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A joint pricing and sustainable closed-loop supply chain network design problem using blockchain technology

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Abstract

In recent years, blockchain technology changed supply chain processes enormously. Moreover, transparency and traceability became necessary in supply chains due to customers' need for more information on services or products. This paper attempts to ascertain transparency in a joint pricing and sustainable closed-loop supply chain network design problem using blockchain technology. To assure supply chain transparency, the pricing process is done using smart contracts. Smart contracts can modify malfunctions while purchasing returned products from customers. Then, using the derived prices of adopting smart contracts, the optimal design of the closed-loop supply chain network is obtained in an optimization process. Afterward, a fuzzy satisfying approach is used to find the optimal solution among economic, social, and environmental objective functions. Then, the model is evaluated using a numerical case problem. Sensitivity analyses are explicitly done to show the impacts of considering a blockchain-based method, production and distribution capacity expansions and sustainability concerns in the proposed problem. It is also shown that implementing a blockchain-based method delivers %5 more profit on average. It is also proved that expansions in production capacity is approximately %15 better than increasing distribution capacities. Finally, it is demonstrated that the fuzzy satisfying approach can deliver an optimal solution maximizing the minimum satisfaction of each objective function.

Keywords: Blockchain technology, supply chain network design, sustainability, transparency, fuzzy satisfying approach

1- Introduction

Business models are changed by new platforms and fast-changing trends in technology and improved by implementing them (Cahen, Jr et al. 2017). Transactions, sizes, and structures of organizations are also redesigned by the emergence of crypto currency and blockchain technology (Furlonger and Valdes 2017). Blockchain technology has many applications and advantages in different areas (Mendling, Weber et al. 2018). The application of blockchain is not excluded to financial or experimental problems

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(Sunny, Undralla et al. 2020). One of the most critical applications of blockchain technology is managing supply chains to improve transparency or traceability (Hackius and Petersen 2017).

Nowadays, supply chain managers are mainly focusing on the demand of customers and the issue of customer satisfaction (Ali 2019). Thus, some other components must be considered in the central systems to deliver greater consumer values (Nozari and Aliahmadi 2022). Paying more attention to transparency and traceability along with improving traditional factors, including quality, price, customer access, social and environmental issues, can bring what a system needs to improve its efficiency (Sheikh Sajadieh and Ziari 2021).

Hence, both aspects are of great importance in supply chain management problems. Finding the best set of optimal prices, designing a suitable structure, making more access, delivering more green products, and considering social values show the necessity of developing an integrated supply chain that can handle operational and strategic costs simultaneously (Ghomi-Avili, Tavakkoli-Moghaddam et al. 2020).

Moreover, mitigating supply disruptions, reducing CO_2 emissions, scarce resources, and increasing environmental concerns make supply chains add a reverse flow and design a closed-loop supply chain capable of reusing the used products (Memari, Rahim et al. 2016). In addition, customers' need to trace goods or products from origin to destination and their attempts to seize more information about products' features highlight the importance of transparency and originality in a supply chain (Kaushik and Jain 2021). Blockchain is a reliable tool for making or increasing transparency and traceability in a system (Janssen, Weerakkody et al. 2020).

The current paper considers the new and traditional aspects via a blockchain-based method in a sustainable closed-loop supply chain network design problem considering pricing decisions. The developed model simultaneously optimizes the strategic location decisions with optimal operational prices. Finding the optimal location of facilities strengthen the network responsiveness while evoking more customers with optimal prices. In addition, the proposed sustainable model considers economic concerns by maximizing profit, environmental concerns by minimizing CO_2 emissions and social concerns by maximizing job opportunities. A blockchain-based method is developed using smart contracts to consider pricing decisions in the optimization process of the multi-objective network design problem. Finally, the fuzzy satisfying approach is applied to find the optimal solution of the derived Pareto region from the optimization process.

The remainder of this paper is organized as follows. Section 2 shows the related literature on blockchain technology and its application in sustainable supply chain management problems. Section 3 discusses the problem structure. Section 4 describes mathematical modeling and blockchain-based method. Section 5 includes results and sensitivity analyses. Finally, section 6 concludes the paper.

2- Literature review

In this section, related literature on the application of blockchain technology in supply chain management is reviewed, and the potential gaps are highlighted. Afterward, the contributions of this paper are described. Transparency and originality are two critical and influential factors in supply chain management problems. Thus, it is necessary to research blockchain technology and how it can empower these two factors (Pant, Prakash et al. 2015). Similarly, Saberi, Kouhizadeh et al. (2019) studied smart contracts and blockchain technology in supply chain management problems defining novel questions on how blockchain can revolutionize supply chains and what are the challenges and obstacles when applying blockchain in supply chains. Zhao, Liu et al. (2019) presented a blockchain-based system for a water supply chain to improve the system transparency and manage water resources. They noticed that the internet of things (IoT) and blockchain technology can greatly help them control the situation. In the case of using (IoT), Prajapati, Jauhar et al. (2022) integrated virtual and regular supply chains into a single framework. They developed a virtual closed-loop supply chain based on blockchain technology and IoT considering circular economy and sustainability. More recently, Al-Ayed and Al-Tit (2023) worked on applying IoT in a resilient supply chain risk management model. They tried to collect questionnaires from Jordanian industrial firms and proved that risk management in a supply chain has indirect and direct effects on resilience via the internet of things.

However, the blockchain application can be extended to more than traditional supply chains. It can be applied to industries, financial, healthcare, and luxury supply chains or systems. One of the main applications of blockchain in luxury supply chains is for diamond, which Choi (2019) did. Using utility theory, they implemented blockchain technology to explore the originality and traceability of diamonds. They developed distinct models and analyzed traditional retail networks with new innovative blockchain sale platforms.

Later on, Choi and Luo (2019) showed that the fashion industry is so sensitive to the quality of data. Thus, they designed a decentralized supply network to prove the importance of data quality, and they were successful in presenting that data quality can noticeably improve profit and social welfare. They also declared that transaction history could be even more crucial than data quality in a blockchain-based system. Sunny, Undralla et al. (2020), Zheng, Xie et al. (2017), and Dabbagh, Sookhak et al. (2019) presented a review paper to analyze the impacts of blockchain technology on traceability and transparency of a supply chain. Rejeb and Rejeb (2020) also tried to review the same issue. But, they focused on describing the effects of blockchain and using different databases on the sustainability of a supply chain. They showed that the economic aspects of blockchain technology may create new business models. Complexity increases by defining new business models, adding participants, expanding companies' geographical bounds, and sharing information. Thus, transparency and traceability become an excellent solution to militate these difficulties. Hence, the related literature on the application of blockchain in supply chain management changed the way to use this technology for the issue of sustainability. Exploring the literature, many papers were found in the field of traditional closed-loop supply chain network design problem by (Ghomi Avili, Jalali Naeini et al. 2018), (Khalafi, Hafezalkotob et al. 2020), (Ziari and Sajadieh 2022), (Haghshenas, Sahraeian et al. 2022), (Amirian, Amiri et al. 2022), (Afshar, Hadji Molana et al. 2022) and (Aliahmadi, Ghahremani-Nahr et al. 2023). But, this researches lacked sustainability or innovative structures of optimization network structure. As this field needs more innovative models to be enriched, Manupati, Schoenherr et al. (2020) studied a multi-stage closed-loop supply chain network seeking to minimize CO2 emissions via a blockchain-based system. To find the best status for applying blockchain technology, Bai and Sarkis (2020) introduced a blockchain-based system to integrate technical features of a sustainable supply chain with transparency. They proposed regret and fuzzy theory in a decision-making problem to ascertain and evaluate blockchain efficiency.

Wong, Yeung et al. (2021) worked on a novel model to investigate sustainability and evaluate big data in a real-world case problem. They proved that machine learning and data-mining can appropriately measure and mitigate inherent risks in a sustainable supply chain. In addition, Kouhizadeh, Saberi et al. (2021) attempted to describe the same proofs. But, they focused on food industries, healthcare systems and supply chain logistics to show the blockchain application. They also used DEMATEL to evaluate the results. Purnomo, Wangsa et al. (2022) proposed a mathematical model for a traceable fish supply chain and included traceability costs to the basic model. They showed that total costs were amended in forward and reverse distribution channels. Ivanov and Dolgui (2021) used a computer model to represent real-time states in a network for twin supply chains. They demonstrated that this model could overcome previous efforts in mitigating the risks of the Covid-19 pandemic. To complete previous research, Yu, Luo et al. (2022) studied the blockchain' operational value for managers and manufacturers. Seydanlou, Jolai et al. (2022) presented a hybrid resilient and blockchain-based model to design a new supply chain for a factory in China. The proposed model was not only agile, but also it was transparent enough. Ma, Qin et al. (2022) used blockchain to recycle the used products in order to achieve triple economic, environmental and social sustainability. They discussed the blockchain impacts on the performance of the proposed supply chain and platform sales format.

To sum up this section, it must be mentioned that most of the previous efforts just concentrated on presenting a systematic review of blockchain application in supply chain management problems. The literature is almost rich in having different review papers or conceptual frameworks to define the role of blockchain technology or even introduce challenges or barriers. But, it lacks mathematical models specifically designed based on blockchain technology to solve supply-chain network design problems. In addition, most previous research left social or environmental issues in the developed models for further practitioners.

Therefore, designing a sustainable model capable of considering economic, environmental, and social issues is vital. This paper tries to cover the existing gaps by developing a joint pricing and sustainable closed-loop supply chain network design model. To ascertain transparency in the proposed model, a blockchain-based method is also used to implement smart contracts which deliver the optimal price decisions in the buying-back process. Thus, it can be the first research attempt to design a sustainable closed-loop supply chain using blockchain technology. Finally, a fuzzy satisfying approach is also used to prepare a unique optimal solution satisfying all economic, environmental, and social objectives. Finally, the paper highlights covering literature gaps can be stated as follows:

- Proposing a new blockchain-based system for a joint pricing and closed-loop supply chain network design problem
- Adding environmental issues by considering a reverse flow and controlling the CO_2 emissions in the production process
- Adding social issues by considering fixed and variable job opportunities while opening production or collection/ distribution centers
- Proposing a blockchain-based system including smart contracts and optimization process to find the optimal prices and network structure
- Using a fuzzy satisfying approach to find a proper optimal solution across Pareto regions

3- Problem definition

In the current paper, different products are delivered to customers in a closed-loop supply chain network. The proposed supply chain has various echelons including, suppliers, production centers, collection/ distribution centers, and disposal centers. Figure 1 depicts the structure of the proposed closed-loop supply chain. As it is clear, the proposed supply chain includes two different forward and reverse flows, respectively. In the forward flow, materials are delivered from suppliers to production centers. Then, the final products are transferred from production centers to collection/ distribution centers. Afterward, the final products will be delivered to customers at the final products' prices.

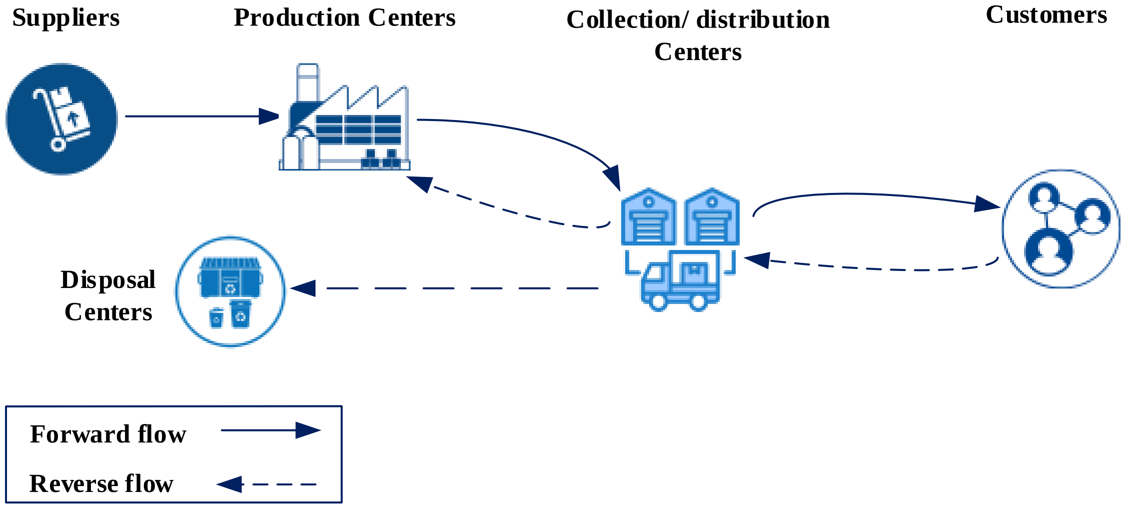

Fig. 1. Structure of the proposed closed-loop supply chain.

In the reverse flow, customers return the used products to the collection/ distribution centers under the proposed returned products' prices in the buy-back process. After that, all the returned products must be examined in the collection/ distribution centers to identify the recoverable products. Then, recovered products are transferred to production centers for manufacturing new final products using the recovered materials from the reverse flow. And the unrecoverable products are delivered to disposal centers. Both raw materials received from suppliers in the forward flow and obtained materials from buying back the returned products in the reverse flow can be used in the production process.

The proposed network should be strengthened by reverse flow due to supply risks in the forward flow and the risk of losing customers in the competitive market. Thus, pricing decisions using a price-dependent demand are considered in this paper to empower the reverse flow. It is assumed that the customer demand is indirectly and directly sensitive to final products and returned products' prices, respectively. Hence, a joint pricing and closed-loop supply chain network design model is developed to make the most efficient network along with offering reasonable prices invoking customers to return the used products.

The proposed joint pricing and closed-loop supply chain network model aim to reach sustainability by increasing market share, maximizing total profit, improving system performance, and solving environmental and social concerns. Economic sustainability modeled by defining economic objective function, is trying to maximize the proposed supply chain profit minus associated strategic and operational costs. Environmental sustainability modeled by defining environmental objective function, is trying to minimize total CO_2 emissions in the production process. To add environmental issues, new production centers can be equipped with green machines producing products with lower CO_2 emissions under extra costs. Finally, social sustainability modeled by defining social objective function, is trying to maximize job opportunities. Opening each production or collection/ distribution center brings fixed job opportunities for managers and variable job opportunities for workers. In this paper, a variable job is calculated based on the number of products handled by a worker.

The sustainable closed-loop supply chain network design model considering pricing decisions can be formulated using the following assumptions.

- A multi-product, multi-period, and multi-echelon model is considered.
- The multi-objective model includes deterministic parameters.
- CO_2 emission is considered per unit of produced product in production centers.
- Number of fixed and variable job opportunities is fixed.
- Number of production and collection/ distribution centers is limited.
- Capacity of production and collection/ distribution centers is limited.
- Capacity of suppliers and disposal centers is fixed.
- Locations of suppliers, customers, and disposal centers are fixed and pre-defined.
- All the used products are collected in the proposed network.
- Shortage is not allowed.

Using the above assumptions, the proposed model attempts to find the optimal locations of production and collection/ distribution centers, optimal returned products' prices, and the quantity of material and products flow among different echelons while empowering transparency, maximizing total profit, minimizing CO_2 emissions and maximizing job opportunities.

4- Mathematical modeling

The model involves the following sets, parameters, and decision variables.

Sets:	
i	Set of suppliers
j	Set of potential nodes for production centers
c	Set of potential nodes for collection/ distribution centers
d	Set of disposal centers
k	Set of customers
n	Set of raw material in forward flow
g	Set of raw material in reverse flow
p	Set of products
t	Set of periods
Parameters:	
F_i	Fixed costs of opening production center j
F_c	Fixed costs of opening collection/ distribution center c
G_i	Cost of equipping production centre j with green machinery
T_{jct}^{p}	Unit transportation cost per product p from the production center j to collection/ distribution center c during the period t

T_{ckt}^{p}	Unit transportation cost per product p from collection/ distribution center c to customer k during the period t
T_{kct}^{p}	Unit transportation cost per returned product p from customer k to collection/ distribution center c during period t
T_{cjt}^{p}	Unit transportation cost per recoverable product p from collection/ distribution center c to production center j during period t
T_{cdt}^{p}	Unit transportation cost per scrapped product p from collection/ distribution center c to disposal center d during period t
f_{t}^{p}	Final price of product p at period t
pr_{ijt}^{n}	Purchase cost of raw materials n from supplier i to production center j during period t
ho_{j}^{p}	Holding cost per unit of the final product p at the production center j
c_{j}^{p}	Production cost per unit of product p produced from forward flow at the production center j
$\bar{c}_{j}^{p}$	Production cost per unit of product p produced from reverse flow at production center j
J_{j}	Fixed jobs created by opening a production center j
J_{c}	Fixed jobs created by opening collection/ distribution center c
V_{jt}	Variable jobs created by opening production center j during period t
V_{ct}	Variable jobs created by opening collection/ distribution center c during time period t
E_{j}	Unit CO_2 emission per unit of produced product at the production center j
ca_{j}	Capacity of the production center j
ca_{c}	Capacity of the collection/ distribution center c
ca_{d}	Capacity of the disposal center d
d_{kt}^{p}	Base market demand of customer k for product p during the period t
α	Final products’ price coefficient in demand function
β	Returned products’ price coefficient in the demand function
w_{n}^{p}	Percent of raw material n in the final product p
r_{g}^{p}	Percent of raw material g in the final product p
w^{p}	Percent of raw material obtained from the product p
λ	Percent of returned products
θ	Disposal rate of products

Decision variables:

Y_{jt}	1 if production center j is opened during period t ; 0, otherwise.
Y_{ct}	1 if collection/distribution center c is opened during period t ; 0, otherwise.
A_{ijt}^{n}	Quantity of raw material n from supplier i to production center j during period t
A_{jct}^{p}	Quantity of final product p from the production center j to collection/ distribution center c during period t
A_{ckt}^{p}	Quantity of final product p from collection/ distribution center c to customer zone k during period t
Z_{kct}^{p}	Quantity of returned product p from customer zone k to collection/ distribution center c during period t

Z_{cjt}^{p}	Quantity of recoverable product p from collection/distribution center c to production center j during period t
Z_{cdt}^{p}	Quantity of scrapped product p from collection/ distribution center c to disposal center d during period t
M_{jt}^{p}	Quantity of product p produced from forward flow in production center j during period t
N_{jt}^{p}	Quantity of product p produced from reverse flow in production center j during period t
I_{jt}^{p}	Inventory of product p in production center j at the end of period t
P_{kt}^{p}	Buy-back price of returned product p for customer k during period t
D_{kt}^{p}	Demand of customer k for product p during period t
R_{kt}^{p}	Quantity of returned product p from customer k during period t

Now, the multi-objective sustainable closed-loop supply chain network design problem considering price-dependent demand can be written as follows:

$$\begin{aligned}Max\ Z_1 = {} & \sum_k\sum_p\sum_t f_t^{\,p} D_{kt}^p - \Big(\sum_j\sum_t (F_j + G_j) Y_{jt} + \sum_c\sum_t F_c Y_{ct} \\ & + \sum_k\sum_p\sum_t P_{kt}^p R_{kt}^p + \sum_n\sum_i\sum_j\sum_t p\, r_{ijt}^n A_{ijt}^n + \sum_p\sum_j\sum_c\sum_t T_{jct}^p A_{jct}^p \\ & + \sum_p\sum_c\sum_k\sum_t T_{ckt}^p A_{ckt}^p + \sum_p\sum_k\sum_c\sum_t T_{kct}^p Z_{kct}^p + \sum_p\sum_c\sum_j\sum_t T_{cjt}^p Z_{cjt}^p \\ & + \sum_p\sum_c\sum_d\sum_t T_{cdt}^p Z_{cdt}^p + \sum_j\sum_p\sum_t c_j^p M_{jt}^p + \sum_j\sum_p\sum_t \bar{c}_j^p N_{jt}^p \\ & + \sum_j\sum_p\sum_t ho_j^p I_{jt}^p \Big)\end{aligned} \tag{1}$$

$$Min Z_2 = \sum_j\sum_c\sum_p\sum_t E_j A_{jct}^p \tag{2}$$

$$\begin{aligned}Max\ Z_3 = {} & \sum_j\sum_t J_j X_{jt} + \sum_j\sum_c\sum_p\sum_t \frac{A_{jct}^p}{V_{jt}} \\ & + \sum_c\sum_t J_c X_{ct} + \sum_c\sum_k\sum_p\sum_t \frac{A_{ckt}^p}{V_{ct}}\end{aligned} \tag{3}$$

$s.t.$

$$\sum_c A_{ckt}^p = D_{kt}^p \qquad (\forall k, p, t) \tag{4}$$

$$D_{kt}^p = d_{kt}^p - \alpha f_t^{\,p} + \beta P_{kt}^p \qquad (\forall k, p, t) \tag{5}$$

$$R_{kt}^p = \lambda D_{kt}^p \qquad (\forall k, p, t) \tag{6}$$

$$\sum_c Z_{kct}^p = R_{kt}^p \qquad (\forall k, p, t) \tag{7}$$

$$\sum_j A_{cjt}^p - (1-\theta)\sum_k Z_{kct}^p = 0 \qquad (\forall c, p, t) \tag{8}$$

$$\sum_d Z_{cdt}^p - \theta\sum_k Z_{kct}^p = 0 \qquad (\forall c, p, t) \tag{9}$$

$$\sum_{k} Z_{kct}^{p} \le ca_c Y_{ct} \qquad (\forall c, p, t) \qquad (10)$$

$$\sum_{i}\sum_{n} A_{ijt}^{n} + \sum_{c}\sum_{p} Z_{cjt}^{p} w^{p} \le ca_j Y_{jt} \qquad (\forall j, t) \qquad (11)$$

$$\sum_{c} Z_{cdt}^{s} \le ca_d \qquad (\forall d, p, t) \qquad (12)$$

$$I_{j,t-1}^{p} + M_{jt}^{p} + N_{jt}^{p} - \sum_{c} A_{jct}^{p} = I_{jt}^{p} \qquad (\forall j, p, t) \qquad (13)$$

$$\sum_{c} A_{jct}^{p} \le M_{jt}^{p} + N_{jt}^{p} + I_{j(t-1)}^{p} \qquad (\forall j, p, t) \qquad (14)$$

$$\sum_{j} A_{jct}^{p} = \sum_{k} A_{ckt}^{p} \qquad (\forall c, p, t) \qquad (15)$$

$$\sum_{p} M_{jt}^{p} w_{n}^{p} \le \sum_{i} A_{ijt}^{n} \qquad (\forall n, j, t) \qquad (16)$$

$$\sum_{p} N_{jt}^{p} . r_{g}^{p} \le \sum_{c}\sum_{p} Z_{cjt}^{p} w^{p} \qquad (\forall g, j, t) \qquad (17)$$

$$Y_{jt}, Y_{ct} \in \{0, 1\} \qquad (\forall j, c) \qquad (18)$$

$$R_{kt}^{p}, D_{kt}^{p}, P_{kt}^{p} \in R^{+} \qquad (\forall k, p, t) \qquad (19)$$

$$A_{ijt}^{n}, A_{jct}^{p}, A_{ckt}^{p}, Z_{kct}^{p}, Z_{cjt}^{p}, Z_{cdt}^{p}, M_{jt}^{p}, N_{jt}^{p}, I_{jt}^{p} \in R^{+} \qquad (\forall k, p, t) \qquad (20)$$

The multi-objective joint pricing and closed-loop supply chain network design model economic objective function is formulated in equation(1). It maximizes the supply chain's total income minus costs of opening production centers, costs of opening collection/ distribution center, costs of buying returned products, transportation costs for shipping raw materials from suppliers to production centers, transportation costs for shipping final products from production centers to collection/ distribution centers, transportation costs for shipping final products from collection/ distribution centers to customers, transportation costs for shipping returned products from customers to collection/ distribution centers, transportation costs for shipping recoverable products from collection/ distribution centers to production centers, transportation costs for shipping unrecoverable products from collection/ distribution centers to disposal centers, production and holding costs in production centers. The environmental objective is formulated in equation(2). It minimizes total CO_2 emissions produced in production centers. The social objective is formulated in equation(3). It maximizes fixed and variable job opportunities by opening production and collection/ distribution centers.

Constraints (4) state that all demands of customers must be fulfilled by the total amount of products from collection/ distribution centers. Constraints (5) show that customer demand depends on the final product and buy-back prices. Constraints (6) ensure that the returned products are just a fraction of the total customer demand. Constraints (7) state that all the returned products are collected in the collection/ distribution centers. Constraints (8) ascertain that the total shipped quantity of products from collection/ distribution centers to production centers equals the total amount of recovered products. Constraints (9) state that total shipped quantity of products from collection/ distribution centers to disposal centers is equal to the total amount of unrecovered products.

Constraints (10) - (12) show capacity limitations in production, collection/ distribution and disposal centers. Constraints (13) and Constraints (14) describe the balance of inventory in the production centers. Constraints (15) assure the total quantity of shipped products from collection/ distribution centers to customers equals the total amount of shipped products from production centers to collection/ distribution centers. Constraints (16) and (17) state the balance of production using material from both forward and reverse flows. And constraints (18) - (20) keep limitations on binary and non-negative decision variables.

4-1- Blockchain framework

As mentioned, the joint pricing and sustainable closed-loop supply chain network design model need transparency. In this part, we discuss how blockchain technology improves transparency in the proposed model. Transparency is obtained via designing smart contracts.

Model data and parameters must be available to apply blockchain technology and design a blockchain-based system. The proposed model sets all the data and parameters based on Table **1**. Then, the simple model without a blockchain-based method is solved to get the primal solutions. Afterward, smart contracts are defined to apply blockchain technology and improve transparency in the proposed sustainable network design problem.

Smart contracts are introduced to record the returned products' prices of used products, perform transactions in the purchase process from customers to collection/ distribution centers and share the related information in the distributed ledger form. Therefore, price data are recorded and kept in the distributed ledger form. Then, it is the correct time to use blockchain technology to make a distributed ledger just by adding prices' data without any involvement. Buy-back prices are set as coins in the purchase transactions of smart contracts. All the purchase transactions are hashed and also automated by manager monitoring. When a used product is purchased in the proposed closed-loop supply chain, the transaction value will be shared as purchase costs. The related data of purchase transactions are keeping in the distributed ledger form which all the stockholders can observe. Moreover, the managers set an upper and a lower bound for the returned products' prices in the smart contracts. Offered returned or buy-back prices from collection/ distribution centers to customers are monitored by smart contracts continuously. Any malfunction or violation due to the defined upper and lower price bounds will be detected by smart contracts to modify the abnormal status. Afterward, the algorithm should be adjusted based on the updated data of purchase transactions, and the optimal price and demand of each facility will be derived to calculate the proposed closed-loop supply chain profit. This cyclic process continues till deriving an optimal solution.

Having the optimal solution, the optimization process triggers using data of blockchain-based method in the distributed ledger form (Manupati, Schoenherr et al. 2020). Figure 2 demonstrates the final optimization process based on the blockchain-based method. In the optimization process, the final optimal decisions of the proposed model are determined while considering different economic, environmental and social objective functions.

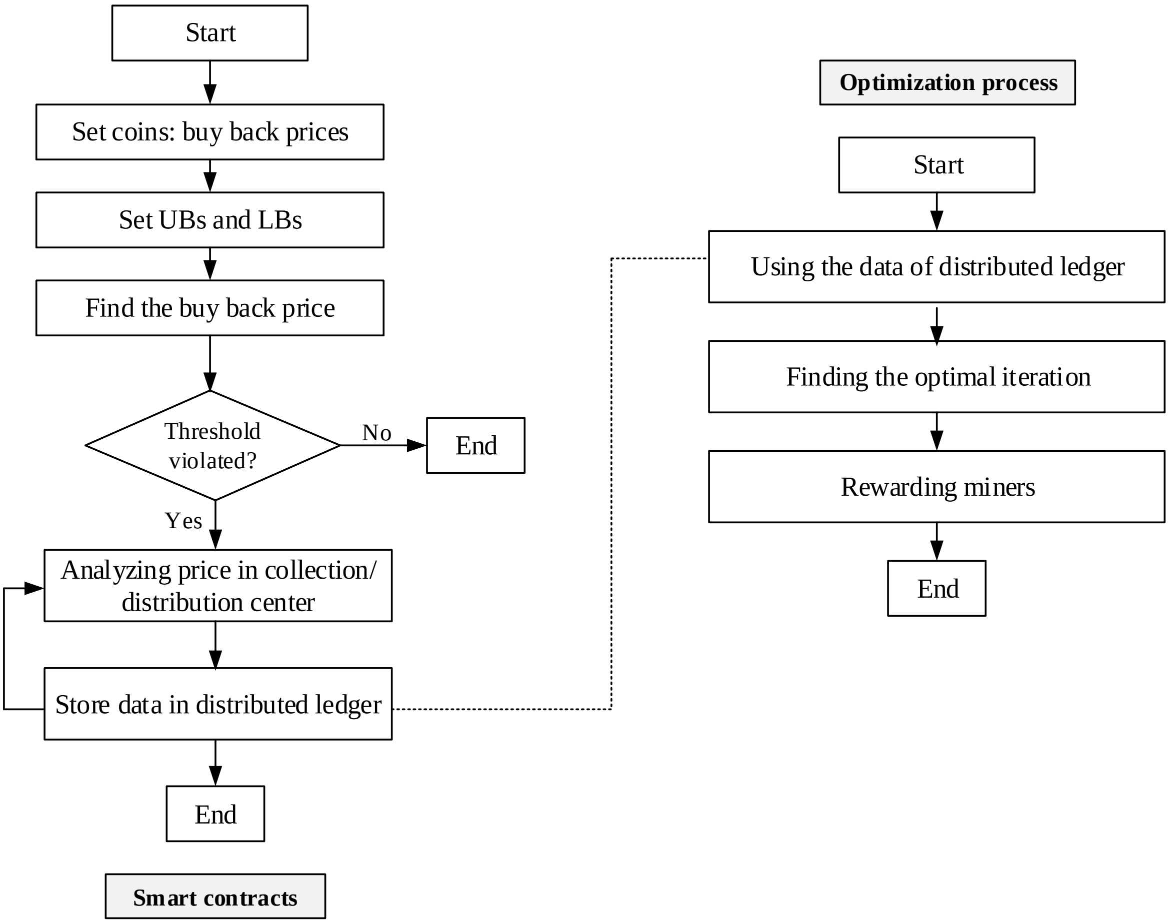

Fig. 2. Optimization process

The optimization process steps are as follows:

Step 1: Smart contracts include buying-back prices. These data are stored in the distributed ledger form of the blockchain-based method. As each facility's associated data is held in the distributed ledger form, it can be used as initial values to start the optimization process.

Step 2: The mixed-integer linear programming model is optimized by applying the data of step 1, and the profit is calculated in each iteration. All data can be seen in distributed ledger forms as transactions. Thus, the iteration delivering the best profit obtained as the optimal solution.

Step 3: A portion of purchasing costs must be rewarded to the miners validating purchase transactions in the optimization process.

4-2- Fuzzy satisfying approach

The developed sustainable closed-loop supply chain network design model has three distinct objective functions. After solving the model and deriving the optimal solution among different iterations of the optimization process, it is crucial to find the optimal point across the derived Pareto regions (Nojavan, Majidi et al. 2017). The fuzzy satisfying approach is used here to convert the Pareto region into a proper optimal value. The rules of this approach can be stated as follows (Huang, Hou et al. 2020):

For minimization objective (f_k) and optimal solution (x_c) on the Pareto region, membership function ($\mu^{f_k(x_c)}$) formulates:

$$\mu^{f_k(x_c)} = \begin{cases} \dfrac{f_k^{max} - f_k(x_c)}{f_k^{max} - f_k^{min}} & f_k^{min} \le f_k(x_c) \le f_k^{max} \\ 0 & otherwise \end{cases} \tag{21}$$

A risk-averse decision-maker seeks to maximize minimum satisfaction:

$$Max(\min_{k} \mu^{f_k(x_c)}) \tag{22}$$

Thus, the optimal solution of the multi-objective model can be achieved using the above formulation.

5- Computational experiments

In this section, a computational study is considered to assess the performance of the proposed model, and the related results are reported. The model is solved using random data, which are summarized in Table **1**, and the sensitivity analyses are done as follows:

Table 1. Required data

Parameter	Value	Parameter	Value
F_j	Uniform [4000000000,6000000000]	ho_j^p	Uniform [20000,70000]
F_c	Uniform [7000000000,9000000000]	c_j^p	Uniform [25000,75000]
G_i	Uniform [105000,110000]	$\bar{c}_j^p$	Uniform [20000,60000]
Pr_{ijt}^n	Uniform [100000,110000]	J_j	Uniform [15,25]
T_{jct}^p	Uniform [15000,90000]	J_c	Uniform [10,20]
T_{ckt}^p	Uniform [15000,90000]	V_{jt}	Uniform [200,300]
T_{kct}^p	Uniform [15000,90000]	V_{ct}	Uniform [300,400]
T_{cjt}^p	Uniform [15000,90000]	E_j	Uniform [0.5,2]
T_{cdt}^p	Uniform [15000,90000]	f_t^p	Uniform [45000,100000]
ca_j	Uniform [350000,800000]	d_{kt}^p	Uniform [4500,7500]
ca_c	Uniform [15000,40000]	λ	Uniform [0.35,0.55]
ca_d	Uniform [1000,40000]	θ	Uniform [0.5,0.7]

5-1- Analysis of a blockchain-based system

In this paper, a blockchain-based system is used considering smart contracts to improve transparency in a closed-loop supply chain under economic, environmental and social objectives. Here, a simple model without blockchain is solved by Cplex. Then, the blockchain-based model is solved in the same test problems. Figure 3 shows the consequent results. There are some test problems that the simple model profit is greater than the blockchain-based system. This trivial differences may occur due to randomly generated data. But, in more than %80 of test problems, blockchain-based system is better than the simple model. As can be seen, the total achieved profit in the blockchain-based system is better than the simple model in most of the defined test problems. The blockchain-based system on average, is approximately %5 better than the simple one. Hence, using the blockchain based system bring more profits and the managers of food, glass, water, agri-food, or other supply chains can implement this method to solve economic concerns. Moreover, transparency improves via blockchain-based technology and smart contracts, increasing customers' satisfaction and consumer values.

5-2- Analysis of production and distribution capacity

The capacity of facilities plays a vital role in supply chains. Due to the importance of this issue, another analysis is done on the capacity of production and collection/ distribution centers to study the profit trend changing these parameters. To this aim, a blockchain-based model is solved by increasing the capacity of production centers in a test problem. Then, the model is solved on the same test problem increasing collection/ distribution capacities to evaluate changes in profit. As seen in Figure 4, blockchain-based system is more sensitive to production capacity than collection/ distribution capacity.

This sensitivity can be seen with more increases in profit while expanding production capacity. By increasing production centers' capacity, a blockchain-based system profit is, on average %15 better than the simple model. Thus, it is recommended that company managers focus on production centers to bring more profit in similar supply chains.

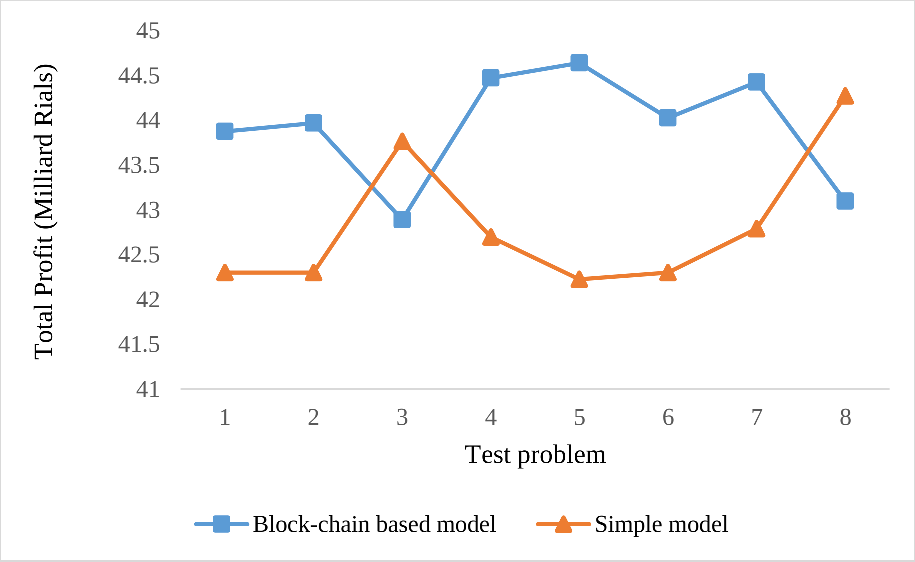

Fig. 3. Blockchain-based system in comparison with a simple model

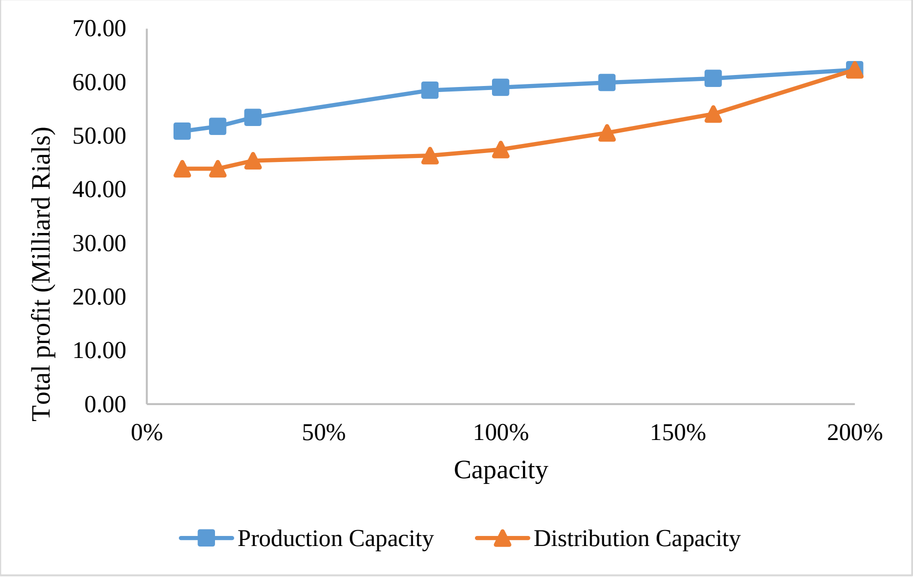

Fig. 4. Profit vs. capacity expansions

5-3- Analysis of considering environmental and social issues

As stated before, the proposed sustainable blockchain-based closed-loop supply chain model includes economic, environmental, and social objectives. Thus, these objectives must be suitably compared with each other to derive an optimal solution for the Pareto region. In this section, the blockchain-based model is solved using smart contracts and an optimization process. The closed-loop supply chain problem is solved in different iterations in the optimization process. Each iteration delivers different economic, environmental and social objective values. The main question is which iteration must be selected as the optimal solution. To this aim, each test problem is solved by fixing a distinct objective function (for example, environmental objective function), and the pair of the other objectives (for example, economic and social objective functions) are analyzed to find out the reciprocal performance of objective functions. Then, the related results are shown in Figure 5 – Figure 7.

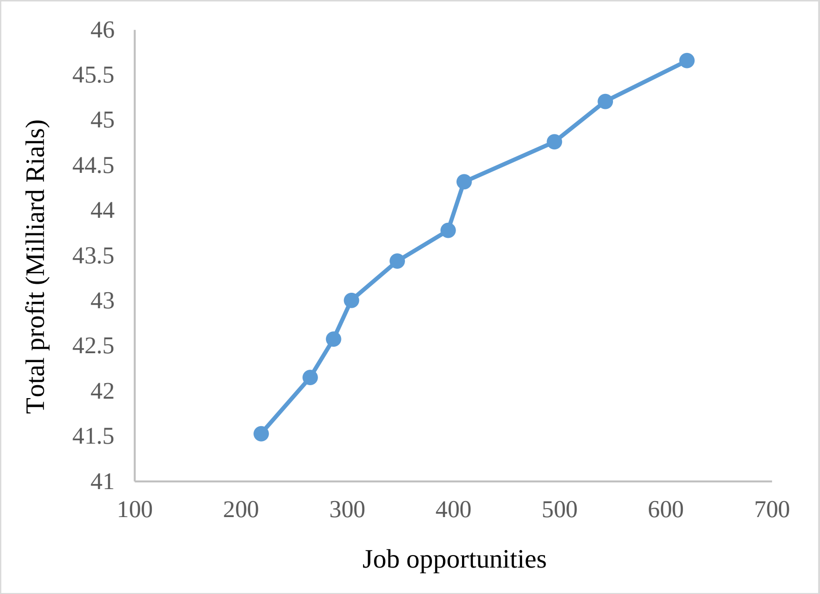

Fig. 5. Total profit vs. job opportunities

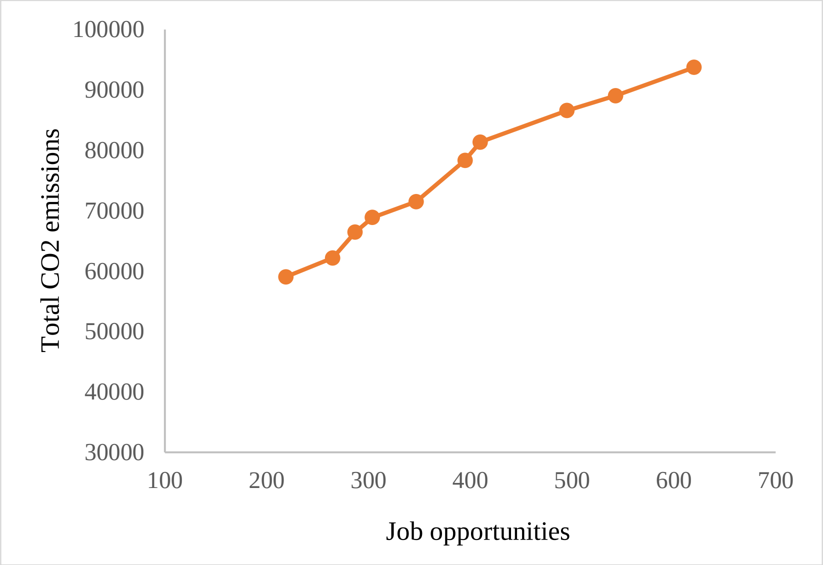

Fig. 6. CO_2 emissions vs. job opportunities

The pairwise conflicts of objective functions and reciprocal behavior show that managers must pay more to reach environmental and social targets compared to situations that only consider economic issues. As stated before, each iteration of the optimization process delivers a distinct economic, social and environmental objective value. Thus, it is essential to know which iteration is the best. The fuzzy satisfying approach is used here on best iterations of a test problem. This approach aims to maximize the minimum satisfaction of each objective function. Thus, the fuzzy satisfying approach is used for the results of different iterations to reach a final optimal solution.

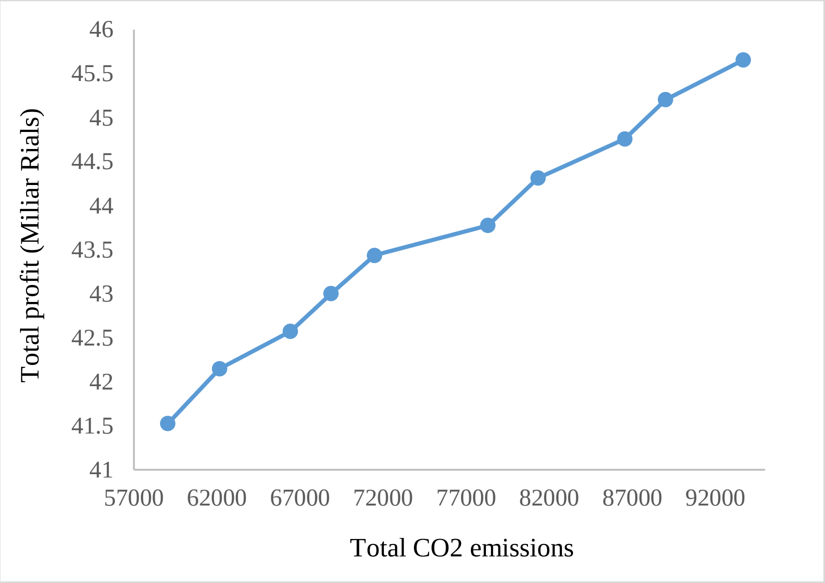

Fig. 7. Total profit vs. CO_2 emissions

The consequent results are summarized in Table **2**. As it is clear, the fourth iteration is selected as the best solution delivering a suitable trade-off among the objective functions. As this approach can balance objective functions and consider a minimum satisfaction for each one, it can be an easy and convenient approach for managers attempting to improve different targets in supply chain management problems

Table 2. Results of applying the fuzzy satisfying approach

Iterations	Z_1	Z_2	Z_3	μ_{Z_1}	μ_{Z_2}	μ_{Z_3}	$min(\mu_{Z_i})$
1	45297326004	87127.0	521	1	0	1	0
2	44857847520	85768.4	487	0.880	0.046	0.892	0.046
3	44403909435	80165.3	408	0.757	0.239	0.641	0.239
4	43534526079	72697.5	351	0.522	0.496	0.460	0.460^*
5	43189028718	66274.8	312	0.428	0.718	0.336	0.336
6	42661388010	64179.2	293	0.285	0.790	0.276	0.276
7	42278904133	60774.8	264	0.181	0.907	0.184	0.181
8	41609186089	58091.3	206	0	1	0	0

6- Conclusion

The current paper proposed a blockchain-based system for a joint pricing and supply chain network design problem to improve transparency. Sustainability is considered in the proposed supply chain due to ever-increasing economic, social, and environmental concerns. More focus on environmental issues, less dependency on suppliers, and the importance of recovering the used products highlight the necessity of configuring a closed-loop supply chain. Hence, the joint pricing and network design model is extended to a closed-loop form before applying the blockchain-based method. Then, to empower transparency in the proposed model, the pricing process for buying back the returned products is done using smart contracts in blockchain technology. To this aim, buy-back processes are changed into transactions that must be recorded in a distributed ledger form. Afterward, smart contracts set lower and upper bounds for returned products' prices. Then, smart contracts are applied to modify the system in the case of violation or malfunction. Finally, deriving each facility' optimal price and demand from distributed ledger forms of smart contracts, the optimization process begins to find the best results among different iterations. As the formulated model tries to maximize profit, minimize CO_2 emissions and maximize job opportunities, a fuzzy satisfying approach is applied to find a proper optimal solution across Pareto regions.

The proposed blockchain-based system application is proven, and sensitivity analyses are done on different test problems to show the impacts of considering a blockchain-based method, production and distribution capacity expansions and sustainability concerns in the proposed problem. It is shown that blockchain-based method is superior to the simple traditional models, and implementing a blockchain-based method delivers %5 more profit on average. Moreover, it is proved that increasing production capacity is, on average %15 better than distribution capacity expansions. And finally, it is proved that applying a fuzzy satisfying approach can deliver a suitable trade-off among the defined objective functions. It is also shown that the blockchain-based system brings more profit, improves system efficiency, and ascertains its transparency simultaneously. Develops on the application of blockchain in supply chain management problems are endless. Further practitioners can find new challenging issues by adding uncertainty or applying utility theory to extend the literature.

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