Li, Y., Lim, M. K. and Wang, C. (2022) An intelligent model of green urban distribution in the blockchain environment. *Resources, Conservation and Recycling*, 176, 105925.

(doi: 10.1016/j.resconrec.2021.105925)

An intelligent model of green urban distribution in the blockchain environment

Abstract

Recently, with the deterioration of the environment, increasing companies choose horizontal cooperation to achieve the goal of reducing environmental pollution and cost in the urban distribution industry. However, companies worry that the business information is leaked in the process of horizontal cooperation. This kind of mistrust often leads to the failure of horizontal cooperation. The emergence of blockchain technology has become a great means to resolve trust problem between partners, which ensures data sharing and trust through peer-to-peer, consensus mechanism and encryption technology. In response, this study proposes an architecture of blockchain-based urban distribution system for horizontal cooperation that analyzes the components and layers of the urban distribution. Meanwhile, a smart contract, the innovative applications of blockchain, is designed to match the resource of supply and demand to design the distribution routes in the urban distribution system. To achieve the above goal, an open vehicle routing model of urban distribution taking into account environmental pollution factors is developed as the mathematical logic of smart contract, which aims at the lowest total cost including fixed, fuel, penalty, carbon emission and pollutant emission costs. Furthermore, the genetic algorithm is developed to support the implementation of smart contract, and the effectiveness of the smart contract is verified through a real case. This study narrows the knowledge gap in applying blockchain technology to urban distribution, and has brought contributions to the fields of blockchain and urban distribution. Finally, the limitation and future research direction are discussed.

Keywords: Blockchain; Smart contract; Urban distribution; Horizontal cooperation; Vehicle routing

1. Introduction

In recent years, the urban distribution industry has developed rapidly with the progress of economy and technology (Yadav and Singh, 2020). However, some negative environmental effects also have followed, including air pollution and global warming (Karaman et al., 2020; Lim et al., 2020). In the face of the continuously expanding urban distribution market, if there is no active action, the environmental problems of urban distribution will be even worse. Therefore, how to reduce environmental pollution in the urban distribution has become an important issue (Wu et al., 2020). In response, scholars have begun the related research in the field of green urban distribution. Previous studies showed that horizontal logistics cooperation between different companies is a feasible solution, that aims optimize the distribution network by integrating tangible (logistics facilities) and intangible (information) logistics resources to achieve the set goals (Allen et al., 2017; Herold and Lee, 2019). More specifically, the related research showed that the distribution cost is reduced by 17.7% (Li et al., 2020b) and the carbon emission is reduced by 25.3% (Liu et al., 2020) through horizontal logistics cooperation mechanism. In addition, it can also increase the vehicle utilization, alleviate traffic congestion and reduce the operating distance of the entire distribution network (Park et al., 2016).

The successful implementation of horizontal logistics is inseparable from the sharing of tangible and intangible logistics resources (Raue and Wieland, 2015). In terms of tangible logistics resources, partners usually need a cooperative hub to promote the exchange of goods and the sharing of logistics facilities (Brown and Guiffrida, 2014). However, the sharing of intangible resources (information) has become a key issue that hinders the development of horizontal logistics. This is because the participants in the horizontal logistics network are both cooperative and competitive, which causes them to worry about business information leakage during information sharing (Pomponi et al., 2015). In this case, the lack of trust often caused the failure of horizontal logistics. According to Hribernik et al., (2020), trust issues reduce the willingness of horizontal logistics cooperation between companies by 16%-18%. Therefore, to ensure the smooth cooperation, it is necessary to manage the horizontal logistics alliance to avoid trust problems. At this stage, most of the relevant research is focused on ensuring the rights of both parties through the formulation of contracts. For example, Raue and Wieland

(2015) discussed the impact of contracts on operational governance in horizontal logistics services, and concluded that contracts ensure the effectiveness of operational governance, which promotes the coordination of cooperation and reduces the risk of opportunistic behavior among partners. However, the artificially defined contract still has certain risks and does not fundamentally solve this problem.

The emergence of blockchain has become a great means to resolve trust problems (Mikl et al., 2020; Orji et al., 2020). At first, blockchain is applied in the financial field, but people have also noticed that it can also bring great changes to non-financial field, including e-government, e-commerce and logistics (Allen et al., 2019; Hald and Kinra, 2019; Juma et al., 2019). The data sharing and trust in horizontal logistics cooperation is realized through the following aspects. First of all, the blockchain adopts the peer-to-peer mechanism that ensures once a partner adds information to the ledger, all participants can obtain data to realize information sharing (Bai and Sarkis, 2020). This mechanism also ensures that the data in the distribution process is immutable, thereby achieving complete product traceability (Kamble et al., 2020). At the same time, distributed ledger eliminates centralized databases, which effectively prevents a partner from controlling the organization (Azzi et al., 2019). In addition, the database can also set different permissions to manage information according to the partner identity (Lim et al., 2021). Secondly, the joining of new members must be approved by all partners in the blockchain, which ensures the reliability of information sources and effectively avoids fraud (Hasselgren et al., 2020). Finally, sensitive data can be encrypted through cryptography technology to avoid the unauthorized third parties reading it (Wang, L.C. et al., 2019). This mechanism ensures that partners can only obtain the information required by the participating links. For example, in the process of distribution, only the delivered products, location and time are known, and other information such as prices are kept confidential.

In addition to using blockchain to realize information sharing and build trust between partners, it is also necessary to design a cooperation mechanism for planning distribution routes in the urban distribution system (Fu et al., 2020). At this time, the innovative applications (smart contracts) of blockchain plays an important role in the integration of decentralized resources in the distribution network (Leng et al., 2018). In other words, the smart contract can match the resource of supply and demand to design the distribution routes that meets the set goal. To solve this problem, an open vehicle routing optimization model (the method for planning distribution routes) with consideration of environmental pollutants is designed as the mathematical logic of smart contract, which aims to minimize the total cost including fixed, fuel, penalty, carbon emission and pollutant emission costs.

Based on above analysis, this research develops an intelligent green urban distribution model for horizontal cooperation in the blockchain environment, which consists of two research content: (1) An architecture of blockchain-based urban distribution system. (2) A smart contract with an open vehicle routing optimization model as the mathematical logic is designed to plan the distribution routes. Although many benefits that blockchain brings to the urban distribution process have been recognized, the knowledge of applying blockchain technology to the urban distribution practice is still limited. The purpose of this research is to narrow the knowledge gap and realize efficient distribution by constructing an architecture of blockchain-based urban distribution system and implementing the smart contract. To the best of our knowledge, this research is an earlier study on applying blockchain technology to the urban distribution. This research has both theoretical and practical contributions. In theory, this research creatively proposes to design a smart contract to match supply and demand resources to plan the distribution routes. In addition, the architecture developed in this research can provide the reference for further in-depth studies to accelerate the development of blockchain in the field of urban distribution. In practice, this research helps companies realize the advantages of blockchain, thereby promoting the implementation of blockchain projects, which brings excellent competitiveness to the development of the enterprise.

The remaining parts of this study as follows. Section 2 reviews the literature. A blockchain-based urban distribution system framework is designed in Section 3. Section 4 introduces the mathematical model of smart contracts. The experiments based on real case are carried out in Section 5. Section 6 presents further discussion including main findings, implications for research and implications for practice. Finally, the conclusion and future research are summarized in Section 7.

2. Literature review

2.1 Blockchain and smart contract

Blockchain is used to establish trust among relevant stakeholders in urban distribution system. Blockchain is a distributed database that does not require the support of a third party, which uses the cryptography, consensus mechanism and smart contract to ensure the safety and efficiency (Drljevic et al., 2020). This emerging technology can bring revolutionary changes to many industries, including the logistics field (Bumblauskas et al., 2020). The information flow, as an important content in the field of logistics, directly affects the management level (Rahmanzadeh et al., 2020). Blockchain technology can ensure the information sharing and increase trust among participants. The information plays an important role in the following aspects. The timely information on the blockchain network can help all parties to make more accurate decisions, covering the registration information and order information of the goods in the circulation process (Longo et al., 2019). Cole et al. (2019) proposed that the information sharing in the supply chain field can promote inventory management, affect the new product design and development, and thereby the performance of sustainable supply chain management is improved. In addition, the blockchain technology ensures that the goods can be traced throughout due to the data is not be changed (George et al., 2019). Feng et al. (2020) explained that blockchain technology can improve the traceability and safety of food, and a framework of a food traceability system is designed to track the food. Hence, the application of blockchain technology in the logistics field is promising, which can ensure information sharing and increase the trust between participants. As far as we know, the research on urban distribution based on blockchain is still very limited. Therefore, this research is innovative.

Smart contract is used to automatically plan the distribution routes. Smart contract is an important application of blockchain technology, which can improve the overall operating efficiency of the system (Hasan et al., 2019). Different from the real world, the smart contract is a set of promises defined in digital form, which are fixed in the form of code (Tanwar et al., 2020). The participants can design their contracts by defining the code and then they are deployed on the blockchain (Singh et al., 2020). The contract terms can be executed automatically when the pre-defined condition is triggered (Abdullah et al., 2020). This process does not require a third party, which has a huge impact on the traditional business model (Zhu et al., 2020). Liu and Li (2020) claimed that the paperwork and labour was reduced through automated code. At present, due to the high degree of automation, the smart contract has been applied in various business scenarios including purchase, warehouse and deliver (Chang et al., 2019). It can be used to model various business, organizational behaviors and rules in the real world, and it affects the interaction behaviors of various entities (Wang, X. et al., 2019). Based on the above analysis, smart contract can be regarded as a basic protocol to automatically match resources to design a distribution route plan. At present, smart contracts in the logistics field are still focused on the settlement of funds. For example, Chang et al. (2019) proposed three types smart contracts in the transaction process including supplier, buyers and logistics contracts, that ensures the stable operation of the system. As far as we know, there is currently no research on smart contracts in the field of vehicle routing optimization, which also means that the potential of related research is huge.

2.2 Open vehicle routing problem

The model of vehicle routing problem is the mathematical logic of smart contract. Therefore, this section reviews the literature of vehicle routing problem. The concept of the sharing economy also has an impact on the distribution model, that is, a vehicle can directly participate in other tasks instead of returning to the distribution center when the distribution is completed, which regarded as the open vehicle routing problem (Shen et al., 2018). Some scholars have carried out many researches in this field. Brandao (2018) proposed an open vehicle routing problem model of a single depot with time windows, and an iterated local search algorithm is designed. Further, Brandao (2020) extended their own research, the multi depots are considered when studied the open vehicle routing problem with the aim of minimum total running distance. Their research studied the multi-depot open vehicle routing problem to meet flexible and fast distribution. As the deepening of research, the goal has gradually evolved from the shortest running distance to the lowest total cost (Li et al., 2020b). Xia and Fu (2018) established a double objective open vehicle routing problem model including the minimum vehicles and total cost. In their research, the traveling cost only depends on the distance. In fact, the load and distance both affect the fuel consumption, thereby the traveling cost is affected (Wang et al., 2017). Therefore, the factor of load and distance are taken into account when calculating fuel consumption in this study.

As the deterioration of the environment, scholars have begun to focus on the optimization of open vehicle routing problem with consideration of the environmental impact (Wei et al., 2020). Shen et al. (2018) considered carbon emission when studied open vehicle routing problem and particle swarm optimization-tabu search (POS-TS) algorithm is proposed to handle the model. However, in the existing research, only carbon dioxide is considered, while ignoring the impact of atmospheric pollutants on the environment, such as CO, PM2.5, HC, and PM10 (Li, R.M. et al., 2019). Therefore, carbon emission and atmospheric pollutants are both considered in this study. Niu et al. (2018) studied the green open vehicle routing problem with time window. However, the time window is a constraint and it is randomly generated in their research. These two points are inconsistent with the actual situation. This study further optimizes their research, which converts the time window into cost, and the setting of the time window is based on an actual case. All the researches mentioned above have studied the same vehicle capacity, however, the logistics enterprises usually have different vehicle capacities in the actual situation (Fachini and Armentano, 2020). Therefore, this study discussed the heterogeneous fleet (with different vehicle capacities) open vehicle routing problem.

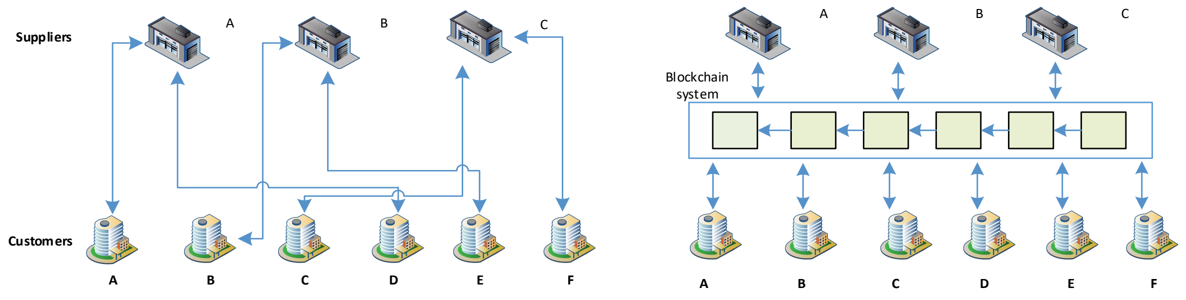
Based on above analysis, the contribution of this study is emphasized. Firstly, blockchain technology is innovatively applied to the field of urban distribution to achieve information sharing. Specifically, an architecture of blockchain-based urban distribution is developed in this study. Secondly, a smart contract is designed to manage the distribution routes. Specifically, a heterogeneous open vehicle routing problem model with consideration of carbon emission and atmospheric pollutants is proposed as the mathematical logic of smart contract, which aims to minimize the total cost, including the fixed, fuel, penalty, carbon emission and pollutant emission costs. Overall, blockchain technology helps realize information sharing and builds trust among partners in the distribution, which provides trusted data for smart contract to plan distribution routes. Further, a cooperation mechanism for planning distribution routes is designed to achieve the lowest cost.

3. System architecture

This section proposes the architecture of blockchain-based urban distribution system. The application of blockchain realizes information sharing and makes the distribution process more transparent.

3.1 Overview of system

To solve the problem of information sharing and trust in the urban distribution, a blockchain-based urban distribution system is designed. The proposed system has a significant impact on distribution, as shown in Fig. 1. In the traditional distribution (see Fig.1 (a)), the deliver is completed separately and the information is stored in the different suppliers. This approach creates obstacles information exchange among different suppliers, resulting in a decrease in distribution efficiency. The emergence of blockchain brings the new solutions to handle above problem. All information is concentrated on the blockchain system (see Fig.1 (b)), and this mechanism can reorganize resources for distribution, which is conducive to reducing environmental pollution and reducing distribution costs.



（a）（b）

Fig. 1. The comparison of different distribution methods.

Although blockchain technology has many advantages, its implementation still has boundaries. Firstly, blockchain technology guarantees the immutability of information through cryptography and consensus mechanisms (Drljevic et al., 2020). Therefore, there is no need for a third-party intermediary to ensure the security of the transaction, which also means that participants no longer need to pay for the operation and management costs of the third-party intermediary (Toennissen and Teuteberg, 2020). However, the construction cost of the blockchain system is high. Secondly, the distributed ledger of the blockchain replaces the central server through a peer-to-peer network, which saves the construction cost of the central server (Savelyev, 2018). However, compared with the traditional centralized management model, the information update of the blockchain network requires more time and cost. This is because each participant in the blockchain network has a distributed ledger that records all transaction information (Hughes et al., 2019). Lastly, smart contracts, as the key technology of the blockchain, are not subject to human influence. As long as the preset conditions are triggered, they can be automatically executed. Therefore, smart contracts reduce the opportunism of participants, especially the problem of lagging transaction funds (Dolgui et al., 2020). In addition, smart contracts can reduce the uncertainty in the transaction process, thereby reducing transaction costs (Hasan et al., 2019). However, smart contracts cannot predict all accidents. When new contract terms are added, costs are incurred. Further, as the number of participants in the network increases, coordination costs will also increase sharply (Pereira et al., 2019). Based on the above analysis, the implementation of blockchain technology needs to be analyzed based on the actual situation of the enterprise.

3.2 Components of system

The blockchain system protects data security from two levels to achieve the trust of partners. The first is the setting of permissions that make stakeholders can only get data related to participating activities, which protects the business information of partners. The second is the use of blockchain technology to ensure that the information in the distribution process cannot be tampered with, thus achieving the product traceability. This process is inseparable from the active response of participants. The blockchain-based urban distribution system involves five participants: supplier, logistics service provider, customer, supervisor, and operator, as shown in Fig. 2. The supplier is the provider of the goods that are stored in different distribution centers to wait for delivery. The logistics service provider delivers the goods from distribution centers to customers. The customer is the receiver of the goods. The supervisor is mainly responsible for the supervision of the entire blockchain, including verifying the compliance of the transaction and finding the source of the problem. The construction and maintenance of the blockchain platform is the responsibility of the operating company. The status of the supplier, logistic enterprise, and customer in the system are equal, and they each have a ledger (Peer 1, 2, and 3 represent the ledger of suppliers, logistics service provider and customer respectively). These ledgers store the products distribution information and cannot be tampered with.

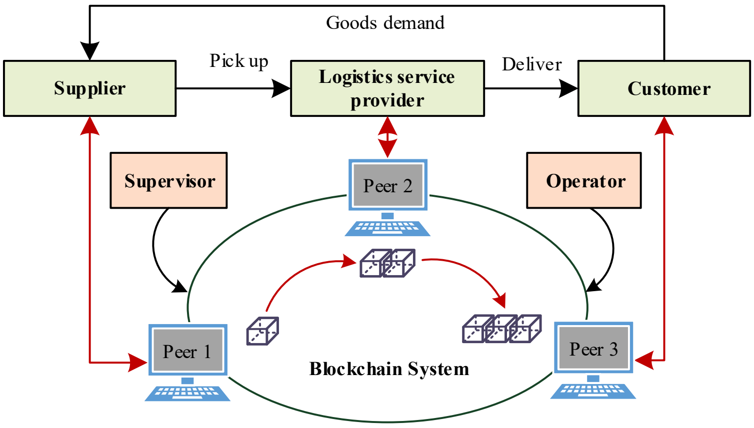


Fig. 2. The participants of blockchain-based urban distribution system.

3.3 Layers of system

The blockchain-based urban distribution system can connect the suppliers, logistics service provider and customers into a network, in which any two nodes can communicate and share information. To ensure the information security, only authorized enterprises can join in the proposed system, which depends on the implementation of alliance chain. The alliance chain is suitable for the cooperation between different organizations, which allows several nodes within different organizations to join together (Hasselgren et al., 2020). The proposed system architecture is composed of three main layers, including infrastructure, blockchain and application, as shown in Fig. 3. It also can be seen that the blockchain layer includes data, network, consensus and contract layers. The layers are connected to each other to jointly maintain the smooth operation of the system and each layer has its own function.

The infrastructure is the bottom layer of the system architecture. Infrastructure refers to the equipment for collecting information, including global positioning system (GPS), geographic information system (GIS), radio frequency identification (RFID) and various sensors. For example, relevant data of the delivery process (including route and time) can be collected through GPS and GIS. The data related to the distribution environment (including temperature and humidity) can be collected by sensors, and RFID helps to collect the circulation trajectory of the product. This layer is mainly used to accurately and timely collect data during the distribution process.

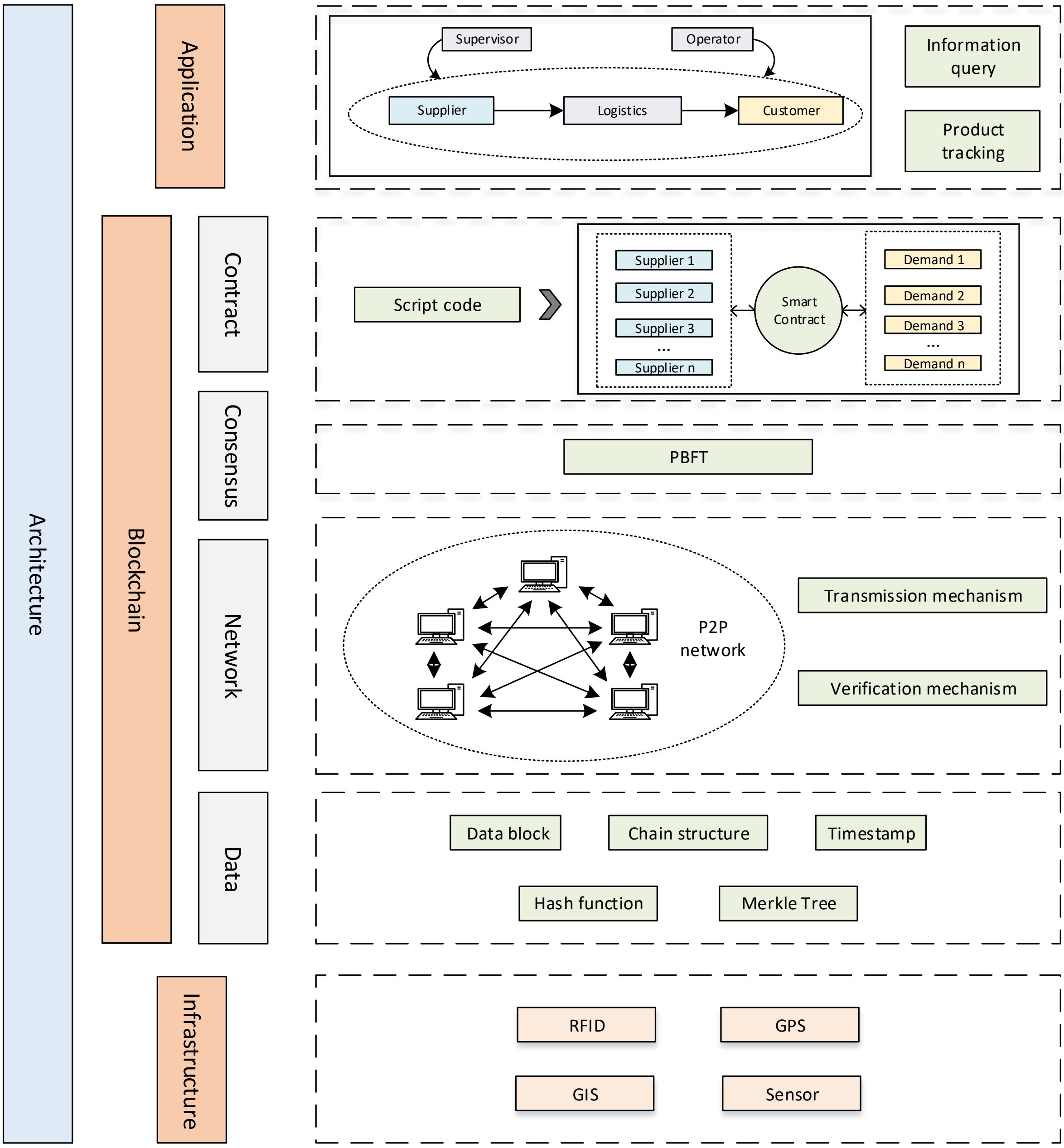


Fig. 3. The architecture of blockchain-based urban distribution system.

The middle layer is the blockchain. The acquired data forms a sequence of blocks connected in chronological order in the blockchain system. In this process, the network and the consensus mechanism ensure the consistency of the data. In addition, smart contracts are designed to manage the distribution process. This layer connects the infrastructure layer and the application layer. The specific description of the blockchain layer is as follows:

(1) Data layer. The acquired data is converted into corresponding data blocks and it is connected to the original block. In the process of data transformation, some technologies such as data block, chain structure, timestamp, hash function and Merkle tree are applied to ensure the security of information (Hasselgren et al., 2020).

(2) Network layer. The network layer uses peer-to-peer (P2P) networks, transmission mechanism and verification mechanism to transmit data. The P2P is adopted to ensure that the supplier, logistic enterprise, and customer in the system are equal, and any participant can participate in the transaction (Savelyev, 2018). The any node broadcasts to other nodes in the network through peer-to-peer technology when it executes the transaction, and all noes reach a consensus to form a new block (Pal et al., 2019). All nodes store ledgers, which makes the data open and transparent. When tracing transaction information and logistics information in the system, nodes can call local data to compare with other nodes to verify the accuracy of the information (Drljevic et al., 2020).

(3) Consensus layer. The consensus layer allows decentralized nodes to reach a consensus on the effectiveness of block data in a decentralized system. It contains the consensus algorithm, which maintains data consistency and immutability (Zhang and Lee, 2020). In practical applications, consensus algorithms need to be selected based on actual needs. The alliance chain composed of supplier, logistics enterprise and customer should use the practical byzantine fault tolerance (PBFT) consensus algorithm, which can tolerate one third of the total nodes as invalid or malicious (Zheng et al., 2017).

(4) Contract layer. The contract layer is composed of script code and smart contract. The smart contract needs to formulate contract content and trigger conditions in advance, and it is converted into code to configure in the blockchain system. When the execution conditions are triggered, the corresponding contract terms are automatically executed, and the outside world

cannot interfere (Singh et al., 2020). In the blockchain-based urban distribution system, the smart contract is designed to match the resource of supplier and demander to plan the deliver routings with the minimum total cost. The operation mechanism of the information matching and transmission is designed as follows:

Step 1: Every participant in the system is assigned a public key and a private key, which are used to encrypt and decrypt the transmission information.

Step 2: Each resource supplier uploads relevant information such as location and inventory, and the resource demander also needs to publish information such as location and demand.

Step 3: The system automatically matches all resource demand parties according to the information provided by the resource suppliers. At the same time, the smart contract is trigged to plan the distribution routings with the minimum total cost, which gets the service relationship.

Step 4: The resource supplier looks up the demander's public key on the demander's address, and compare the result with the public key provided by the demander. If the identity is confirmed, then the supplier sends a message to the demand side. The message includes the specific content of the resource, which is encrypted by the supplier using the public key of the demander. Meanwhile, this information also includes the digital signature of the supplier, which is encrypted using its own private key.

Step 5: When the demand side receives the message, it first uses the supplier's public key to decrypt the digital signature. After confirming the identify, the demander uses its own private key to decrypt the information to obtain the information content. Once the transaction is successful, the system broadcasts the information to all nodes and updates the information in the blockchain to complete a new round of consensus.

Step 6: After the supply and demand transaction is completed, the deliver plan is sent to the logistics company to carry out the actual logistics distribution. At the same time, the system also supervises the distribution process to ensure the safety of the transaction.

The top layer is a medium for information interaction between different participants (supplier, logistics, customer, supervisor and operator) and systems. In the top layer, many functions have been achieved. The participants can operate the logistics business (information release and order query) through the application layer, and the real-time information (status, location, and ownership) of the goods at any time is searched.

4. Design and implementation of the smart contract

Smart contracts are fixed in the blockchain system in the form of code. Before forming the code, it is necessary to clarify the rules of the smart contract. Therefore, the first step in building a smart contract is to propose a mathematical model and the coding work is completed in the second step. Since the proposed open vehicle routing problem considers the environmental factors, environmental pollutants are analyzed in Section 4.1. Then, the objective function is proposed in Section 4.2. Finally, Section 4.3 introduces the implementation of smart contract.

4.1 Calculation of environmental pollutants

The driving power of a vehicle comes from fuel, and the consumption of fuel generates automobile exhaust that pollutes the environment. This section introduces the calculation method of carbon emissions and atmospheric pollutants.

(1) Carbon emission. In order to measure the carbon emission EM, it is necessary to measure the fuel consumption $\sum W$, and then EM is calculated according to $EM = \mu \sum W$, μ represents the carbon emission factor. $\sum W$ is not only related to the distance, but also to the load, and the calculation equation is $\sum W = \sum d_{ij} R(U)$, in which d_{ij} is the distance from i to j, $R(U)$ represents fuel consumption per unit distance. The calculation of $R(U)$ is shown in equation (1), in which R_0 represents the fuel consumption at no load, R represents the fuel consumption at full load, Q is the capacity of the vehicle and U indicates the load of vehicle in a certain routing. Therefore, the calculation of EM is shown in equation (2).

$$R(U) = R_0 + \frac{R-R_0}{Q} U \tag{1}$$

$$EM = \mu \sum d_{ij} \left(R_0 + \frac{R-R_0}{Q} U \right) \tag{2}$$

(2) Pollutant emission. It refers to automobile exhaust including carbon monoxide(CO), hydrocarbons (HC), nitrogen oxides (NO_X), inhalable particulate matter (PM_{10}), fine particulate matter $(PM_{2.5})$ and motor vehicle evaporative emissions (HC). According to *'Technical Guidelines for the Preparation of Air Pollutants Emission Inventory for Road Vehicles'* (Ministry of Ecology and Environment of the People's Republic of China, 2014), the pollutant emission $E = E_1 + E_2$, in which E_1 indicates the automobile exhaust, E_2 indicates the evaporative emissions. The calculation of E_1 is shown in equation (3), in which m represents the type of pollution source, including CO、HC、NO_X、PM_{10}、$PM_{2.5}$, EF_m represents the unit distance emissions of the m type pollution source, VKT is the running distance. The calculation of E_2 is shown in equation (4), in which EF_1, EF_2 are evaporation emission coefficient (*EEC*) during driving and during parking respectively.

$$E_1 = \sum_m EF_m \times VKT \tag{3}$$

$$E_2 = EF_1 t + EF_2 \tag{4}$$

The determination process of EF_m: EF_m is shown in equation (5), in which BEF_m is the comprehensive emission factor of the m type pollution source, φ_n represents environmental correction factor in n area, γ_n is the average speed correction factor (*ASCF*) in n area, λ is the deterioration correction factor of the vehicle (*DCFV*), θ_m is a correction factor (*CF*) for other usage conditions (such as load factor, oil quality, etc.). φ_n is affected by three factors: temperature, humidity, and altitude, its calculation is shown in equation (6), φ_{Temp} indicates temperature correction factor (*TCF*), φ_{RH} indicates humidity correction factor (*HCF*), φ_H indicates altitude correction factor (*ACF*). Therefore, the calculation of pollutant emission is shown in equation (7).

$$EF_m = BEF_m \times \varphi_n \times \gamma_n \times \lambda \times \theta_m \tag{5}$$

$$\varphi_n = \varphi_{Temp} \times \varphi_{RH} \times \varphi_H \tag{6}$$

$$E = VKT \times \left(\sum_m BEF_m \times \left(\varphi_{Temp} \times \varphi_{RH} \times \varphi_H\right) \times \gamma_n \times \lambda \times \theta_m\right) + (EF_1 t + EF_2) \tag{7}$$

4.2 Objective function

The proposed open vehicle routing model aims to minimize the total cost, which contains fixed, fuel, penalty, carbon emission and pollutant emission costs. In above sub-cost, pollutant emission cost reflects the greening capabilities of the smart contract. The meanings of symbols are shown in Table 1.

(1) Fixed cost. It refers to the cost of using vehicles, including driver wages and vehicle losses, and it is only related to the number of vehicles used for distribution. The calculation of fixed cost is shown in equation (8).

$$T_1 = \sum_{h\in H} C_h \cdot W_h \tag{8}$$

(2) Fuel cost. It refers to the cost incurred by the vehicle due to fuel consumption during distribution. The expression of fuel cost is shown in equation (9).

$$T_2 = \sum_{d\in D} \sum_{i,j\in N} \sum_{\mathrm{h}\in H} P_{ij}^{h}\, C_f d_{ij}(R_0 + (R - R_0)U/Q) \tag{9}$$

(3) Penalty cost. The goods must be delivered within the latest time required by the customer. The deliver time later than the requested time affects customer satisfaction and the penalty cost is generated. The penalty cost is shown in equation (10), in which $max\{t_i^h - L_i, 0\}$ represents the vehicle arrived later than the prescribed time.

$$T_3 = \sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H}\left(C_l \cdot max\{t_i^h - L_i, 0\}\right) \tag{10}$$

(4) Carbon emission cost. The carbon emission is shown in equation (2), therefore the carbon emission cost is expresses as in equation (11).

$$T_4 = C_t \cdot \sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H} P_{ij}^{h} \cdot \mu \cdot d_{ij}(R_0 + (R - R_0)U/Q) \tag{11}$$

(5) Pollutant emission cost. The calculation process of pollutant emissions is introduced in section 4.1, thus the pollutant emission cost as follows in equation (12).

$$T_5 = C_w \times 10^{-3}\left(\sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H} P_{ij}^{h}\, d_{ij}(BEF_m \times \varphi_n \times \gamma_n \times \lambda \times \theta_m) + (EF_1 t + EF_2)\right) \tag{12}$$

Based on above analysis, the objective function of the open vehicle routing problem model contains fixed, fuel, penalty, carbon emission and pollutant emission costs, as shown in equation (13).

$$T_{min} = \left(\begin{array}{c} \sum_{h\in H} C_h \cdot W_h + \sum_{d\in D} \sum_{i,j\in N} \sum_{\mathrm{h}\in H} P_{ij}^h \, C_f \, d_{ij} \left(R_0 + \frac{R-R_0}{Q} U \right) + \\ C_t \cdot \sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H} P_{ij}^h \cdot \mu \cdot d_{ij} \left(R_0 + \frac{R-R_0}{Q} U \right) + \\ \sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H} \left(C_l \cdot max\left\{ t_i^h - L_i, 0 \right\} \right) + \\ C_w \times 10^{-3} \left(\sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H} P_{ij}^h \, d_{ij} (BEF_m \times \varphi_n \times \gamma_n \times \lambda \times \theta_m) + (EF_1 t + EF_2) \right) \end{array} \right) \tag{13}$$

Constraints:

$$\sum_{\mathrm{h}\in H} \sum_{i\in N} \sum_{d\in D} P_{ij}^h = 1, \forall\, j \in N \tag{14}$$

$$\sum_{\mathrm{i}\in N} \sum_{j\in N} \sum_{d\in D} P_{ij}^h = 1, \forall\, h \in H \tag{15}$$

$$\sum_{\mathrm{i}\in N} \sum_{d\in D} \sum_{h\in H} q_i \, P_{ij}^h \leq Q \,, \forall\, j \in N \tag{16}$$

$$t_j^h = t_i^h + t_s + d_{ij}/v \tag{17}$$

Equation (14) represents each customer must be delivered by a vehicle; Equation (15) indicates the vehicle departs from the distribution center and ends with the last customer. Equation (16) represents the load of vehicle cannot exceed maximum load. The delivery time is continuously expressed in Equation (17).

Table 1. The meanings of symbols.

Symbols	Meaning
D	Distribution center, $D\{d \mid d = 1,2,3 \dots, a\}$
N	Customer, $N\{n \mid n = 1,2,3 \dots, b\}$
H	Vehicle，$H\{h \mid h = 1,2,3 \dots, d\}$
C_h	Vehicle cost，Unit：$CNY/vehicle$
C_f	Fuel cost，Unit：CNY/kwh
C_l	Lately cost of the vehicle，Unit：RMB/h
C_t	Carbon emission cost，Unit：CNY/kg
C_w	Pollutant emission cost，Unit：RMB/kg
t_i^h	Time of vehicle h arrives at customer i
q_i	Demand of vehicle i
L_i	Latest delivery time
Q	Maximum load of vehicle，Unit: t
W_h	0,1 variable，vehicle k is used，$W_h = 1, or\ W_h = 0$
P_{ij}^h	0,1 variable，vehicle h delivers customer j through i，$P_{ij}^h = 1, or\ P_{ij}^h = 0$

4.3 Implementation of the smart contract

To transform the mathematical model into an executable smart contract, a suitable algorithm is needed to obtain a feasible solution. There are many researches have been studied the solving algorithms of vehicle routing problem, and the algorithms are divided into two categories: the exact algorithms and the heuristic algorithms (Li, Y. et al., 2019). As the size of the data increases, exact algorithms are gradually replaced by heuristic algorithms including genetic algorithm (Li et al., 2020a), ant colony algorithm (Zhang et al., 2019) and particle swarm optimization (Chen and Shi, 2019). By comparing these algorithms, ant colony algorithm and particle swarm optimization both have a slow convergence speed and they are easy to fall into a local optimal solution, genetic algorithms have the following advantages (Baniamerian et al., 2019; Pierre and Zakaria, 2017; Xiao and Konak, 2017): (1) The genetic algorithm has a good global search ability, and solutions in the solution space are quickly searched. (2) The genetic algorithm has good parallelism, which makes solving of the solution faster. (3) The genetic algorithm uses probabilistic search technology, which generates more excellent individuals. Therefore, the genetic algorithm is designed in this paper, which makes the smart contracts more efficient. The concrete steps of genetic algorithm are as follows and the flow chart is shown in Fig. 4.

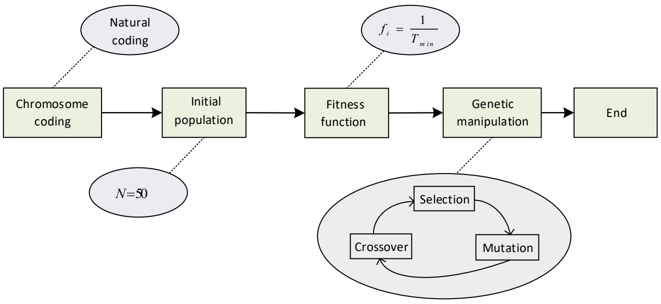


Fig. 4. The flow chart of genetic algorithm.

Step 1. Chromosome coding. The natural coding is selected, and the gene coding on the chromosomes is based on customer grouping. 0 represents the distribution center, 1、2、3…represents the customers. For example, the chromosome code is 0256, which means the distribution order is 0-2-5-6.

Step 2. Initial population. The population size, that is the number of individuals in the population, is set according to a random manner.

Step 3. Fitness function. The goal of the model is to minimize the total cost. For chromosomes, the smaller the total cost, the higher the fitness value. Therefore, the inverse of the total cost is selected as the fitness function, as shown in equation (18).

$$f_i = 1/T_{min} \tag{18}$$

Step 4. Genetic manipulation. The fitness of the individuals in the population is changed through genetic operations, which continuously improves the fitness of the individuals. The genetic operations include selection, crossover, and mutation.

Selection. The roulette method is used for selection. If the population size is M and the fitness function of the individual is f_i, then the probability of the individual i is selected according to formula (19).

$$P_i = f_i/\sum_{i \in M} f_i \tag{19}$$

Crossover. Crossover is a new chromosome generated by chromosomal mating and recombination in the process of simulating biological evolution. The partial matching crossover method is used in this paper. The steps are as follows, and the process is shown in Fig. 5.

1) Select the intersection area, and cross 961 in F1 and 95 in F2.
2) Put the intersections in F1 and F2 to the top of each other's genes respectively, and F11 and F21 are get.
3) Remove the duplicate genes in the original chromosome to get P1 and P2.

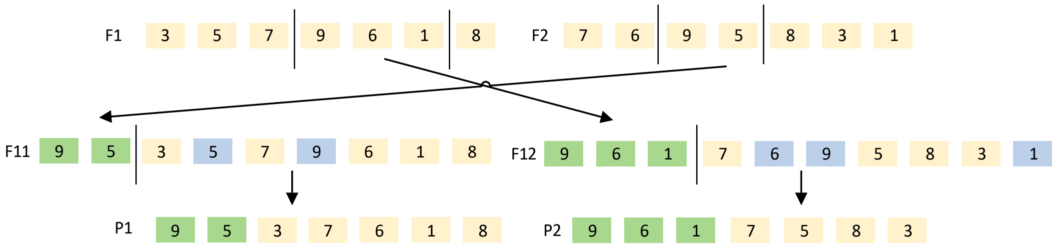


Fig. 5. Crossover operation process.

Mutation. The mutation operation is a process of simulating a biological gene mutation to generate a new chromosome. The mutation operation in this paper includes inversion, swapping and insertion.

1) Inversion. Select the inversion region, such as 376 in P1, and reverse the order in the mutation region to obtain 673 to obtain a new gene fragment. The process is shown in Fig.7 (a).
2) Swapping. Select the genes to be swapped, such as 5 and 1 in P1, and swap the two gene positions to obtain new gene fragments. The process is shown in Fig.7 (b).
3) Insertion. Select the gene 3, and then select another insertion point gene 1, and insert gene 3 to a position before gene 1. The process is shown in Fig.7 (c).

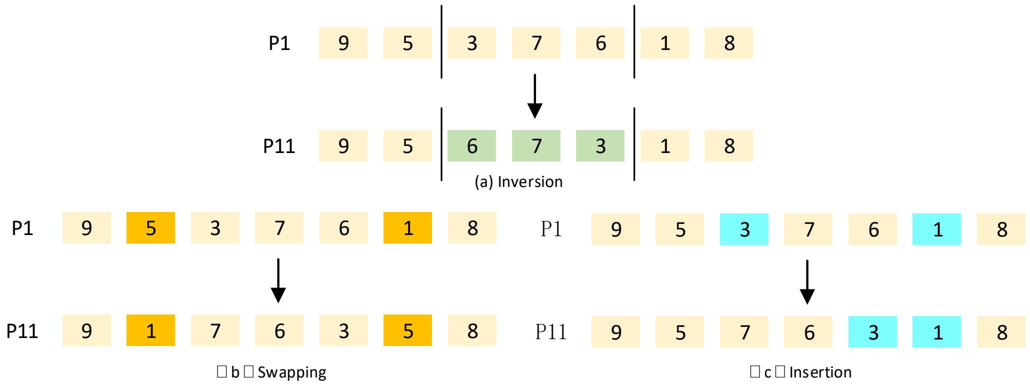


Fig. 6. Mutation operation process.

Step 5. Termination conditions. When the algorithm meets the termination conditions, the evolution is stopped, and the number of iterations is set to 300.

5. Case study

This section discusses the urban distribution in the blockchain environment. A case in Chongqing (a city in China) is selected to verify the effectiveness of the smart contract. The following explains the reasons for choosing the enterprises in Chongqing as the case. The total cost of social logistics in Chongqing was 311.5 billion yuan in 2018, accounting for 15.3% of GDP, which is higher than the national average (Li et al., 2020b). Hence, reducing logistics cost is an important task. In terms of blockchain, Chongqing has established the first provincial-level blockchain application innovation industry in 2020 (People.cn, 2020). Therefore, it is representative to choose the enterprise of Chongqing as the research object. There is an inclusive relationship between the blockchain and smart contracts, and smart contract is an important function in the blockchain system. The purpose of the blockchain platform is to create a safe trading environment, which allows participants to trade with confidence, and the smart contract focuses on planning distribution routes. Therefore, Section 5.1 is intended to explain the advantages of blockchain platforms, while Section 5.2 evaluates smart contracts.

5.1 Benefits of implementing blockchain system

To ensure the operation of the blockchain system, the work of the blockchain system is divided into three stages. The first stage is the collection of the key data, including the location of participants (suppliers and customers) and the demand of customers. In this process, blockchain technology provides trusted data for designing the distribution routes. The collected data is stored in the blockchain system, as shown in Table A1 and Table A2. In the second stage, the smart contract is automatically executed, which matches the resource of suppliers and demanders to develop the distribution plan with the lowest total cost. Further, the distribution plan is sent to the stakeholders once the smart contract is executed, and the stakeholders can only get information related to distribution. In the third stage, the logistics service provider performs distribution, and the process is supervised by the blockchain.

The implementation of blockchain can ensure information security, which depended on the peer-to-peer model, cryptographic technology and consensus mechanism. All information is concentrated on the blockchain platform, which helps to realize information sharing. In other words, the stakeholders can search transaction information in the blockchain system at any time. However, different permissions get different information, which protects the privacy of information to build the trust between participants. It is emphasized that the information is maintained by all participants, once they reach a consensus, the transaction information cannot be changed. In addition, the blockchain can improve the traceability of products. The blockchain technology creates a block for each link of goods from manufacturing to sales, and then connects these blocks, which record the entire process information. This makes it possible to trace the product throughout the process, and it strengthens the supervision of all links in the distribution process to ensure product safety. It can also locate problem links in a timely manner when an emergency occurs, and quickly respond to product recalls to minimize damage.

5.2 Performance of smart contract

Blockchain provides technical support for the implementation of smart contracts. To better evaluate the performance of the proposed smart contract, two experiments are performed. The sensitivity analysis of algorithm parameters is carried out in the first experiment to determine the best parameters (Section 5.2.1). The second experiment proves the validity of the proposed smart contract (Section 5.2.2). MATLAB software is used in a Windows 10 system to carry out experiments.

5.2.1 Experiment 1. Algorithm experiment

The parameters of the genetic algorithm affect the quality of the solution. In this section, the optimal range of parameters is determined by analyzing the operation results under different parameter combinations. The parameters include the population size (*G*), cross probability (*Pc*), and mutation probability (*Pm*), and the values of these parameters are set according to Li et al. (2020a). The settings of model parameters are shown in Table A3. The experimental results are shown in Table 2. First, the population size is studied. The population size is set to $G=60,80,100,120,140$ to carry out experiments 1-5, and the lowest total cost 2375.18 is obtained when $G=100$. Second, the influence of crossover probability on the results is discussed. The settings of *Pc* are *0.2, 0.3, 0.4, 0.5, 0.6* to design experiments 6-10. It concludes that the lowest total cost 2362.67 is obtained when $Pc=0.3$. Last, the value of *Pm* is studied, and the *Pm* is set to $Pm=0.01,0.02,0.03,0.04,0.05$ to carry out experiments 11-15. The lowest total cost 2313.87 is obtained when $Pm=0.02$. In above, the optimal values of the genetic algorithm parameters are set $G=100$, $Pc=0.3$, $Pm=0.02$.

Table 2. Results of different genetic algorithm parameters.

Experiment	G	Pc	Pm	T (RMB)
1	60	0.5	0.01	2443.02
2	80	0.5	0.01	2456.72
3	100	0.5	0.01	2375.18
4	120	0.5	0.01	2414.42
5	140	0.5	0.01	2478.98
6	100	0.2	0.01	2375.39
7	100	0.3	0.01	2362.67
8	100	0.4	0.01	2370.23

9	100	0.5	0.01	2375.18
10	100	0.6	0.01	2463.57
11	100	0.3	0.01	2362.67
12	100	0.3	0.02	2313.87
13	100	0.3	0.03	2379.01
14	100	0.3	0.04	2441.99
15	100	0.3	0.05	2595.68

5.2.2 Experiment 2. Model experiment

The purpose of model experiment is to verify the effectiveness of the proposed smart contract. First, the different objective functions are explored. Objective function 1 includes the fixed cost, fuel cost and penalty cost, as shown in equation (20). On the basis of the objective function 1, the carbon emission cost is added to form the objective function 2, as shown in equation (21). The objective function 3 is as shown in equation (13), which adds the pollutant discharge cost on the basis of the objective function 2. The vehicle with 4t capacities is used in this experiment. The results are shown in Table 3, and the distribution routings is shown in Fig. 7.

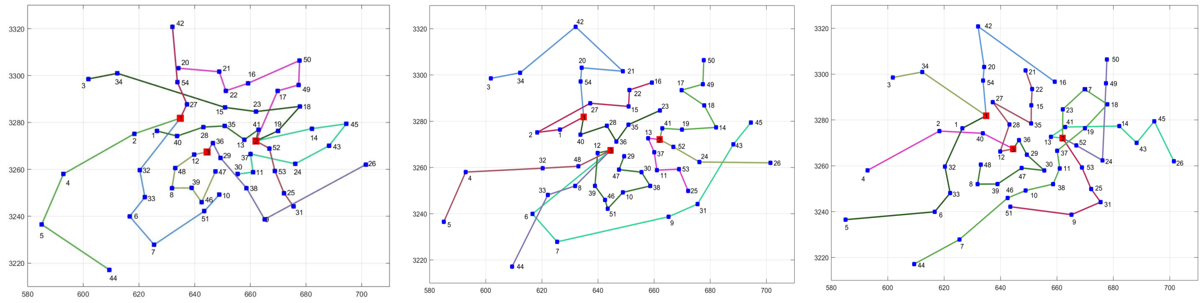
$$T_{min} = \begin{pmatrix} \sum_{h\in H} C_h \cdot W_h + \sum_{d\in D} \sum_{i,j\in N} \sum_{\mathrm{h}\in H} P_{ij}^h \, C_f d_{ij} \left(R_0 + \frac{R-R_0}{Q} U \right) + \\ \sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H} \left(C_l \cdot max\{ t_i^h - L_i, 0 \} \right) \end{pmatrix} \tag{20}$$

$$T_{min} = \begin{pmatrix} \sum_{h\in H} C_h \cdot W_h + \sum_{d\in D} \sum_{i,j\in N} \sum_{\mathrm{h}\in H} P_{ij}^h \, C_f d_{ij} \left(R_0 + \frac{R-R_0}{Q} U \right) + \\ C_t \cdot \sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H} P_{ij}^h \cdot \mu \cdot d_{ij} \left(R_0 + \frac{R-R_0}{Q} U \right) + \\ \sum_{d\in D} \sum_{i,j\in N} \sum_{h\in H} \left(C_l \cdot max\{ t_i^h - L_i, 0 \} \right) \end{pmatrix} \tag{21}$$

From Table 3, it concluded that Objective function 3 performs better in terms of carbon emission reduction and pollutant emission reduction. The analysis process is as follows: The carbon emission and pollutant emission are closely related to the running distance through formula (2) and (7). This study aims to minimize the total cost, when the carbon emission cost is added to the total cost, Objective function 2 searches the distribution routings with less carbon emission (from 484.78kg to 463.74kg) to reduce the total cost. This process is achieved by reducing the running distance (from 735.12km to 717.03km), and the shorter distance has also led to less pollutant emissions (from 3.4kg to 3.12kg). Objective function 3 further adds the pollutant emission cost, so the running distance is reduced further to 703.28 km, the carbon emission is reduced to 45.42kg, and the pollutant emission is reduced to 2.91kg. Therefore, the smart contract proposed in this paper is more effective in reducing carbon emission and pollutant emission. From the perspective of cost, the total cost is increased when the environmental factors are considered in the objective function 2. However, the cost of adopting objective function 3 is lower than the objective function 2, which further illustrates the effectiveness of the proposed open vehicle routing model.

Table 3. Results of different objective functions.

Objective function	Vehicles	Distance （km）	Carbon emission （kg）	Pollutant emission （kg）	Total cost (RMB)
1	10	735.12	484.78	3.40	2313.87
2	10	717.03	463.74	3.12	2535.86
3	10	703.28	451.42	2.91	2521.11



（a）Objective function 1　　（b）Objective function 2　　（c）Objective function 3

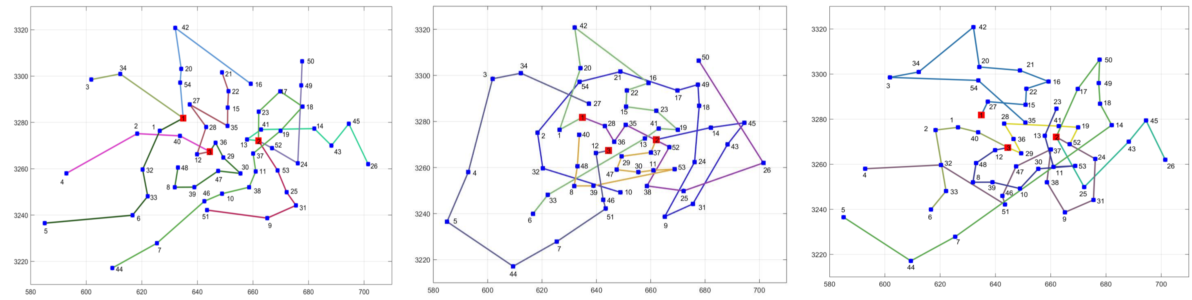
Fig. 7. The distribution routings of different objective functions.

Further, the effectiveness of heterogeneous fleets is discussed. Three types heterogeneous fleets are set, including 4t alone, 6t alone and 4t - 6t mixed. When the 6t is used, $R_0 = 0.21L/km$, $R = 0.43L/km$, $C_{\mathrm{h}} = 120$. The results of different capacities are shown in Table 4, and the distribution routings are shown in Fig. 8.

Table 4. Results of different capacities.

M	N	D	T_1	T_2	T_3	T_4	T_5	T	EM	E
(t)	(Vehicles)	(km)	(RMB)						(kg)	(kg)
4t	10	703.27	1000	1210.08	82.4	225.71	2.91	2521.11	451.42	2.91
6t	5	750.23	600	1630.29	141.95	304.09	3.44	2749.77	608.18	3.44

4t+6t	7	716.87	760	1074.66	86.77	200.45	2.72	2124.59	400.90	2.72



（a）$Q = 4$ （b）$Q = 6$ (c) $Q = 4$ and $Q = 6$

Fig. 8. The distribution routings of different capacities.

From Table 4, the following conclusions are obtained: The shortest running distance does not necessarily have the lowest fuel consumption. The running distance is 703.27*KM* and the fuel cost is 1210.08 *RMB* when the 4t vehicle is used, however, the running distance is increased 13.6 *KM* and the fuel cost is reduced 135.42 *RMB* when the 4t and 6t vehicles mixed. The reason for this result can be known from formula (1), the fuel cost is not only related to the running distance, but also related to the load. The customer satisfaction is reduced as the number of vehicles decreases. The penalty cost is 141.95 *RMB* under the 6t vehicle, that is higher than the 82.4 *RMB* under 4t vehicle. This is due to the increase in customers that delivered by per vehicle, which leads the deliver time by per vehicle is longer. As a result, delivery time is delayed and customer satisfaction is reduced. The heterogeneous fleet vehicle is more effective. The sub-cost of using 4t and 6t mixed vehicle for distribution is lower than the results of using 4t and 6t alone under the premise of not reducing customer satisfaction, which indicates adopting heterogeneous fleet vehicle is more conducive to reduce total cost, carbon emission cost and pollutant emission cost.

6. Discussion

6.1 Main findings

In the traditional urban distribution process, the trust between the participants is weak, information sharing and security cannot be guaranteed (Zhang and Guin, 2020). The application of blockchain in the urban distribution can effectively solve the above problems, that has been confirmed by some researches (Lim et al., 2021; Liu and Li, 2020; Manupati et al., 2020). The P2P model promotes information sharing. The cryptography and consensus mechanism ensure the information security of the transaction parties, which results in once the information is uploaded, it cannot be modified (Lu, 2018; Singh and Kim, 2018). In addition, the joint use of blockchain technology and sensors makes it possible to track the location of the product in real time (Helo and Shamsuzzoha, 2020). Therefore, this research strongly recommends the introduction of blockchain into urban distribution to provide participants with a trusted environment. To better apply blockchain technology to the distribution field, this research proposes a three-layer architecture of the blockchain-based urban distribution system, including infrastructure, blockchain and application layers. Meanwhile, a smart contract is designed to matches the supply and demand resources to plan economical and environmentally friendly distribution routings.

The performance of the smart contract is evaluated through the simulation experiments. In the algorithm experiment, the sensitivity analysis of algorithm parameters is conducted to determine the optimal range of parameters. The optimal values of the genetic algorithm parameters are set $G=100, Pc=0.3, Pm=0.02$ according to the results of the experiments. In the model experiment, the effectiveness of the smart contract proposed in this study is verified from two angles. Firstly, three different objective functions are compared, that is, without considering environmental factors, only considering carbon emission factors, and both considering carbon emissions and environmental pollutants. The results show that the objective function proposed in this study is the most effective in reducing carbon emissions and environmental pollution, but the total cost has risen compared with no consideration of environmental factors. Therefore, a balance should be reached between the total cost and environment. Furthermore, the government can also give enterprises some subsidies to reduce the increase in distribution cost. Secondly, the utility of heterogeneous fleets is discussed, in which three types are designed, including 4t alone, 6t alone, and 4t - 6t mixed. The results show that, compared with the same capacity, heterogeneous fleets are more conducive to reducing costs and environmental pollution. This result means that the model proposed in this research is effective, and it can provide a reference for the choice of vehicle capacities.

6.2 Theoretical implication

This research is an innovative work on how to apply blockchain technology to urban distribution to build the trust among participants and achieve the information sharing, which enriches the related literature in two fields of blockchain and urban distribution.

First, this research further illustrates that the application of blockchain in the urban distribution can establish the trust and achieve the information sharing among the participants. This finding is consistent with the research of Azzi et al. (2019). However, previous researches mainly focused on the supply chain field (Bai and Sarkis, 2020; Chang et al., 2019), and the specific field of urban distribution is still very limited. To our knowledge, only one research explores the blockchain-based urban distribution. Specifically, Hribernik et al., 2020 proposed a blockchain decision framework for a horizontal collaboration in urban distribution. However, their research is focused on exploring the process of decision by providing users with different solutions to a series of problems, which makes the research still qualitative. This research proposes the architecture of blockchain-based urban distribution system, which is composed of the components and layers of system. It shows the operating mechanism of blockchain and provides a basic understanding for further in-depth studies.

Second, in terms of urban distribution, this research creatively proposes to design a smart contract to match supply and demand resources to plan the distribution routes. At present, the most common application of smart contracts is asset transfer in the supply chain. For example, Chang et al. (2019) designed a payment contract, which requires that once the consignee completes the goods inspection, the remuneration will be paid to the stakeholders automatically. This research expands the use of smart contracts in planning distribution routes. The subsequent researches can be inspired by this research to explore the different functions of smart contracts, for example, benefit distribution. In addition, regarding the objective function of the urban distribution, this research not only considers the economic factors but also environmental factors (pollutants and carbon emission), which promotes the quantitative research on sustainable development of urban distribution.

6.3 Practical implication

The valuable insights are provided for relevant practitioners based on the findings of this research. First, the support of the leadership is the driving force for practical development. They should realize that strengthening horizontal logistics cooperation with the same type companies promotes common development. The related research shows that the horizontal logistics cooperation can bring many benefits (1) reducing the total running distance, environmental pollution and cots, (2) improving the vehicle utilization and service level, (3) alleviating traffic congestion. In short, horizontal logistics cooperation can not only reduce cost, but also reduce the impact on the environment. Only by recognizing these advantages of horizontal logistics cooperation can its development be supported.

Second, the company should explore the use of emerging technologies to strengthen logistics operations and make them more efficient. The application of blockchain to urban distribution can maximize the use of existing resources and realize information sharing. In addition, blockchain technology can ensure the cooperation among partners is reliable and safe through supervising the entire distribution process. Therefore, the enterprise should recognize the advantages of the blockchain and promote the implementation of blockchain projects, which brings excellent competitiveness to the development of the enterprise. The blockchain-based urban distribution architecture proposed in this research can realize the allocation of resources through smart contracts, which provides the reference for its application.

Third, the excellent companies should not only focus on economic benefits, but also consider environmental benefits to achieve sustainable development. There are two ways to reduce the impact on the environment, one is the innovation of the management model, and the other is the use of clean energy equipment. Without increasing additional costs, the first situation presents a good research prospect. This research analyzes the innovation of the management model from two perspectives. The first is the formulation of distribution goals, and the second is the design of the distribution fleet. These methods provide references for the sustainable development of enterprises. In addition, companies should recognize that green distribution can bring new business opportunities, that is, people are more inclined to products with green footprints.

Finally, the variables in the smart contract can be changed according to the actual situation.

For the variable Q (maximum load of vehicle), the enterprise can plan the distribution routes that meets the actual situation according to the actual load of vehicle. For the variable C_t (carbon emission cost) and C_w(pollutant emission cost), this research can provide a reference for the government to formulate the carbon price and pollutant price. Further, the objective function can be set according to the actual situation. If the goal is to maximize customer satisfaction, the objective function is to minimize T_3. If the goal is to minimize the pollution, the objective function is to minimize T_4+ T_5.

7. Conclusion

This research proposes an architecture of blockchain-based urban distribution system for horizontal cooperation, which is consisted of three layers, including infrastructure, blockchain and application. Meanwhile, a smart contract is designed to match the resource of supply and demand to achieve the lowest total cost of distribution, which includes fixed, fuel, penalty, carbon emission and pollutant emission costs. To reach this goal, an open vehicle routing model of urban distribution taking into account environmental pollution factors is developed as the mathematical model of smart contract. Based on a real case, the validity of the smart contract is verified from two aspects: algorithm experiment and model experiments. The results show that the proposed smart contract has positive significance for reducing cost and emissions. It is worth mentioning that the model proposed in this research is universal, which can be used in the design of distribution routes in other cities. This research has made positive contributions to both theory and practice. At the same time, some limitations still exist due to its exploratory nature. Firstly, only the architecture of blockchain is proposed in this research. In the future, the specific implementation based on the architecture can be carried out. Secondly, the smart contract is used to plan the distribution routes, and its mathematical model has limitations, e.g. this research considers a static vehicle routing optimization model, that is, customer needs and customer locations do not change during the delivery process. In the ever-changing market environment, the dynamic vehicle routing optimization problem is worth studying. Finally, the other functions of smart contracts deserve to be explored in subsequent research.

Appendix A. supplementary data

Appendix A, Table A1 shows the customer information. Table A2 shows the supplier location. Table A3 explains the value of variable in the model.

Reference

Abdullah, S., Rothenberg, S., Siegel, E., Kim, W., 2020. School of Block-Review of Blockchain for the Radiologists. Acad. Radiol. 27(1), 47-57.

Allen, D.W.E., Berg, C., Davidson, S., Novak, M., Potts, J., 2019. International policy coordination for blockchain supply chains. Asia & the Pacific Policy Studies 6(3), 367-380.

Allen, J., Bektas, T., Cherrett, T., Friday, A., McLeod, F., Piecyk, M., Piotrowska, M., Austwick, M.Z., 2017. Enabling a Freight Traffic Controller for Collaborative Multidrop Urban Logistics Practical and Theoretical Challenges. Transportation Research Record(2609), 77-84.

Azzi, R., Chamoun, R.K., Sokhn, M., 2019. The power of a blockchain-based supply chain. Computers & Industrial Engineering 135, 582-592.

Bai, C., Sarkis, J., 2020. A supply chain transparency and sustainability technology appraisal model for blockchain technology. International Journal of Production Research 58(7), 2142-2162.

Baniamerian, A., Bashiri, M., Tavakkoli-Moghaddam, R., 2019. Modified variable neighborhood search and genetic algorithm for profitable heterogeneous vehicle routing problem with cross-docking. Appl. Soft. Comput. 75, 441-460.

Brandao, J., 2018. Iterated local search algorithm with ejection chains for the open vehicle routing problem with time windows. Computers & Industrial Engineering 120, 146-159.

Brandao, J., 2020. A memory-based iterated local search algorithm for the multi-depot open vehicle routing problem. Eur. J. Oper. Res. 284(2), 559-571.

Brown, J.R., Guiffrida, A.L., 2014. Carbon emissions comparison of last mile delivery versus customer pickup. International Journal of Logistics-Research and Applications 17(6), 503-521.

Bumblauskas, D., Mann, A., Dugan, B., Rittmer, J., 2020. A blockchain use case in food distribution: Do you know where your food has been? International Journal of Information Management 52.

Chang, S.E., Chen, Y.C., Lu, M.F., 2019. Supply chain re-engineering using blockchain technology: A case of smart contract based tracking process. Technological Forecasting and Social Change 144, 1-11.

Chen, J., Shi, J., 2019. A multi-compartment vehicle routing problem with time windows for urban distribution - A comparison study on particle swarm optimization algorithms. Computers & Industrial Engineering 133, 95-106.

Cole, R., Stevenson, M., Aitken, J., 2019. Blockchain technology: implications for operations and supply chain management. Supply Chain Manag. 24(4), 469-483.

Dolgui, A., Ivanov, D., Potryasaev, S., Sokolov, B., Ivanova, M., Werner, F., 2020. Blockchain-oriented dynamic modelling of smart contract design and execution in the supply chain. International Journal of Production Research 58(7), 2184-2199.

Drljevic, N., Aranda, D.A., Stantchev, V., 2020. Perspectives on risks and standards that affect the requirements engineering of blockchain technology. Comput. Stand. Interfaces 69, 7.

Fachini, R.F., Armentano, V.A., 2020. Logic-based Benders decomposition for the heterogeneous fixed fleet vehicle routing problem with time windows. Computers & Industrial Engineering 148, 18.

Feng, H.H., Wang, X., Duan, Y.Q., Zhang, J., Zhang, X.S., 2020. Applying blockchain technology to improve agri-food traceability: A review of development methods, benefits and challenges. Journal of Cleaner Production 260, 15.

Fu, Z., Dong, P., Ju, Y., 2020. An intelligent electric vehicle charging system for new energy companies based on consortium blockchain. Journal of Cleaner Production 261.

George, R.V., Harsh, H.O., Ray, P., Babu, A.K., 2019. Food quality traceability prototype for restaurants using blockchain and food quality data index. Journal of Cleaner Production 240.

Hald, K.S., Kinra, A., 2019. How the blockchain enables and constrains supply chain performance. International Journal of Physical Distribution & Logistics Management 49(4), 376-397.

Hasan, H., AlHadhrami, E., AlDhaheri, A., Salah, K., Jayaraman, R., 2019. Smart contract-based approach for efficient shipment management. Computers & Industrial Engineering 136, 149-159.

Hasselgren, A., Kralevska, K., Gligoroski, D., Pedersen, S.A., Faxvaag, A., 2020. Blockchain in healthcare and health sciences-A scoping review. International Journal of Medical Informatics 134.

Helo, P., Shamsuzzoha, A.H.M., 2020. Real-time supply chain-A blockchain architecture for project deliveries. Robotics and Computer-Integrated Manufacturing 63.

Herold, D.M., Lee, K.-H., 2019. The influence of internal and external pressures on carbon management practices and disclosure strategies. Australasian Journal of Environmental Management 26(1), 63-81.

Hribernik, M., Zero, K., Herold, D.M., 2020. City logistics: Towards a blockchain decision framework for collaborative parcel deliveries in micro-hubs. *Transportation Research Interdisciplinary Perspectives.* In press. Available at: https://doi.org/10.1016/j.trip.2020.100274

Hughes, A., Park, A., Kietzmann, J., Archer-Brown, C., 2019. Beyond Bitcoin: What blockchain and distributed ledger technologies mean for firms. Business Horizons 62(3), 273-281.

Juma, H., Shaalan, K., Kamel, I., 2019. A Survey on Using Blockchain in Trade Supply Chain Solutions. Ieee Access 7, 184115-184132.

Kamble, S.S., Gunasekaran, A., Sharma, R., 2020. Modeling the blockchain enabled traceability in agriculture supply chain. International Journal of Information Management 52, 16.

Karaman, A.S., Kilic, M., Uyar, A., 2020. Green logistics performance and sustainability reporting practices of the logistics sector: The moderating effect of corporate governance. Journal of Cleaner Production 258.

Leng, K., Bi, Y., Jing, L., Fu, H.-C., Van Nieuwenhuyse, I., 2018. Research on agricultural supply chain system with double chain architecture based on blockchain technology. Future Generation Computer Systems-the International Journal of Escience 86, 641-649.

Li, R.M., Chen, W.W., Xiu, A.J., Zhao, H.M., Zhang, X.L., Zhang, S.C., Tong, D.Q., 2019. A comprehensive inventory of agricultural atmospheric particulate matters (PM10 and PM2.5) and gaseous pollutants (VOCs, SO2, NH3, CO, NOx and HC) emissions in China. Ecol. Indic. 107, 14.

Li, Y., Lim, M.K., Hu, J., Tseng, M.-L., 2020a. Investigating the effect of carbon tax and carbon quota policy to achieve low carbon logistics operations. Resour. Conserv. Recycl. 154.

Li, Y., Lim, M.K., Tan, Y., Lee, S.Y., Tseng, M.-L., 2020b. Sharing economy to improve routing for urban logistics distribution using electric vehicles. Resour. Conserv. Recycl. 153.

Li, Y., Lim, M.K., Tseng, M.-L., 2019. A green vehicle routing model based on modified particle swarm optimization for cold chain logistics. Industrial Management & Data Systems 119(3), 473-494.

Lim, M.K., Li, Y., Wang, C., Tseng, M.-L., 2021. A literature review of blockchain technology applications in supply chains: A comprehensive analysis of themes, methodologies and industries. Computers & Industrial Engineering 154.

Lim, M.K., Wang, J.X., Wang, C., Tseng, M.L., 2020. A novel method for green delivery mode considering shared vehicles in the IoT environment. Industrial Management & Data Systems 120(9), 1733-1757.

Liu, G., Hu, J., Yang, Y., Xia, S., Lim, M.K., 2020. Vehicle routing problem in cold Chain logistics: A joint distribution model with carbon trading mechanisms. Resour. Conserv. Recycl. 156.

Liu, Z.Y., Li, Z.P., 2020. A blockchain-based framework of cross-border e-commerce supply chain. International Journal of Information Management 52, 18.

Longo, F., Nicoletti, L., Padovano, A., d'Atri, G., Forte, M., 2019. Blockchain-enabled supply chain: An experimental study. Computers & Industrial Engineering 136, 57-69.

Lu, Y., 2018. Blockchain and the related issues: a review of current research topics. J. Manag. Anal. 5(4), 231-255.

Manupati, V.K., Schoenherr, T., Ramkumar, M., Wagner, S.M., Pabba, S.K., Singh, R.I.R., 2020. A blockchain-based approach for a multi-echelon sustainable supply chain. International Journal of Production Research 58(7), 2222-2241.

Mikl, J., Herold, D.M., Pilch, K., Cwiklicki, M., Kummer, S., 2020. Understanding disruptive technology transitions in the global logistics industry: the role of ecosystems. Review of International Business and Strategy.

Ministry of Ecology and Environment of the People’s Republic of China, 2014. Technical Guidelines for the Preparation of Air Pollutants Emission Inventory for Road Vehicles. Available at: http://www.mee.gov.cn/gkml/hbb/bgg/201501/t20150107_293955.htm. (Accessed 15 October 2020)

Niu, Y., Yang, Z., Chen, P., Xiao, J., 2018. Optimizing the green open vehicle routing problem with time windows by minimizing comprehensive routing cost. Journal of Cleaner Production 171, 962-971.

Orji, I.J., Kusi-Sarpong, S., Huang, S., Vazquez-Brust, D., 2020. Evaluating the factors that influence blockchain adoption in the freight logistics industry. Transportation Research Part E-Logistics and Transportation Review 141.

Pal, O., Bashir, A., Thakur, V., Sight, S., 2019. Key management for blockchain technology. ICT Express In press.

Park, H., Park, D., Jeong, I.-J., 2016. An effects analysis of logistics collaboration in last-mile networks for CEP delivery services. Transport Policy 50, 115-125.

People.cn, 2020. The country's first provincial-level blockchain application innovation industry alliance settled in Chongqing. Available at: http://cq.people.com.cn/n2/2020/0414/c365411-33948483.html. (Accessed 20 October 2020)

Pereira, J., Tavalaei, M.M., Ozalp, H., 2019. Blockchain-based platforms: Decentralized infrastructures and its boundary conditions. Technological Forecasting and Social Change 146, 94-102.

Pierre, D.M., Zakaria, N., 2017. Stochastic partially optimized cyclic shift crossover for multi-objective genetic algorithms for the vehicle routing problem with time-windows. Appl. Soft. Comput. 52, 863-876.

Pomponi, F., Fratocchi, L., Tafuri, S.R., 2015. Trust development and horizontal collaboration in logistics: a theory based evolutionary framework. Supply Chain Manag. 20(1), 83-97.

Rahmanzadeh, S., Pishvaee, M.S., Rasouli, M.R., 2020. Integrated innovative product design and supply chain tactical planning within a blockchain platform. International Journal of Production Research 58(7), 2242-2262.

Raue, J.S., Wieland, A., 2015. The interplay of different types of governance in horizontal cooperations A view on logistics service providers. International Journal of Logistics Management 26(2), 401-423.

Savelyev, A., 2018. Copyright in the blockchain era: Promises and challenges. Comput. Law Secur. Rev.

34(3), 550-561.

Shen, L., Tao, F., Wang, S., 2018. Multi-Depot Open Vehicle Routing Problem with Time Windows Based on Carbon Trading. Int. J. Environ. Res. Public Health 15(9).

Singh, A., Parizi, R.M., Zhang, Q., Choo, K.-K.R., Dehghantanha, A., 2020. Blockchain smart contracts formalization: Approaches and challenges to address vulnerabilities. Computers & Security 88.

Singh, M., Kim, S., 2018. Branch based blockchain technology in intelligent vehicle. Computer Networks 145, 219-231.

Tanwar, S., Parekh, K., Evans, R., 2020. Blockchain-based electronic healthcare record system for healthcare 4.0 applications. J. Inf. Secur. Appl. 50, 13.

Toennissen, S., Teuteberg, F., 2020. Analysing the impact of blockchain-technology for operations and supply chain management: An explanatory model drawn from multiple case studies. International Journal of Information Management 52.

Wang, L.C., Shen, X.Y., Li, J., Shao, J., Yang, Y.X., 2019. Cryptographic primitives in blockchains. J. Netw. Comput. Appl. 127, 43-58.

Wang, S., Tao, F., Shi, Y., Wen, H., 2017. Optimization of Vehicle Routing Problem with Time Windows for Cold Chain Logistics Based on Carbon Tax. Sustainability 9(5).

Wang, X., Yang, W., Noor, S., Chen, C., Guo, M., D, K.H.V., 2019. Blockchain-based smart contract for energy demand management. Energy Procedia 158, 2719-2724.

Wei, M., Jing, B.B., Yin, J., Zang, Y., 2020. A Green Demand-Responsive Airport Shuttle Service Problem with Time-Varying Speeds. Journal of Advanced Transportation 2020, 13.

Wu, H., Tao, F., Qiao, Q., Zhang, M., 2020. A Chance-Constrained Vehicle Routing Problem for Wet Waste Collection and Transportation Considering Carbon Emissions. Int. J. Environ. Res. Public Health 17(2).

Xia, Y., Fu, Z., 2018. An Adaptive Tabu Search Algorithm for the Open Vehicle Routing Problem with Split Deliveries by Order. Wireless Personal Communications 103(1), 595-609.

Xiao, Y., Konak, A., 2017. A genetic algorithm with exact dynamic programming for the green vehicle routing & scheduling problem. Journal of Cleaner Production 167, 1450-1463.

Yadav, S., Singh, S.P., 2020. Blockchain critical success factors for sustainable supply chain. Resour. Conserv. Recycl. 152, 11.

Zhang, H., Zhang, Q., Ma, L., Zhang, Z., Liu, Y., 2019. A hybrid ant colony optimization algorithm for a multi-objective vehicle routing problem with flexible time windows. Information Sciences 490, 166-190.

Zhang, S., Lee, J.-H., 2020. Analysis of the main consensus protocols of blockchain. Ict Express 6(2), 93-97.

Zhang, Y., Guin, U., 2020. End-to-End Traceability of ICs in Component Supply Chain for Fighting Against Recycling. Ieee Transactions on Information Forensics and Security 15, 767-775.

Zheng, Z., Xie, S., Dai, H., Chen, X., Wang, H., 2017. An Overview of Blockchain Technology: Architecture, Consensus, and Future Trends, in: Karypis, G., Zhang, J. (Eds.), 2017 Ieee 6th International Congress on Big Data. pp. 557-564.

Zhu, S., Song, M.L., Lim, M.K., Wang, J.L., Zhao, J.J., 2020. The development of energy blockchain and its implications for China's energy sector. Resour. Policy 66, 10.