.

Each member of the supply chain can provide a certain amount of transparency if it joins the blockchain. Depending on the type of activity and the characteristics of that member, the amount of transparency can be determined. Therefore, not all members can provide the same transparency to the blockchain network. For this reason, in addition to the minimum number of blocks, the amount of transparency provided by the participants in the blockchain should be analyzed. In Fig. 10, the minimum value in the transparency range increases. The results demonstrate that improving transparency in link-based models is more cost-effective than in member-based models. Furthermore, in member-based models, component tracing is cost-effective, while in link-based models, product tracing is cost-effective. It is important to note that product tracing based on members incurs higher costs for creating transparency due to two reasons. Firstly, the involvement of members in strategic decisions increases the cost. Secondly, limitations in tracing throughout the supply chain are another important cause of major cost changes in product tracing.

Here, we take into account the cost of joining the blockchain as a conversion factor of the cost of transportation links as well as a conversion factor of the cost of installing members of the supply chain. To do so, the sensitivity of these conversion factors is analyzed in Figs. 11 and 12. It is worth noting that our developed models are capable of considering any amount of cost to join the blockchain. With the increase in costs caused by the flow of information in the blockchain, according to Fig. 11, it is reported that the models related to product tracing are

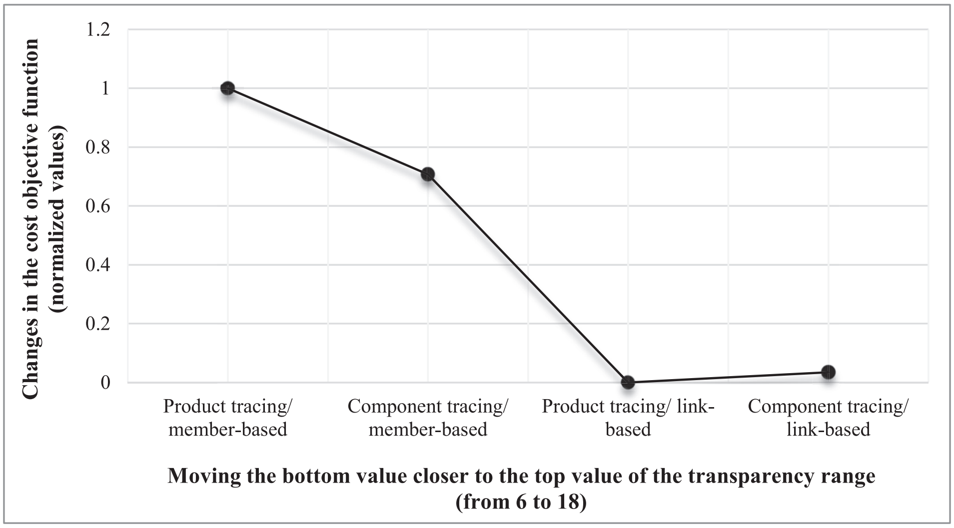


Fig. 10. Analysis of the minimum required transparency ($\underline{z}$).

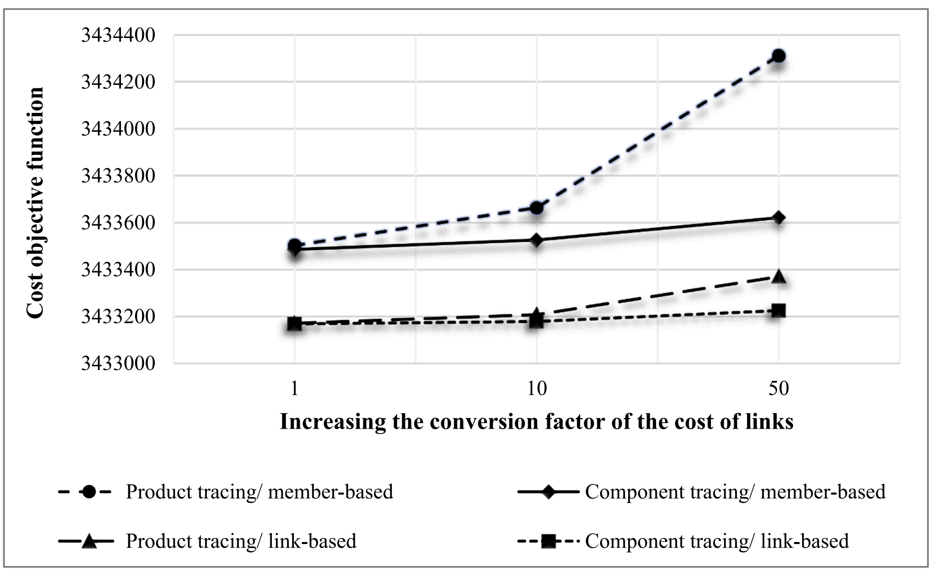


Fig. 11. Analysis of the conversion factor of the links' costs (π).

more affected in terms of costs compared to the models related to component tracing. As noted in Constraints (26), (29), and (31) for the second and fourth cases, component tracing models have fewer constraints. Therefore, it is expected that the cost increase will be more noticeable in product tracing models. The cost of processing blockchain transactions is accounted for in both the member-based and link-based cases. In the case of the link-based, the responsibility lies in registering and verifying information through the links. Conversely, in the case of a member-based, (a portion of) the cost of information transactions between members is the responsibility of the member equipped with blockchain. This cost should be considered based on the communication links between members to provide a more realistic estimate of the cost incurred by the supply chain manager when using blockchain.

Cost changes in the objective functions for adopting blockchain in supply chain members are reported in Fig. 12. In this figure, the cost conversion factor from 0.001 to 0.1 is examined. The results show that the adoption of blockchain in the objective function related to product tracing is more effective compared to the objective function related to component tracing. The results and analysis obtained from the figures in this section should take into account this case, which is based on a three-level supply chain and serves as an example for the case study discussed in this work. It is important to note that while other cases may yield different results, the conducted analyses can be applied and investigated in all cases. In Fig. 12, the cost analysis is based on member cases. For instance, shipping may be conducted by third-party logistics providers with information recorded on the blockchain. Hence, the cost analysis solely pertains to the cases of the members. If members bear the cost of blockchain processing between them, the analyses related to Fig. 11 hold true.

4. 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 recorded and stored in a secure, transparent, and traceable manner with

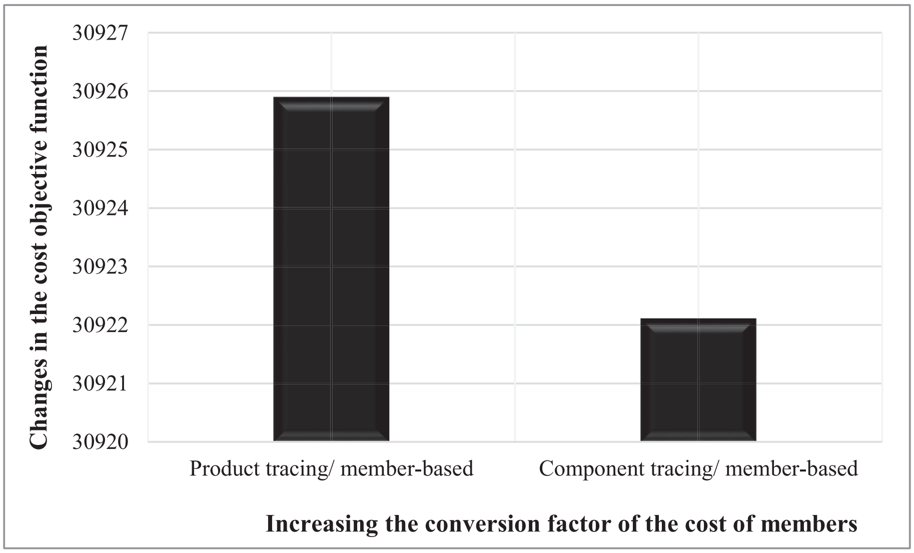


Fig. 12. Analysis of the conversion factor of the members' costs (θ).

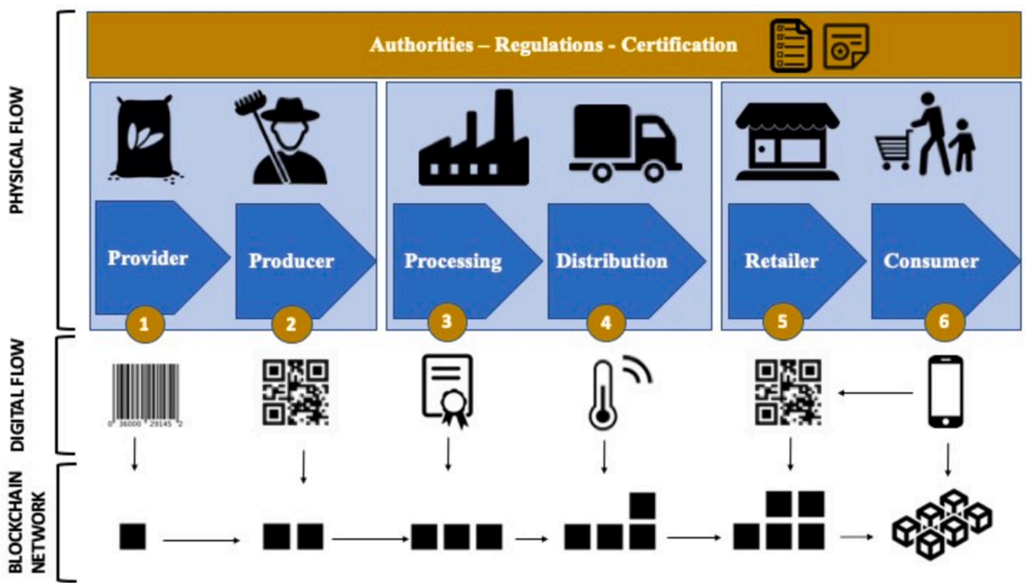


Fig. 13. Traditional supply chain, digitized supply chain, and blockchain network (Kamilaris et al., 2019).

the consensus of the blockchain participants. To enable the supply chain with blockchain, it is necessary to record the physical flow through IoT tools in the blockchain network. For this purpose, studies such as Kamilaris et al. (2019) and Bhat et al. (2021) considered three layers; i.e. (*i*) physical flow, (*ii*) digital flow, and (*iii*) blockchain network, as given in Fig. 13. In this way, the physical flow transforms into the digital flow. Then, the blockchain network based on the encrypted digital flow and verified by the blockchain participants is obtained.

There is a notable point in transforming the traditional supply chain into a blockchain-enabled supply chain. The point is which components of the supply chain must participate in the blockchain network. Some researchers considered the members of the supply chain as participants in the blockchain (Liu et al., 2021; Babaei et al., 2022; Babaei et al., 2023a; Babaei et al., 2023b). Others addressed the links in the supply chain as participants in the blockchain (De Carvalho et al., 2022). What is clear is that there is still no clear classification of how to adopt blockchain in the supply chain in the research literature. Our work was prepared with the aim of addressing this issue. For this purpose, two perspectives were considered here. From one perspective, the transparency of the relationship between the buyer and the seller is examined. In other words, this perspective seeks to implement blockchain in terms of the components of the supply chain. In the second perspective, product tracing is important. Blockchain is deployed in the supply chain in such a way that the authenticity of the goods can be made known and validated to all participants in the blockchain. In each of these perspectives, blockchain participants can be supply chain members or supply chain links, or both members and links. Therefore, the adoption of blockchain in the supply chain has been comprehensively investigated in this study. It is worth mentioning that managers and decision-makers can make their supply chain efficient and reliable based on the nature of activities and characteristics of their supply chain and these classes (product tracing/ member(link)-based, component tracing/ member(link)-based, product tracing (hybrid), component tracing (hybrid)).

The mentioned classes were implemented in a two-echelon supply chain that includes plants, warehouses, and customers. In addition, we

Table 4
Managers' strategies and goals and related actions.

Supported by	Strategies and goals	Actions
Fig. 5	Cost minimization [a]	• Using the link-based strategy instead of the member-based strategy • Employing the component tracing strategy instead of the product tracing strategy
Fig. 6	Density maximization [a]	• Utilizing the link-based strategy instead of the member-based strategy
Fig. 6	Decentralization maximization [a]	• Using the member-based and the product tracing strategy
Fig. 7	Cost minimization [b]	• Employing the component tracing strategy instead of the product tracing strategy
Fig. 8	Decentralization maximization [b]	• Applying the component tracing strategy
Figs. 9 & 10	Maximizing transparency cost-effectively [a]	• Increasing transparency through the minimum number of blocks based on component strategy • Enhancing transparency through the amount of transparency resulting from joining participants based on the link-based strategy
Figs. 11 & 12	Coping with cost-related conversion factor changes	• Using the component tracing strategy (Regarding the cost of joining the blockchain) • Employing the product tracing (link-based) strategy instead of the product tracing strategy (member-based)

[a] Non-Hybrid blockchain network.
[b] Hybrid blockchain network.

formulated the state-of-the-art optimization models for each class. Then, we solved the optimization models and obtained their solutions by the proposed B&E algorithm which is able to consider both common criteria (cost and services) and our innovative criterion (transparency). Therefore, we classified the types of blockchain adoption in the supply chain and formulated and solved mathematical models for each class. Therefore, we achieved the objectives of our research. In this line, we analyzed the results of different classes from important factors. These factors are listed below:

i. *Cost*: This factor is one of the most significant aspects that generally affect the decisions of supply chain managers. The cost includes supply chain and blockchain deployment costs. Most of the articles that provide optimization models for supply chain planning aim to minimize costs. This confirms the significance of this aspect in the decision of supply chain managers.
ii. *Density*: This factor provides how connected the members of the supply chain are (Kshetri, 2022). The way of connection is calculated relatively (according to the number of available and possible links) to make a more fair comparison between the cases.
iii. *Decentralization*: By strengthening this factor, data manipulation in the blockchain-enabled supply chain is reduced. For this reason, the more blockchain participants there are, the less likely fraud is. It is important to mention that the nature of blockchain seeks to decentralize decision-making authorities.
iv. *Transparency*: As the number of blocks increases, data manipulation becomes extremely difficult (Maity et al., 2021). Hence, blockchain-enabled supply chain transparency is enhanced. In addition, each member/link of the supply chain is able to bring transparency to the blockchain according to the characteristics of their activity and in cooperation with other members/links.

In Table 4, the managerial implications derived from blockchain adoption in the proposed two-echelon supply chain are summarized based on our findings in the current and previous sections.

5. 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 supply chain networks in an integrated manner. In the research that focuses on the supply chain and blockchain adoption, the methods of adopting blockchain technology in the supply chain have not been clearly defined. Addressing this important issue regarding how to adopt blockchain in the supply chain that has been neglected in the research literature, This research is conducted to classify the ways of adopting blockchain in supply chain design. For this purpose, an optimization-based decision support tool is proposed to address four general cases based on two perspectives and two authorities. In the first perspective, green products are traced throughout the supply chain, while in the second perspective, green products are traced between two components of the supply chain that tend to transparently interact with each other. Since the participants and members of the blockchain have the authority to generate blocks and record, store, and confirm information, it is necessary to identify the members of the supply chain who are members of the blockchain and who have the authority for such activities. In this regard, we considered such an authority both for the links in stages of the supply chain and for the supply chain members. Hence, the presented cases for the comprehensive investigation of blockchain adoption in the supply chain were provided based on link/member authority and component/product traceability.

Accordingly, the four cases were product tracing/member-based, component tracing/member-based, product tracing/link-based, and component tracing/link-based. In addition, we examined two other cases in the research; where both links and supply chain members can have authority at the same time. These were called hybrid cases with product /component traceability. Based on these cases, we developed four single-objective optimization models in order to minimize the physical costs of the supply chain and the costs of blockchain adoption. We solved the models through the improved B&E, where this algorithm, along with common criteria like cost and service, can consider the criteria related to transparency due to the adoption of blockchain. Accordingly, classifying blockchain adoption in the supply chain as well as formulating and solving the mathematical models related to each class were pursued as the objectives of our research. All developed models were solved under fair conditions and based on the case study described in Petridis et al. (2017) with respect to the two-echelon supply chain network. Results showed that the improved algorithm has been able to support the mentioned Proposition in such a way that this algorithm can reduce the costs in each iteration. Therefore, adopting this algorithm is recommended for supply chain managers who focus on reducing costs in addition to integrating supply chain design and blockchain adoption. In general, the costs generated by the member-based model are higher than the link-based model. From a cost point of view, component tracing models are more cost-effective than product tracing models. In this regard, the hybrid component tracing model is more cost-effective than the hybrid product tracing model. Member-based models are more decentralized than link-based models, and the component tracing hybrid model is more decentralized than the product tracing hybrid model. Accordingly, supply chain managers who are concentrated on greater transparency can plan based on member-based and component tracing hybrid models. Raising the number of blocks, increasing transparency, and increasing conversion factors affect product tracing models more than component tracing models in terms of cost.

Based on the obtained results, supply chain managers can better understand the consequences of blockchain adoption decisions in the supply chain design from the perspectives of blockchain network structure, cost, and transparency. In short, our main contributions include the classification of blockchain adoption methods in the supply chain, formulation of the mathematical optimization models for each class, presentation of a solution algorithm based on common and innovative criteria, and the provision of analysis based on cost, transparency, and decentralization.

Finally, it must be noted that there are two main limitations in this research. First, the previous studies did not provide such a comprehensive classification for the adoption of blockchain in supply chain design, and thus our access to related references was limited. Second, due to the innovative nature of the blockchain issue, many industries have not yet adopted blockchain or published their data, so access to data extracted from blockchains used in supply chains was limited. The limitations arising from insufficient research in the literature may have hindered our ability to fully examine the adoption of blockchain in the supply chain. To address this, we defined four general cases and a hybrid of these cases, and provided separate formulations for each. However, it is notable that these formulations may not be applicable to all industries. Additionally, our research may be incomplete from a real-world perspective due to limited access to industries that have already implemented blockchain in the supply chain. Nevertheless, we employed valid data from the articles in the supply chain field to make our analysis as realistic as possible. Given the limitations of our study, we recommend that future researchers customize and implement the general models presented in this work in collaboration with industries across various sectors.

Since this research could provide a comprehensive classification in the field of supply chain design and blockchain adoption, it can bring many research opportunities for researchers on blockchain and supply chain integration. Considering the uncertain conditions in adopting blockchain in the supply chain can better model the real world. In addition, the development of multi-objective models based on the opinions of supply chain managers, the use of other data-driven models, and the investigation of other case studies are suggestions for further research. Moreover, the main focus of this study was on presenting a blockchain-enabled two-echelon supply chain. This research can be further conducted on supply chains with more echelons. Moreover, develop this research on general supply chain networks.

One of the future works that we strongly recommend to researchers is to explore the configuration of the blockchain network as a secure and transparent counterpart of the traditional supply chain. Kamilaris et al. (2019) and Yadav and Singh (2022) contribute all the processes (such as holding, ordering, purchasing, and transportation) and components (such as provider, producer, distributor, retailer, and consumer) of the traditional supply chain correspondingly in the blockchain network. With the increase in the number of processes and components of the supply chain, the costs of participating in the blockchain and the cost of deploying the blockchain in the supply chain increase. In addition to the deployment cost, the energy consumption of IoT devices is of interest to researchers (Prajapati et al., 2022). The energy consumption of IoT devices creates environmental concerns and pushes industries away from clean production. As supply chain components and processes increase, the number of IoT devices and the time to receive and transmit data may increase. Such increases are effective in energy consumption and cause more dependence on IoT tools to convert physical flow into an encrypted digital flow. Hence, it is necessary to form a transparent and secure counterpart in terms of configuration for the traditional supply chain to be cost-effective and lead industries to clean production with less energy consumption. One of our key recommendations for future research is to address the issue of insecurity felt by buyers and sellers in the supply chain. The fact that they may not be familiar with the blockchain mechanism can discourage them from adopting it. Additionally, it is crucial for the blockchain system to enhance its security measures. One way to achieve this is by implementing a two-step authentication process, which can increase the sense of security for both buyers and sellers. However, there is a noticeable gap in the literature regarding the use of blockchain with two-step authentication in the supply chain network. Therefore, we encourage researchers to further explore this area of study.

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.

Appendix A. Proof of the proposition

Suppose that ‘‘ ℵ’’ represents the set of non-efficient solutions in each iteration. The values of the binary variables related to the installation of the inefficient warehouses are equal to zero according to Constraint (A2). In this regard, all the variables, both continuous and binary variables, that are affected by the installation of the inefficient warehouses take zero value (such as the variables in Constraints (6)-(9), (11), (14)-(20)). According to Equation (A1), the values of these variables in the objective function are equal to zero. In other words, the values related to inefficient solutions are removed from the cost-related objective function. Since inefficient solutions are extracted from the feasible space in each iteration, according to Figure A1, the feasible space of the next iteration is smaller than the feasible space of the previous iteration. In other words, the superset of the problem contains all warehouses (Ω). But with each iteration, the number of efficient warehouses decreases by means of efficiency cuts (As shown in Figure A1, it reaches β in the first iteration and α in the next iteration). Therefore, according to Equation (A1), Constraint (A2) and Figure A1, the value of the cost objective function in each iteration is lower than its previous iteration.

$$\text{minimize} \sum_{j\in\aleph}\theta f_j^c z_j^{BA} + \sum_{i\in I}\sum_{j\in\aleph} c_{ij}^v q_{ij}^{12} + \sum_{i\in I}\sum_{j\in\aleph} c_{ij}^f x_{ij}^{12} + \sum_{j\in\aleph}\sum_{k\in K} c_{jk}^v q_{jk}^{23} + \sum_{j\in\aleph}\sum_{k\in K} c_{jk}^f x_{jk}^{23} + \sum_{j\in\aleph} f_j^c y_j = 0 \tag{A1}$$

subject to

$$y_j \le (\xi_j = 0) \qquad \forall j \in \aleph. \tag{A2}$$

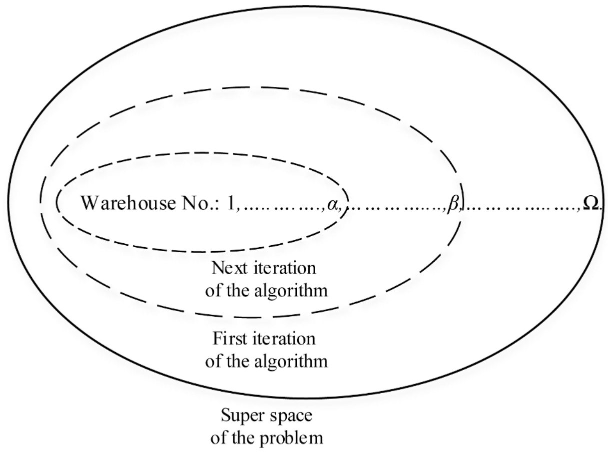


Fig. A1. Solution space of the algorithm.

Appendix B. Input data

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Table B1
Production for each plant.

Plant	Production cost
1	34.35
2	168.65
3	110.08
4	60.23
5	58.44

Table B2
Fixed and variable transportation costs from plants to warehouses.

Warehouse	Fixed transportation cost (Echelon 1)					Variable transportation cost (Echelon 1)				
	Plant					Plant				
	1	2	3	4	5	1	2	3	4	5
1	61.203	91.545	59.105	51.707	58.708	4.515	11.931	4.025	1.742	12.033
2	67.492	61.541	82.286	79.257	66.532	7.922	10.229	5.943	10.808	0.540
3	92.814	83.287	78.037	81.061	65.845	5.520	0.901	3.945	2.537	3.922
4	53.356	88.793	88.498	69.468	66.104	3.047	15.662	4.927	14.680	19.014
5	75.011	65.183	64.890	67.936	98.199	18.726	18.915	12.930	2.265	6.711
6	99.906	55.525	83.055	62.152	99.680	8.453	11.929	14.699	9.767	11.885
7	78.937	75.119	87.791	62.321	68.495	2.693	12.147	1.709	15.912	5.184
8	99.557	58.009	81.372	56.525	68.644	7.721	7.250	3.007	9.841	12.813
9	88.113	93.623	64.193	96.672	88.599	7.493	11.881	8.684	10.671	3.105
10	56.535	63.256	54.321	68.997	69.834	5.370	13.597	3.739	0.212	9.200
11	81.986	64.291	55.126	89.170	95.655	18.967	10.132	13.854	10.877	7.867
12	57.976	79.698	82.063	65.002	55.979	3.779	3.185	15.259	9.023	16.109
13	62.504	86.136	77.265	56.274	86.774	5.950	13.138	3.096	19.507	10.820
14	83.446	81.412	51.576	87.444	52.771	1.491	10.478	7.788	3.677	7.814
15	71.768	73.190	89.618	53.462	78.815	8.027	2.488	13.909	3.271	11.156
16	67.985	70.665	53.638	60.101	52.570	2.034	19.734	16.916	0.493	18.655
17	67.572	55.885	58.783	50.253	50.300	7.678	4.562	12.254	3.556	6.975
18	56.575	65.711	76.282	63.481	70.061	6.482	13.513	19.519	1.226	0.166
19	57.505	52.328	87.510	74.993	75.994	3.843	15.536	0.538	0.333	18.977
20	79.456	66.928	58.906	57.564	81.444	2.247	18.649	3.749	16.713	11.438

Table B3
Fixed and variable transportation costs from warehouses to customers.

Warehouse	Fixed transportation cost (Echelon 2)					Variable transportation cost (Echelon 2)				
	Customer					Customer				
	1	2	3	4	5	1	2	3	4	5
1	66.68	99.19	88.32	55.5	99.74	11.86	13.68	3.175	6.636	6.317
2	79.02	58.32	82.17	67.22	95.62	10.4	7.276	3.355	13.66	10.11
3	95	50.81	68.43	83.22	79.67	11.52	14.4	13.67	0.397	16.8
4	51.73	92.09	96.6	75.4	64.98	14.2	3.11	12.21	13.23	3.887
5	74.83	52.25	88.69	76.65	87.34	7.27	12.48	14.63	8.279	3.15
6	86	81.58	55.75	98.56	85.34	0.25	0.203	19.04	19.53	19.33
7	99.31	92.74	81.07	85.07	85.04	17.13	2.832	0.995	11.06	3.681
8	89.54	80.51	52.72	74.26	52.63	19.88	16.18	6.124	1.748	8.61
9	84.93	59.74	61.3	90.68	99.59	6.994	2.347	11.72	8.911	8.246
10	87.53	85.92	50.03	63.19	91.19	18.29	4.276	4.483	10.85	12.62
11	90.98	93.02	60.63	72.84	51.92	6.549	2.976	18.58	5.021	1.252
12	66.15	71.99	65.77	56.74	90.55	6.203	0.804	16.42	4.619	8.201
13	70.84	57.09	73.28	64.15	94.78	6.052	8.898	14.32	11.86	2.624
14	53.22	70.73	67.08	73.41	82.13	3.225	6.313	11.44	5.374	0.728
15	82.18	66.88	55.04	95.29	60.87	13.73	13.49	6.643	15.2	3.536
16	95.94	72.59	54.5	68.71	70.75	13.65	13.46	16.62	10.3	5.661
17	70.21	55.58	87.56	90.17	51.18	11.11	8.28	1.468	16.12	6.654
18	74.04	63.93	95.08	50.88	84.05	1.694	11.44	0.441	14.84	18.1
19	97.55	95.01	94.94	93.72	69.55	11.22	9.457	14.35	10.26	17.74
20	75.21	91.56	80.11	54.11	78.89	15.43	2.802	5.29	13.65	8.996

Table B4
Installation costs, capacity coefficients, and inventory level held at warehouses.

Warehouse	Installation	Capacity coefficient	Inventory level held
1	98,276.24	0.009795	70.49
2	97,894.74	0.003893	41.59
3	94,961.33	0.007867	54.98
4	66,377.28	0.009663	34.50
5	72,854.95	0.009541	69.96
6	79,809.01	0.003303	93.35
7	93,931.18	0.003925	46.93
8	58,533.63	0.002933	21.36
9	81,680.11	0.002566	51.08
10	88,579.48	0.007581	36.57
11	78,472.3	0.003431	93.54
12	51,383.89	0.007826	6.80
13	90,549.69	0.006557	50.39
14	63,946.48	0.003619	39.24
15	71,667.46	0.007666	20.49
16	66,813.11	0.00107	52.95
17	79,432.13	0.008799	58.91
18	78,719.58	0.001136	34.58
19	77,171.07	0.004855	25.29
20	78,908.08	0.004228	54.77

Table B5
Demand of each customer.

Customer	Demand
1	773,740.9
2	529,133.4
3	688,861.1
4	987,033.5
5	689,909.4

Data availability

Data will be made available on request.

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