

## Article

# Research on Multimodal Transport of Electronic Documents Based on Blockchain

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**Abstract:** Multimodal transport document collaboration is the foundation of multimodal transport operations. Blockchain technology can effectively address issues such as a lack of trust and difficulties in information sharing in current multimodal transport document collaboration. However, in current research on blockchain-based electronic documents, the bottleneck lies in the collaboration aspect of multimodal transport among multiple entities, known as the “one-bill coverage system” collaborative problem. The collaboration problem studied in this paper involves selecting suitable transport routes according to the shipper’s transport needs, and selecting the most suitable specific carrier from numerous carriers. To address the collaboration problem among multiple parties in the multimodal transport “one-bill coverage system”, a multiparty collaboration mechanism is designed. This mechanism includes two aspects: firstly, designing the architecture of the multimodal transport blockchain transport platform, which reengineers the operation process of the “one-bill coverage system” for container multimodal transport; secondly, constructing a multiparty collaboration decision-making model for the “one-bill coverage system” in multimodal transport. The model is solved and analyzed, and the collaboration strategy obtained is embedded in the application layer of the platform. Smart contracts related to the “one-bill coverage system” for multimodal transport are written in the Solidity language and deployed and executed on the Remix platform. The design of this mechanism can effectively improve the collaboration efficiency of participants in the “one-bill coverage system” for multimodal transport.

**Keywords:** multimodal transport; electronic documents; “one-bill coverage system” blockchain; smart contract



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## 1. Introduction

Multimodal transport, as a comprehensive transport system, provides an effective organizational method that optimizes transport structures, enhances efficiency, reduces carbon emissions, and minimizes overall logistics costs [1]. Multimodal transport documents are fundamental elements for conducting multimodal transport operations, spanning the entire process from consignment initiation to the completion of goods delivery. Currently, there is no standardized document used in multimodal transport, leading to additional time and costs for the segment carriers involved in various transport modes, such as road, railway, and waterway transport, for carrying out document exchange operations [2]. Therefore, numerous countries have explored and implemented initiatives to standardize multimodal transport documents. For instance, companies such as France’s CMA CGM and Germany’s Hamburg Sud have established electronic platforms for multimodal transport documents [3,4]. China introduced the concept of a “one-bill coverage system” for multimodal transport. This concept involves a single multimodal transport document facilitating a one-time consignment, a one-time settlement of charges, and a one-time insurance mechanism throughout the entire process of multimodal transport [5]. From 2021 to 2023, various Chinese government departments, including the State Council and the

Ministry of Transport, have issued multiple policies urging the expedited development of the multimodal transport “one-bill coverage system” [6–8].

However, achieving data sharing for the multimodal transport “one-bill coverage system” involves multiple parties, including shippers, consignees, roads, railways, waterways, ports, and more. Business collaboration encompasses the commercial secrets, core competitiveness, and numerous contract terms of each entity, leading to a lack of mutual trust and difficulties in sharing information. As a result, the realization of the “one-bill coverage system” becomes challenging. The emergence of blockchain technology provides a novel approach to addressing these issues. Firstly, blockchain technology can establish an alliance blockchain for multimodal transport, breaking down information barriers among various entities and resolving the challenge of information sharing in the “one-bill coverage system”. Additionally, blockchain networks feature decentralized governance and mutual supervision. By deploying smart contracts, contractual terms can be automatically executed, thereby enhancing the level of trust among the entities involved in multimodal transport [9].

In recent years, numerous companies have actively explored the application of blockchain technology in the field of multimodal transport. In 2018, Maersk collaborated with IBM to develop the blockchain transport platform TradeLens; however, the project was concluded at the end of 2022 due to not achieving the expected returns [10]. In 2018, the European Rail Freight Association (EFHA) and DB Cargo jointly established the E-CIM system based on blockchain technology, aiming to enhance the efficiency and convenience of multimodal transport [11]. In 2021, China COSCO Shipping Corporation established the Global Shipping Business Network (GSBN)—an international shipping blockchain alliance [12]. Although the aforementioned blockchain-based multimodal transport business platforms have improved trust among collaboration entities, ensured the security of information sharing, and streamlined document exchange processes to some extent, the realization of a “one-bill coverage system” in multimodal transport has yet to be achieved.

The blockchain-based “one-bill coverage system” in multimodal transport has garnered significant attention in academic circles. Chen et al. (2022) utilized real-time big data stream processing technology to study a blockchain-based “one-bill coverage system” big data platform, ensuring the secure collaboration of data among various entities [13]. Ji (2020) conducted an analysis of key issues in a multimodal transport electronic “one-bill coverage system” in conjunction with blockchain technology. The research focused on the format and content of electronic documents, leading to the design of an electronic bill of lading for the “one-bill coverage system” [14]. Moody (2019) proposes storing electronic documents in a blockchain format for international trade processes, utilizing blockchain to record ownership at each step, and designing documents as smart contracts [15]. From the above, it is evident that current research on blockchain-based electronic documents in multimodal transport mainly focuses on platform architecture, data exchange, “one-bill coverage system” document design, and smart contract design for electronic documents. However, there is a lack of research on the collaboration operation mechanisms and collaboration mechanisms among multiple parties in multimodal transport based on blockchain. Additionally, there is a deficiency in the design of smart contracts for the “one-bill coverage system”, making it challenging to achieve the streamlined operation of a blockchain transport platform for multimodal transport.

In order to realize the “one-bill coverage system” operation of the multimodal blockchain transport platform and improve the operation efficiency of the “one-bill coverage system” process of multimodal transport, we have designed the architecture of a blockchain transport platform for multimodal transport, reshaping the collaboration processes for different modes of transport based on the blockchain platform. It proposes a collaboration model for multimodal transport under the “one-bill coverage system”, embedding the obtained collaboration strategies into the platform’s application layer. Finally, using the Solidity language, we have written relevant smart contracts for a multimodal transport “one-bill coverage system”, including order smart contracts and alliance partner smart contracts, and deployed and executed them on the Remix platform.

The remaining organizational sections of this paper are as follows. The Section 2 provides a literature review. The Section 3 outlines the design of a blockchain transport platform for multimodal transport, detailing the multimodal transport business processes based on the blockchain platform. The Section 4 establishes the “one-bill coverage system” collaboration model. The Section 5 designs and implements relevant smart contracts for the “one-bill coverage system”. The Section 6 concludes and provides prospects for future research.

## 2. Literature Review

The following section will provide a review of research in two aspects: collaboration mechanisms among multiple parties in multimodal transport and the design of blockchain smart contracts. This paper will also outline the contributions made by the research reviewed.

### 2.1. Research on Multimodal Transport Multiparty Collaboration

The problem of multiparty collaboration in multimodal transport includes many research directions, such as transport mode selection and route planning, information cooperation, benefit distribution, etc.

In terms of transport mode selection and route planning, Zhang et al. [16] studied low-carbon route optimization under conditions of double uncertainty in order to improve the efficiency of multimodal transport. A hybrid robust stochastic optimization model considering transportation costs, time costs, and carbon emission costs was established. To solve this problem, a mutating adaptive genetic algorithm based on Monte Carlo sampling was designed and its effectiveness verified. Through numerical experiments, it was found that uncertainty will affect the decisions made in multimodal transport, including the decisions regarding the route and mode of transport. Robust optimization with uncertain demand will increase the total cost of low-carbon multimodal transport due to the pursuit of stability, and the impact of time uncertainty on the total cost is significant and fuzzy. Liu et al. [17] mainly studied the transportation route optimization of cold chain containers in multimodal transport systems, and built an optimization model with the sum of carbon emission cost, transportation cost, time window penalty cost, and cold chain cargo damage cost as the objective function. In addition, the Hummingbird Evolutionary Genetic Algorithm was adopted as a solution tool, and it was found that the optimized multimodal transport route could significantly reduce carbon emissions, thereby reducing the impact on the environment. Second, this study revealed the complex effects of time-varying networks on transportation costs and carbon emissions, highlighting the importance of optimizing transportation strategies over different time periods. Li et al. [18] studied the problem of cargo transportation planning and constructed a multi-commodity network flow model considering carbon emissions and transportation costs. In order to solve the model, the fuzzy expected value method and fuzzy chance constraint programming method were used to de-blur the model. Combining the game theory method with the weighted sum method, a multi-objective optimization method based on cooperative game theory was proposed. Through numerical experiments, it was found that uncertainty factors will significantly increase transportation costs and carbon emissions, and affect the choice of transportation routes and modes.

In terms of information synergy, Zhu et al. [19] studied the collaborative effect evaluation of container multimodal transport based on a BP neural network algorithm. Firstly, they decided to use a multi-attribute decision-making method to comprehensively evaluate the synergistic effect of container multimodal transport. Secondly, they solved the model and converted the problem into finding the shortest path under the condition of not exceeding the cost and time limit. The simulation results show that the evaluation model of the container multimodal transport synergy effect based on a BP neural network can accurately evaluate the synergy effect, and container multimodal transport can indeed improve transport efficiency and save costs. Fang et al. [20] analyzed the operation process of container multimodal transport from the research perspective of the whole process of container multimodal transport, and regarded it as a production system composed of four subsystems: facilities and equipment, organization and management, business operations, and information interaction. Through in-depth interviews and an analysis of the

academic literature and policy documents, this paper constructed an evaluation index system and measurement model of the cooperation degree of container multimodal transport based on cooperation theory and case studies. The research results are in agreement with the actual situation. From 2015 to 2018, the coordinated development of the container multimodal transport system in China's Port G was slow, but it was generally developing in a more orderly direction.

In terms of benefit distribution, Liu et al. [21] discussed the hot metal multimodal transport system composed of railway companies, liner companies, and emerging multimodal transport operators. It was found that although the entry of multimodal transport operators poses a threat to competition, their service efforts directly affect the market demand and promote the profits of each carrier. However, multimode operators can deal with the negative effects of the free-rider effect through service strategies and promote the optimization of system efficiency. Specifically, by discussing the profit maximization decision preference of each carrier, it was found that the multimode operator strategy could achieve win-win-win Pareto optimization, and the system efficiency was also the best. Algaba et al. [22] studied multimodal public transport systems involving several transport companies. Supposing they cooperate by providing travel cards that can be used on all available means of transport, in order to solve the problem of profit distribution among the companies involved, a color graph is first introduced to describe the traffic network, and then a game-theoretic method was proposed to distribute the profits among the companies. Two new distribution rules are proposed, namely the solution of color equalitarianism and the solution of the color cost ratio. The experiment shows that these two solutions can provide a stable profit distribution scheme.

To sum up, multiparty collaboration is an important problem in multimodal transport, and the solution to multiparty collaboration problems can effectively improve the efficiency and quality of multimodal transport. However, most of the current research focuses on operation and management under the traditional mode. Although these studies have explored the coordination and efficiency optimization between different multimodal transport entities to a certain extent, they have ignored the profound changes brought by the rapid development of blockchain technology to the multimodal transport industry.

## 2.2. Research on the Application of Blockchain Smart Contracts

In the application research of smart contracts, Mohanta et al. [23] identified a number of different smart contract application scenarios, and designed a diverse smart contract architecture for these fields to achieve the deep integration of blockchain technology. At the same time, many scholars have conducted in-depth studies on how blockchain smart contract technology can deeply empower different fields. In the field of supply chains, Jiao et al. [24] explained the problems of repeated content filling, slow production speed, and difficult information sharing in current multimodal transport documents. By integrating the documents involved in various modes of transportation, the traditional documents were transformed into digital documents, and smart contracts were developed to realize the automation of document circulation. Experiments were carried out on the Ethereum platform. The results show that the digital documents of multimodal transportation avoid problems such as repeated content filling, slow production speed, and difficult information sharing, which is conducive to improving logistics efficiency and reducing logistics costs. Agrawal et al. [25] studied the design of a blockchain-based collaboration framework for resource sharing using smart contracts. Based on a systematic literature review, a demonstration framework for stakeholder interaction was developed through a blockchain-enabled procurement and distribution unit. The framework includes (a) a network architecture that demonstrates partner interaction; (b) network operating principles and rules based on supply collaboration requirements; (c) a UML diagram that defines the interaction order of smart contracts; and (d) smart contract network validation and a validation algorithm. The suitability of these smart contracts was verified by being deployed on the Ethereum blockchain. The presentation framework ensures quality and data authenticity in the supply network, so it is useful for efficient resource use in networks.

where outsourcing and overproduction are major issues. Shen et al. [26] discussed the evolution path of port cold chain logistics enterprises participating in information sharing by using evolutionary game theory and analyzing evolutionary stability strategies. They designed an incentive mechanism based on blockchain smart contracts to encourage cold chain logistics enterprises to actively participate in in-chain information sharing. Smart contracts can continuously encourage enterprises to participate in information sharing by adjusting the incentive participation cost of participating enterprises in a timely manner. In the medical field, Wang et al. [27] proposed a blockchain-based medical waste supervision model to connect participants and introduce digital credentials to protect operators' information privacy and ensure the authenticity and trustworthiness of the entire data process. By setting up smart contracts, the regulatory information of different stages of medical waste treatment is integrated and recorded on the blockchain to form the chain of custody of medical waste. The designed regulatory model can provide digital certificates for China's health, environmental protection, and other administrative departments to handle tracking information. It can provide an authoritative basis for the accountability of medical waste disposal supervision and support the construction of a new generation of medical waste supervision and information system in China. Musamih et al. [28] describe a solution based on the private Ethereum blockchain for managing controlled drugs to ensure transparency, accountability, security, and data sourcing by developing smart contracts that record all operations on an immutable ledger. Algorithms for different stages are presented in the proposed solution to illustrate how to perform each stage, demonstrating the functionality of the proposed solution by performing tests and validating smart contracts. Performance evaluations showed that the solution was secure against common attacks and vulnerabilities and protected patient privacy and confidentiality. In the field of agriculture, Jamil et al. [29] provided a blockchain optimization method for the greenhouse system of agricultural products in order to improve the output of agricultural products and reduce the cost. Firstly, the Kalman filter algorithm was used to predict the greenhouse sensor data. Next, the optimal parameters of indoor greenhouse environment were calculated. Finally, the control module used the optimized parameters to operate and adjust the state of the actuator to meet the expected setting of the indoor environment. In addition, a series of experiments on throughput, latency, and resource utilization were conducted based on the Hyperledger caliper. Pincheira et al. [30] explore how IoT-based sensing and blockchain technologies can be used to incentivize benign behavior in agricultural practices. A system architecture was designed that includes constrained IoT devices for measuring water consumption, for use as direct data source participants, public blockchain infrastructure, and smart contracts representing the interests of different water management stakeholders. By using the Ethereum network as a practical implementation of a complete use case for the public blockchain, the usability of their results is further validated, contributing to the sustainable development of agriculture. In the field of energy trading, Merrad et al. [31] introduced a blockchain-based P2P energy trading platform, on which producers and consumers can autonomously trade energy without the intervention of a central authority. Multiple production consumers can cooperate to produce energy, forming a single supplier. Smart contracts invoked on the blockchain enable autonomous transaction interactions between parties and manage account behavior in the Ethereum state. Decentralized P2P trading platforms employ autonomous pay-per-use billing and energy routing, monitored by smart contracts. Zhang et al. [32] developed an intelligent carbon trading process optimization framework based on blockchain technology. Firstly, this paper analyzes the current situation of carbon trading in China's power industry. Secondly, based on the structure and characteristics of blockchain technology, the framework of an intelligent carbon trading system is built to optimize the carbon trading process. Third, smart contracts for smart carbon trading systems (including execution logic, transaction matching, contract fulfillment and other elements) are built. Finally, some policy suggestions are put forward to solve the current problems and challenges. Studies have shown that blockchain-powered

carbon trading can guarantee the security and efficiency of transactions, keep accurate transaction records, and provide a high level of automated settlement.

To sum up, many scholars have tried to design smart contracts based on blockchain technology in many fields. In the research on electronic documents of multimodal transport, some scholars have used blockchain smart contract technology to solve the problem of repeated filling in multimodal transport documents, but there is no work on the design of smart contracts to achieve effective collaboration between multimodal transport participants.

### 2.3. Literature Summary

The issue of a “one-bill coverage system” in multimodal transport based on blockchain technology has attracted wide attention from the academic community, but the current research on a “one-bill coverage system” in multimodal transport mainly focuses on the design of information systems and platform architecture, and the optimization of document level, etc., all of which assume that the multiple parties involved in multimodal transport have realized collaboration. There is no discussion on how to cooperate among the participants of the “one single system” of multimodal transport; scholars have tried to design smart contracts based on blockchain technology in many fields, but in the study of the multimodal transport “one-bill coverage system”, there is no further design work on smart contracts, resulting in the “one-bill coverage system” not being able to be further applied in the blockchain platform.

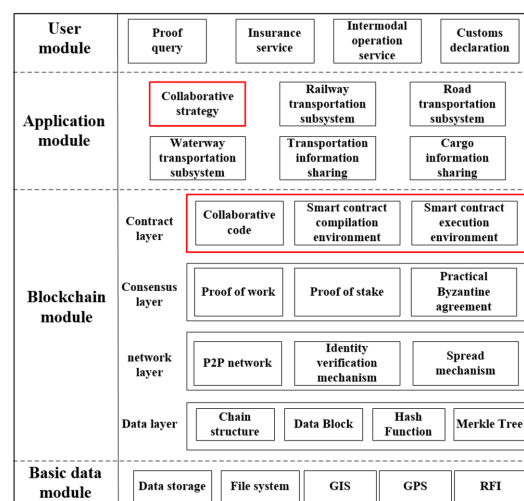
We first designed the architecture of a multimodal blockchain transport platform, reshaping the multimodal transport business process; a “one-bill coverage system” collaboration model based on a blockchain is proposed. A genetic algorithm is used to solve the model, and an example analysis is given. The obtained collaboration strategy is embedded in the application layer of the platform. At last, this paper designs smart contracts to ensure the automatic execution of the collaboration strategy.

## 3. Design of Multimodal Transport Blockchain Platform and Business Process

The emergence of blockchain technology promises to optimize multimodal transport business processes. The following sections will outline the design of a blockchain-based multimodal transport platform and its associated business processes.

### 3.1. Design of Multimodal Transport Blockchain Platform

In the blockchain-based multimodal transport platform, participants will share information such as consignment demands and transport resources. Each entity in multimodal transport will upload information to the blockchain for collaboration information sharing. This study primarily focuses on designing collaboration strategies in the application modules and contract layers in the blockchain modules, as illustrated in Figure 1.



**Figure 1.** Blockchain-based multimodal transport electronic document platform architecture.

### 3.2. Multimodal Transport Business Process Based on Blockchain Platform

This paper has re-engineered the multimodal transport business processes based on the blockchain platform, as depicted in Figure 2. The specific process is as follows:

- (1) When a shipper generates a consignment demand and uploads it to the blockchain transport platform for multimodal transport, the application layer of the platform provides collaboration strategies. This involves intelligently matching a combination of carriers and proposing a transport plan.
- (2) After the shipper and carriers jointly confirm the order, transport information, and collaboration strategies, the system generates electronic documents. These electronic documents are simultaneously sent to various nodes, and once confirmed by electronic signatures from involved parties, they become effective and are stored on the blockchain. According to the collaboration strategies, relevant carriers form a dynamic alliance, collaborating to complete the transport of one or more orders.
- (3) The shipper delivers the goods and pre-pays the freight, which is stored in the smart contract account corresponding to the order. Each transport party carries out transport according to the order requirements, and there is no need for document exchange during each delivery or customs inspection and quarantine.
- (4) The consignee receiving the goods marks the end of the multimodal transport business process. After the dynamic alliance completes all the orders it is responsible for, the blockchain platform, through smart contracts, initiates the payment of transport fees to carriers within the alliance, and the dynamic alliance dissolves.

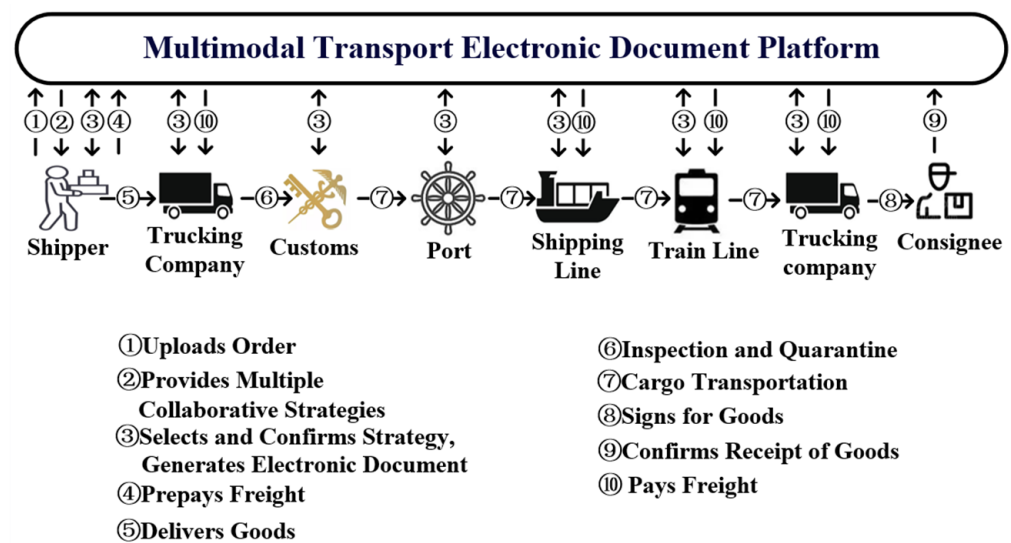


Figure 2. Multimodal transport electronic document platform.

### 4. Construction and Solution of “One-Bill Coverage System” Collaboration Model Based on Blockchain

By constructing and solving the “one-bill coverage system” collaboration model, we can obtain the collaboration strategies in the application module depicted in Figure 1. This involves determining the transport route for goods and specifying the carriers involved in the collaboration.

#### 4.1. Construction of “One-Bill Coverage System” Collaboration Model

##### 4.1.1. Problem Description

Multimodal transport involves various modes such as road, railway, and waterway, with one or more carriers providing transport services under each mode. Different carriers under each mode possess distinct capacities, transport routes, costs, timeframes, carbon emissions, and more. In the collaboration process, it is essential to find the optimal combination of transport routes and carriers based on factors such as the volume of goods,

time constraints, and the origin and destination of the transport in each mode of transport network. This paper establishes a “one-bill coverage system” collaboration model with cost and time as the optimization objectives. The cost objective function incorporates transport, trans-shipment, and carbon emission costs, while the time objective function considers transport and trans-shipment times.

#### 4.1.2. Model Assumption

As for the setting of objective functions and constraints, we refer to the actual business situation of multimodal transport enterprises. At the same time, we also read the relevant papers on multimodal transport path optimization and learned the settings of objective functions and constraints in these studies, so as to ensure that our setting of objective functions and constraints was reasonable.

The “one-bill coverage system” collaboration model is based on the following premise assumptions:

- (1) Shippers and carriers submit all their order information to the blockchain transport platform for multimodal transport, and the platform makes unified decisions.
- (2) Carriers in multimodal transport have limited capacity, and each mode of transport corresponds to different costs and rated payloads.
- (3) Each order corresponds to a single delivery address.
- (4) Transport between any two nodes considers only one mode of transport, and at most one trans-shipment occurs at each node.
- (5) The weight, destination, and origin of the goods corresponding to each order are known.
- (6) Train schedules and ship voyages are not considered for railways and ships.

#### 4.1.3. Model Parameter

$O = \{1, 2, 3, \dots, o\}$ : Order set;  
 $V = \{1, 2, 3, \dots, i, j\}$ : Transport node set;  
 $M = \{1, 2, 3, \dots, m, m'\}$ : Transport type set;  
 $N = \{1, 2, 3, \dots, n\}$ : A collection of carriers for a certain transport mode;  
 $Q = \{q_1, q_2, q_3, \dots, q_n\}$ : The mass of cargo transported for orders 1, 2, ..., n;  
 $V = \{v_1, v_2, v_3, \dots, v_n\}$ : The volume of cargo transported for orders 1, 2, ..., n;  
 $d_{ij}^i$ : The distance between transport nodes i and j;  
 $t_o$ : The transport time limit for order o;  
 $ET$ : Carbon tax, the cost of emitting one unit of carbon;  
 $q_{ij}^{mn}$ : The transport capacity of carrier n in mode m selected between nodes i and j;  
 $v_{ij}^{mn}$ : The unit transport speed of carrier n in mode m for the transport between nodes i and j;  
 $c_{ij}^{mn}$ : The unit transport price of carrier n in mode m for the transport between nodes i and j;  
 $c_i^{mn'}$ : The trans-shipment cost at node i for switching transport mode m to mode m';  
 $t_{ij}^{mn}$ : The transport time of carrier n in mode m for the transport between nodes i and j;  
 $t_i^{mm'}$ : The transfer time of goods when switching transport mode m to mode m' at node i;  
 $e_{ij}^{mn}$ : The unit carbon emission of carrier n in mode m for the transport between nodes i and j;  
 $x_{ij}^{mn}$ : Whether to select carrier n in mode m for the transport between nodes i and j.  
 When  $x_{ij}^{mn} = 1$ , it should be selected. When  $x_{ij}^{mn} = 0$ , it should not be selected;  
 $y_i^{mm'}$ : Whether a transfer is required at transport node i from mode m to mode m'.  
 When  $y_i^{mm'} = 1$ , it is required. When  $y_i^{mm'} = 0$ , it is not required.

#### 4.1.4. Model Construction

The “one-bill coverage system” collaboration model considers two objective functions: minimizing the total transport cost and minimizing the transport time. The first objective is to minimize the total transport cost:

$$\text{Min } Z_1 = q_o [\sum_{ij \in V} \sum_{m \in M} \sum_{n \in N} d_{ij} * c_{ij}^{mn} * x_{ij}^{nm} + \sum_{i \in V} \sum_{m, m' \in M} c_i^{mm'} * y_i^{mm'} + ET * (\sum_{ij \in V} \sum_{m \in M} \sum_{n \in N} d_{ij} * e_{ij}^{mn} * x_{ij}^{nm} + \sum_{i \in V} \sum_{m, m' \in M} e_i^{mm'} * y_i^{mm'})] \quad (1)$$

In Equation (1),  $q_o \sum_{ij \in V} \sum_{m \in M} \sum_{n \in N} d_{ij} * c_{ij}^{mn} * x_{ij}^{nm}$  represents the transport cost,  $q_o \sum_{i \in V} \sum_{m, m' \in M} c_i^{mm'} * y_i^{mm'}$  represents the trans-shipment cost, and  $q_o * ET * (\sum_{ij \in V} \sum_{m \in M} \sum_{n \in N} d_{ij} * e_{ij}^{mn} * x_{ij}^{nm} + \sum_{i \in V} \sum_{m, m' \in M} e_i^{mm'} * y_i^{mm'})$  represents the carbon emissions cost.

The second objective is to minimize the transport time:

$$\text{Min } Z_2 = \sum_{ij \in V} \sum_{m \in M} \sum_{n \in N} t_{ij}^{mn} * x_{ij}^{nm} + \sum_{i \in V} \sum_{m, m' \in M} q_o * t_i^{mm'} * y_i^{mm'} \quad (2)$$

In Equation (2),  $\sum_{ij \in V} \sum_{m \in M} \sum_{n \in N} t_{ij}^{mn} * x_{ij}^{nm}$  represents transport time and  $\sum_{i \in V} \sum_{m, m' \in M} q_o * t_i^{mm'} * y_i^{mm'}$  represents trans-shipment time. The constraints are as follows:

$$t_{ij}^{mn} = \frac{d_{ij}}{v_{ij}^{mn}}, i, j \in V, m \in M, n \in N \quad (3)$$

$$\sum_{m \in M} \sum_{n \in N} x_{ij}^{mn} \leq 1, i, j \in V \quad (4)$$

$$\sum_{m \in M} \sum_{m'} \in M \quad (5)$$

$$q_o \leq q_{ij}^{mn}, i, j \in V, m \in M, n \in N, o \in O \quad (6)$$

$$\sum_{ij \in V} \sum_{m \in M, n \in N} \sum_{n \in N} t_{ij}^{mn} * x_{ij}^{nm} + \sum_{i \in V} \sum_{m, m' \in M} q_o * t_i^{mm'} * y_i^{mm'} \leq t_o, o \in O \quad (7)$$

$$x_{ij}^{mn} \in \{0, 1\}, i, j \in V, m \in M, n \in N \quad (8)$$

$$y_i^{mm'} \in \{0, 1\}, i \in V, m, m' \in M \quad (9)$$

where Equation (3) represents that the transport time is determined by the speed; Equation (4) indicates that at most one carrier is selected for transporting orders between any two adjacent transport nodes; Equation (5) signifies that each node undergoes at most one mode of transport conversion; Equation (6) states that the selected carrier's capacity must meet the order's transport volume requirements; Equation (7) asserts that the total transport time of the selected carrier should meet the order's time constraints; and Equations (8) and (9) impose 0–1 constraints on the variables  $x_n^m$  and  $v_m^n$ .

#### 4.2. Model Solving

In solving the “one-bill coverage system” collaboration model, there are many combinations and selections of variables. The collaboration strategy will exponentially increase with the increase in transport network nodes, making the problem significantly more difficult. Additionally, it is a typical NP-hard problem. A genetic algorithm is one of the effective metaheuristic algorithms used for solving such problems. It is inspired by the genetics of natural populations and solves problems based on this principle, possessing strong global optimization capabilities [33]. Based on these characteristics of the model, a genetic algorithm is designed for the solution. Moreover, if traditional methods are used to encode the decision variables of the problem in binary, a large number of infeasible solutions may occur, greatly reducing the algorithm's convergence speed. Therefore, we used real number encoding, dividing the chromosome into two segments: the first segment represents the transport nodes, and the second segment represents the transport modes. The numbers 1, 2, and 3 were used to represent the road, railway, and waterway transport modes, respectively. The specific process of the genetic algorithm is as follows:

Step 1: Parameter assignment, including population size, the number of variables, crossover probability, mutation probability, and the termination generation of genetic operations.

Step 2: Set the variable range.

Step 3: Encoding, where the mapping from the problem space to the coding space is established.

Step 4: Generate the initial population. Set the evolution generation  $t = 0$ ; set the maximum evolution generation  $T$ ; randomly generate  $M$  individuals as the initial population  $p(0)$ .

Step 5: Fitness evaluation. Substitute the initial population into the fitness function to calculate the fitness values.

Step 6: Selection. Perform proportional selection operation.

Step 7: Crossover. Execute the crossover operation according to the crossover probability.

Step 8: Mutation. Execute discrete mutation operation according to the mutation probability. The population  $p(t)$  undergoes selection, crossover, and mutation operations to obtain the next generation population  $p(t + 1)$ .

Step 9: Calculate the fitness values of each individual in the local optimum obtained in Step 6 and execute the optimal individual preservation strategy.

Step 10: Termination condition judgment. Check whether the termination generation of genetic operations is met. If  $t \leq T$ , then set  $t = t + 1$  and return to Step 5; if  $t > T$ , output the individual with the maximum fitness obtained during the evolution process as the optimal solution, and terminate the operation.

#### 4.3. Case Analysis

We constructed a multimodal transport network, starting from Dalian and ending in Nanjing, passing through six cities. The network included three modes of transport: road, railway, and waterway, as shown in Figure 3.

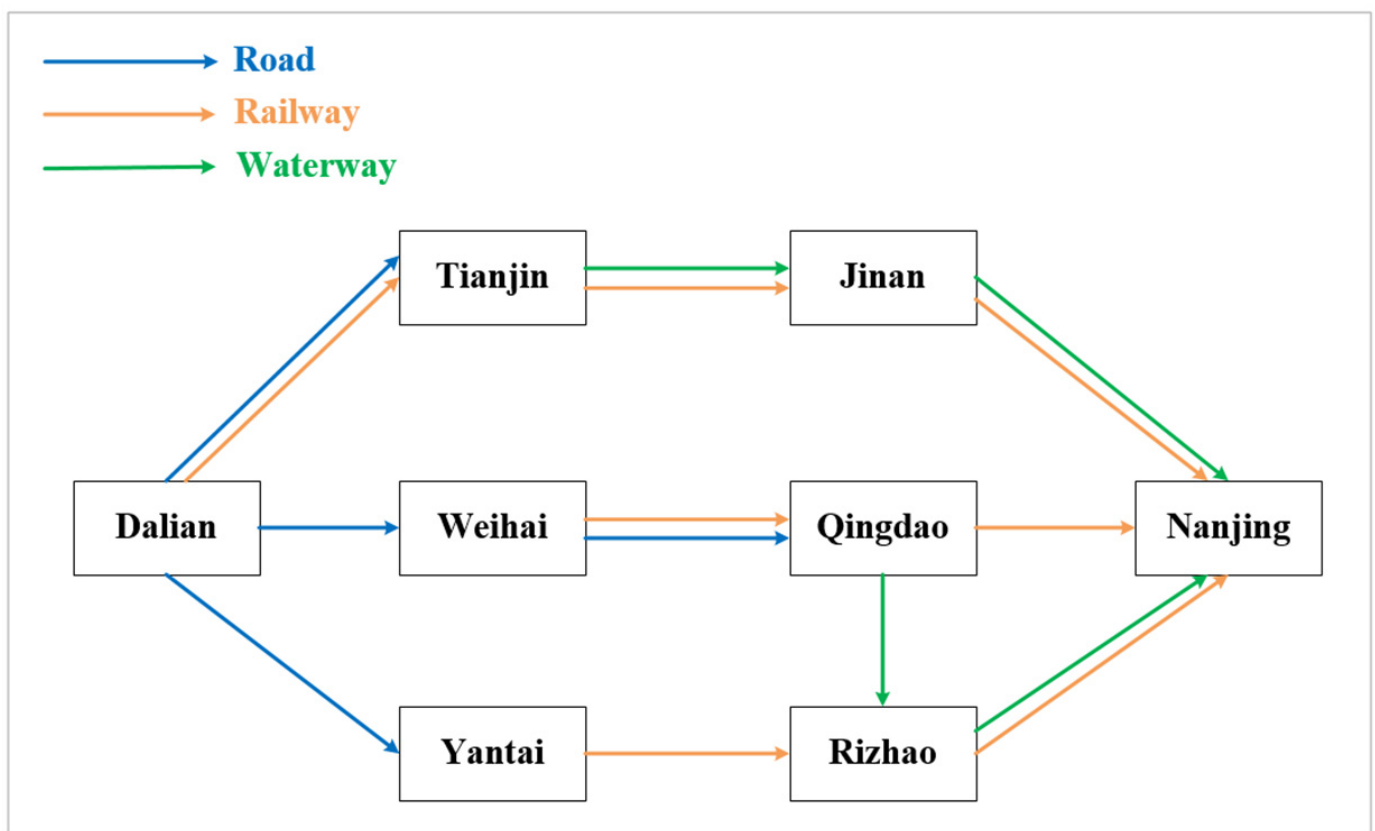


Figure 3. Transport network.

By referring to the relevant websites (<https://wenku.baidu.com> (accessed on 10 December 2023)), <https://www.amap.com> (accessed on 10 December 2023)), the corresponding distances between cities by road, railway, and waterway were obtained. By consulting the reasonable capacity range of each mode of transport, and generating a random number within this range as the capacity value of each carrier, several pieces of information about carriers for roads, railways, and waterways were obtained, as shown in Table 1.

**Table 1.** Carrier information.

| Modes of Transport | Carrier | Transport Origin | Transport Destination | Distance (km) | Transport Capacity (t) |
|--------------------|---------|------------------|-----------------------|---------------|------------------------|
| Road               | 1       | Dalian           | Tianjin               | 834           | 3948                   |
|                    | 2       | Dalian           | Tianjin               | 834           | 1624                   |
|                    | 3       | Tianjin          | Jinan                 | 326           | 3587                   |
|                    | 4       | Tianjin          | Jinan                 | 326           | 2568                   |
|                    | 5       | Jinan            | Nanjing               | 618           | 2329                   |
|                    | 6       | Jinan            | Nanjing               | 618           | 1768                   |
|                    | 7       | Jinan            | Nanjing               | 618           | 3083                   |
|                    | 8       | Weihai           | Qingdao               | 262           | 1557                   |
|                    | 9       | Qingdao          | Nanjing               | 567           | 562                    |
|                    | 10      | Qingdao          | Nanjing               | 567           | 1033                   |
|                    | 11      | Yantai           | Rizhao                | 334           | 1044                   |
|                    | 12      | Rizhao           | Nanjing               | 438           | 3809                   |
| Railway            | 13      | Tianjin          | Jinan                 | 325           | 797                    |
|                    | 14      | Tianjin          | Jinan                 | 325           | 2705                   |
|                    | 15      | Jinan            | Nanjing               | 663           | 3688                   |
|                    | 16      | Jinan            | Nanjing               | 663           | 3438                   |
|                    | 17      | Jinan            | Nanjing               | 663           | 2290                   |
|                    | 18      | Qingdao          | Rizhao                | 300           | 3512                   |
|                    | 19      | Qingdao          | Rizhao                | 300           | 2157                   |
|                    | 20      | Rizhao           | Nanjing               | 437           | 2850                   |
|                    | 21      | Rizhao           | Nanjing               | 437           | 3006                   |
|                    | 22      | Rizhao           | Nanjing               | 437           | 70                     |
| Waterway           | 23      | Dalian           | Tianjin               | 218           | 3709                   |
|                    | 24      | Dalian           | Tianjin               | 218           | 5838                   |
|                    | 25      | Dalian           | Weihai                | 93            | 998                    |
|                    | 26      | Dalian           | Weihai                | 93            | 1023                   |
|                    | 27      | Dalian           | Yantai                | 89            | 14,012                 |
|                    | 28      | Weihai           | Qingdao               | 200           | 19,506                 |
|                    | 29      | Weihai           | Qingdao               | 200           | 17,550                 |
|                    | 30      | Weihai           | Qingdao               | 200           | 15,750                 |

According to the data from Chen et al. [34], the transport cost, speed, carbon emission coefficients, and related trans-shipment information for each mode of transport were obtained. The meaning of the cost unit in Table 2 is the CNY required per kilometer for each ton of goods transported, and the meaning of the carbon emission coefficient is the carbon emission generated per kilometer for each ton of goods transported. The meaning of the carbon emission coefficient in Table 3 is the carbon emission per ton of goods transported. The specific data are presented in Tables 2 and 3.

**Table 2.** The costs, speeds, and carbon emissions of the three modes of transport.

| Modes of Transport                                 | Road    | Railway | Waterway |
|----------------------------------------------------|---------|---------|----------|
| Costs/(CNY t <sup>-1</sup> km)                     | 0.5     | 0.1     | 0.042    |
| Speed/(kmh <sup>-1</sup> )                         | 80      | 55      | 30       |
| Carbon emission coefficient/(kgt <sup>-1</sup> km) | 0.04795 | 0.00841 | 0.01733  |

**Table 3.** Trans-shipment information of the three modes of transport.

|                      | Trans-shipment Costs<br>(CNY t <sup>-1</sup> ) | Trans-shipment Time<br>(ht <sup>-1</sup> ) | Carbon Emission<br>Coefficient (kgt <sup>-1</sup> ) |
|----------------------|------------------------------------------------|--------------------------------------------|-----------------------------------------------------|
| Road–Railway         | 6                                              | 0.009                                      | 0.0324                                              |
| Railway–<br>Waterway | 10                                             | 0.012                                      | 0.0424                                              |
| Road–Waterway        | 7                                              | 0.006                                      | 0.0424                                              |

The assumed shipper order information is shown in Table 4.

**Table 4.** Shipper order information.

| Order Information |         |             |          |                             |                            |
|-------------------|---------|-------------|----------|-----------------------------|----------------------------|
|                   |         | Destination | Terminus | Transport Time<br>Limit (h) | Volume of<br>Transport (t) |
| Shipper 1         | Order 1 | Dalian      | Nanjing  | 40                          | 1000                       |
| Shipper 1         | Order 2 | Dalian      | Nanjing  | 35                          | 1000                       |
| Shipper 2         | Order 3 | Dalian      | Nanjing  | 40                          | 1000                       |

We used a genetic algorithm for the solution, and MATLAB (R2002a) was used to write the code, with a population size of 80, 100 iterations, a crossover probability of 0.7, and a mutation probability of 0.2. In the objective function, the weights for cost and time were set at (0.7, 0.3), respectively. The collaboration strategies for each order are shown in Table 5: Order 1 and Order 2 are transported via Dalian–Tianjin–Jinan–Nanjing, while Order 3 is transported via Dalian–Yantai–Rizhao–Nanjing. Carriers 4, 5, and 23 transport Order 1, carriers 3, 7, and 24 transport Order 2, and carriers 11, 20, and 27 transport Order 3.

**Table 5.** Optimization results.

| Order<br>Number | Path                         | Carrier<br>Selection | Target<br>Value | Cost    | Time (h) |
|-----------------|------------------------------|----------------------|-----------------|---------|----------|
| 1               | Dalian–Tianjin–Jinan–Nanjing | 4, 5, 23             | 484,310         | 807,162 | 32.79    |
| 2               | Dalian–Tianjin–Jinan–Nanjing | 3, 7, 24             | 484,310         | 807,162 | 32.79    |
| 3               | Dalian–Yantai–Rizhao–Nanjing | 11, 20, 27           | 166,820         | 278,010 | 38.03    |

This chapter has completed the design of the “one-bill coverage system” collaboration strategy (Figure 1). The next chapter will discuss how to design smart contracts at the contract layer to implement the “one-bill coverage system” collaboration of the multimodal transport platform based on the blockchain.

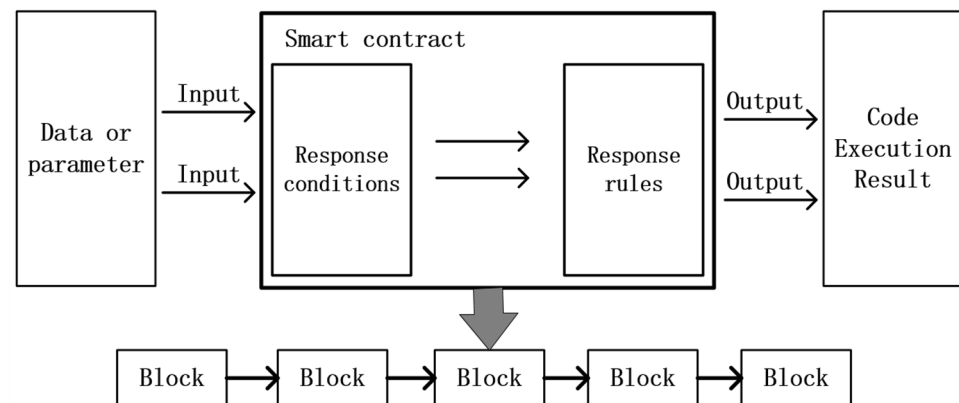
## 5. Design and Implementation of “One-Bill Coverage System” Smart Contracts

Two types of smart contracts were designed based on the “one-bill coverage system” business process: the order smart contract and the alliance partner smart contract. Through the interaction between these two smart contracts, the automatic execution of the “one-bill coverage system” collaboration strategy is achieved. The following sections provide a detailed introduction to these two smart contracts and their interactions, and the Solidity language was used to implement these smart contracts on the Remix platform.

### 5.1. Smart Contract Model

The smart contract model consists of inputs, response conditions, response rules, and outputs, as shown in Figure 4. In this model, inputs are relevant data or parameters, response conditions are predefined variables, and when inputs satisfy the response conditions, it triggers the execution of response rules, resulting in the output of the executed code. Response rules in the smart contract include functions and events, which are two important components.

Functions are typically used to execute specific operations or calculations, while events are used to record and monitor specific activities or state changes on the blockchain.



**Figure 4.** Smart contract model.

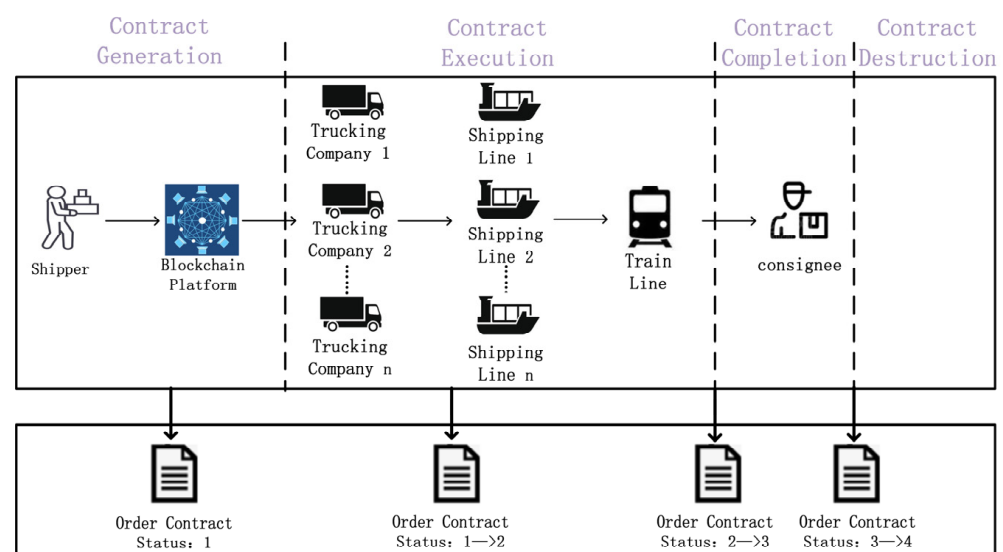
### 5.2. Design of Order Smart Contract

Each agreement reached on the multimodal transport blockchain platform generates an order smart contract. The input of the order smart contract consists of four status parameters contained in the order information, as shown in Table 6.

**Table 6.** Status parameters of the order smart contract.

| State Parameters | Parameter Description   |
|------------------|-------------------------|
| 1                | Cargo delivery          |
| 2                | Transport start         |
| 3                | Transport completion    |
| 4                | Confirmation of receipt |

The status parameters of the order smart contract correspond to the status of the real multimodal transport logistics, as shown in Figure 5. Each change in the status parameter becomes an input to the smart contract of the order, triggering a change in the status of the smart contract and the execution of the corresponding preset contract content until the goods are shipped.



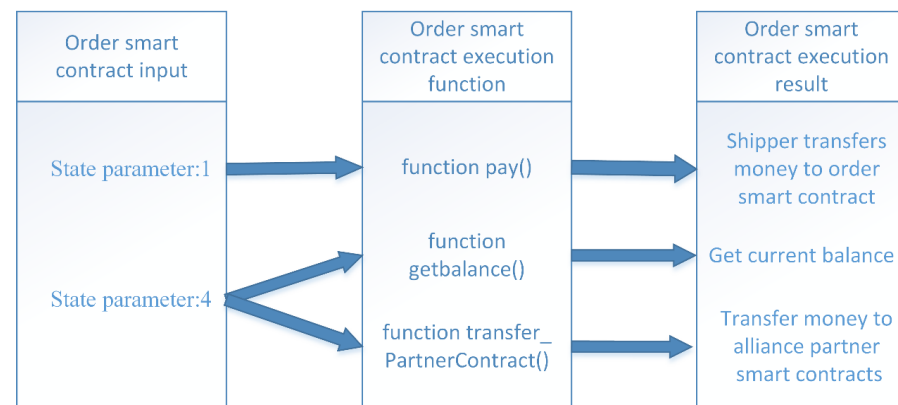
**Figure 5.** Order smart contract status change process.

The functions in the order smart contract primarily handle tasks such as retrieving account balances, and executing transfers. See Table 7 for details.

**Table 7.** Functions in the order smart contract.

| Function                            | Explanation                                       |
|-------------------------------------|---------------------------------------------------|
| function getbalance()               | Obtain current account balance                    |
| function transfer_PartnerContract() | Transfer funds to alliance partner smart contract |
| function pay()                      | The shipper transfers funds to the order contract |

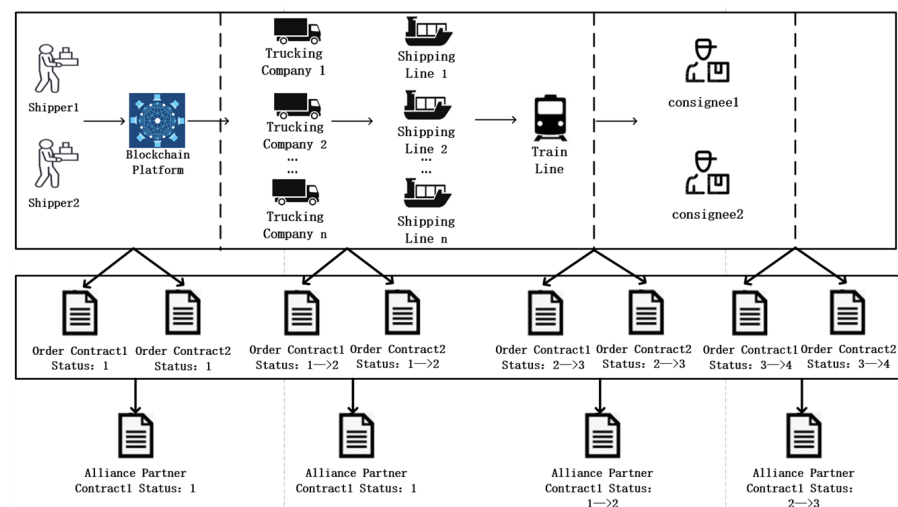
When the input of the order smart contract, that is, the status parameter contained in the order information, is 1, the pay() function is executed to complete the transfer function of the shipper to the order smart contract; when the input status parameter is 4, the getbalance() and transfer\_PartnerContract() functions are executed. The current account balance is obtained and funds are transferred to the affiliate partner contract, as shown in Figure 6.



**Figure 6.** Execution process of order smart contract.

### 5.3. Design of Alliance Partner Smart Contract

The smart contract for alliance partners was designed in accordance with the “one-bill coverage system” business process. Each carrier participating in the collaboration strategy will jointly sign the alliance partner smart contract. Once all orders are completed, the alliance partner smart contract will pay the transport fees to each carrier. Each alliance partner smart contract may interact with multiple corresponding order smart contracts, as shown in Figure 7.



**Figure 7.** Alliance partner smart contract status change process.

The input of the alliance partner smart contract is the output status parameters from the order smart contract, as shown in Table 8.

**Table 8.** Alliance partner smart contract status parameters and meanings.

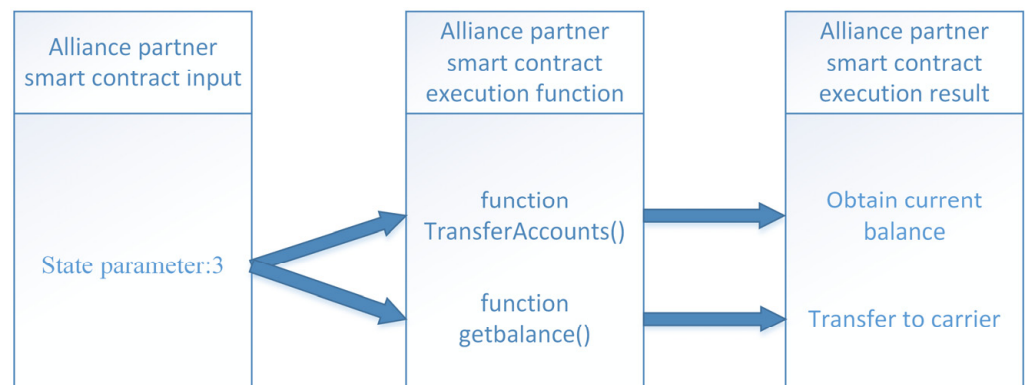
| State Parameter | Parameter Description                                         |
|-----------------|---------------------------------------------------------------|
| 1               | All alliance orders have been delivered                       |
| 2               | All alliance orders have been completed                       |
| 3               | All internal transfers within the alliance have been finished |

The functions in the response conditions of the alliance partner smart contract are shown in Table 9.

**Table 9.** Functions in the alliance partner smart contract.

| Function                                          | Explanation                        |
|---------------------------------------------------|------------------------------------|
| function TransferAccounts() payable returns(bool) | Transfer funds to carriers         |
| function getbalance() returns(uint256)            | Obtain the current account balance |

The alliance partner smart contract mainly realizes the functions of obtaining the current account balance and transferring money to the carrier. When the status parameter of the alliance partner smart contract is 3, the above functions will be performed, as shown in Figure 8.



**Figure 8.** Alliance partner smart contract execution process.

#### 5.4. Design of Collaboration between Smart Contracts

Smart contracts can interact with each other, meaning they can call each other and pass parameters as well as handle return values. In the “one-bill coverage system” workflow, a change in logistics status serves as the trigger condition for the order smart contract, causing its state parameters to update accordingly and triggering the corresponding events to execute the predefined contract content. The results of the “one-bill coverage system” collaboration strategy will be written into the alliance partner smart contract. The alliance partner smart contract can retrieve variable values from the order smart contract, such as order number, order amount, shipper, and carrier information. It can then invoke the order smart contract to obtain its status parameters as trigger conditions, update the contract status, and execute contract content. The collaboration between the two contracts enables the synchronization of logistics, fund flow, and information flow in the “one-bill coverage system” business process, ensuring the automatic and mandatory execution of collaboration strategies.

An alliance partner smart contract interacts with one or more order smart contracts, and during the interaction process, there are changes in the smart contract’s state parameters (the state parameters and their meanings are listed in Tables 6 and 8). Meanwhile, the

participation of various multimodal transport entities is also required, as shown in Figure 9. The specific interaction process is as follows:

- (1) Firstly, the multimodal transport blockchain platform releases order smart contracts to all participants. After confirmation from each party, alliance partner smart contracts are released. Once all parties confirm the information and complete their electronic signatures, both the order smart contracts and alliance partner smart contracts become effective. The shipper delivers the goods to the carrier, and each shipper of the order transfers the required payment to their respective order smart contracts. The state parameter of the order smart contract changes to 1. The alliance partner smart contract retrieves the state value by calling the order smart contract. Once the state parameters of all order smart contracts responsible for the alliance partner contract become 1, the state value of the alliance partner smart contract changes to 1.
- (2) When the transport of goods begins, the state parameter of the order smart contract changes from 1 to 2. At this point, the state value of the alliance partner smart contract is 1.
- (3) When the transport is completed, the state parameter of the order smart contract changes to 3. After all order smart contracts have a state parameter of 3, the state parameter of the alliance partner smart contract changes from 1 to 2.
- (4) After the recipient confirms receipt, the state parameter of the order smart contract changes to 4. Simultaneously, the amount within the contract is transferred to the alliance partner smart contract, and the order smart contract is completed. When all order smart contracts under an alliance partner smart contract are in a completed state, the state parameter of the alliance partner smart contract changes to 3. This triggers a transfer of funds to the carrier responsible for transport, and subsequently, the alliance partner smart contract concludes.

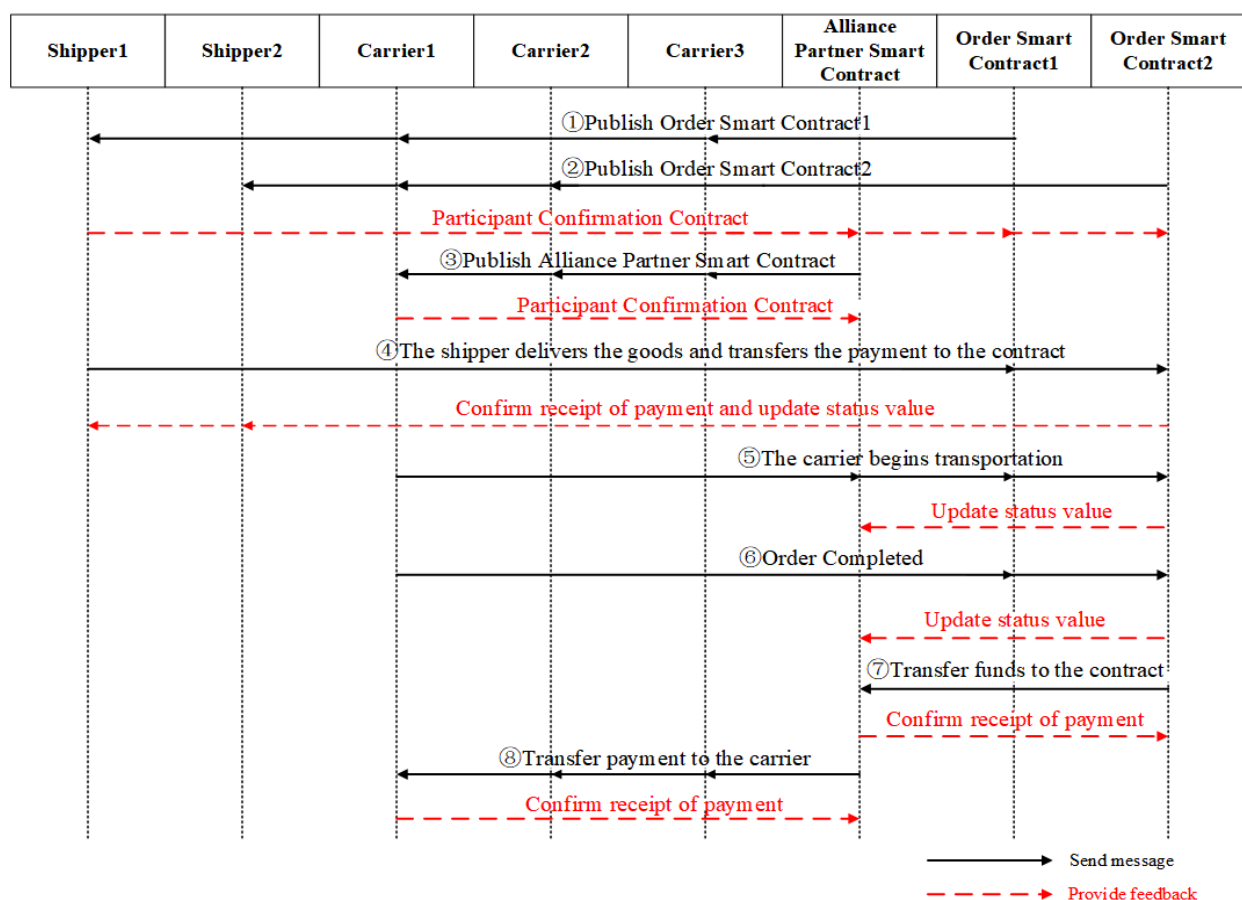


Figure 9. Interaction process between smart contracts.



### 5.5.2. Smart Contract Deployment

After compilation, we successfully deployed three contracts on the Remix platform using external accounts, incurring certain Ether and Gas costs. The addresses and hash values of the three contracts were obtained, as shown in Figures 11 and 12.

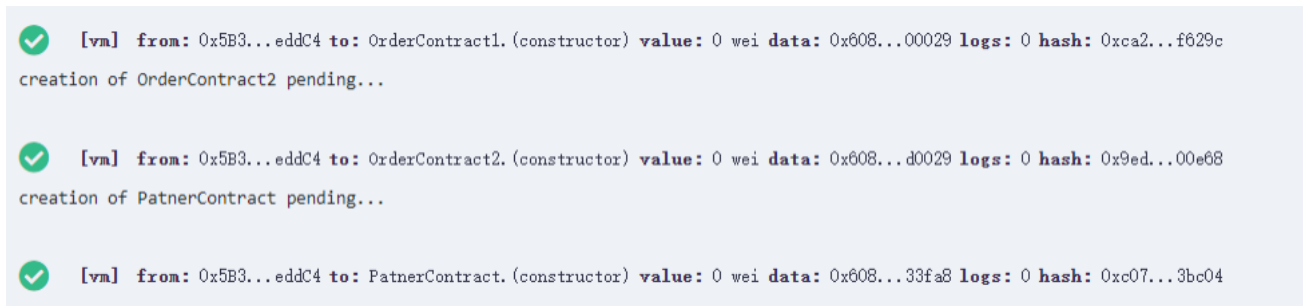


Figure 11. Contract successfully deployed.

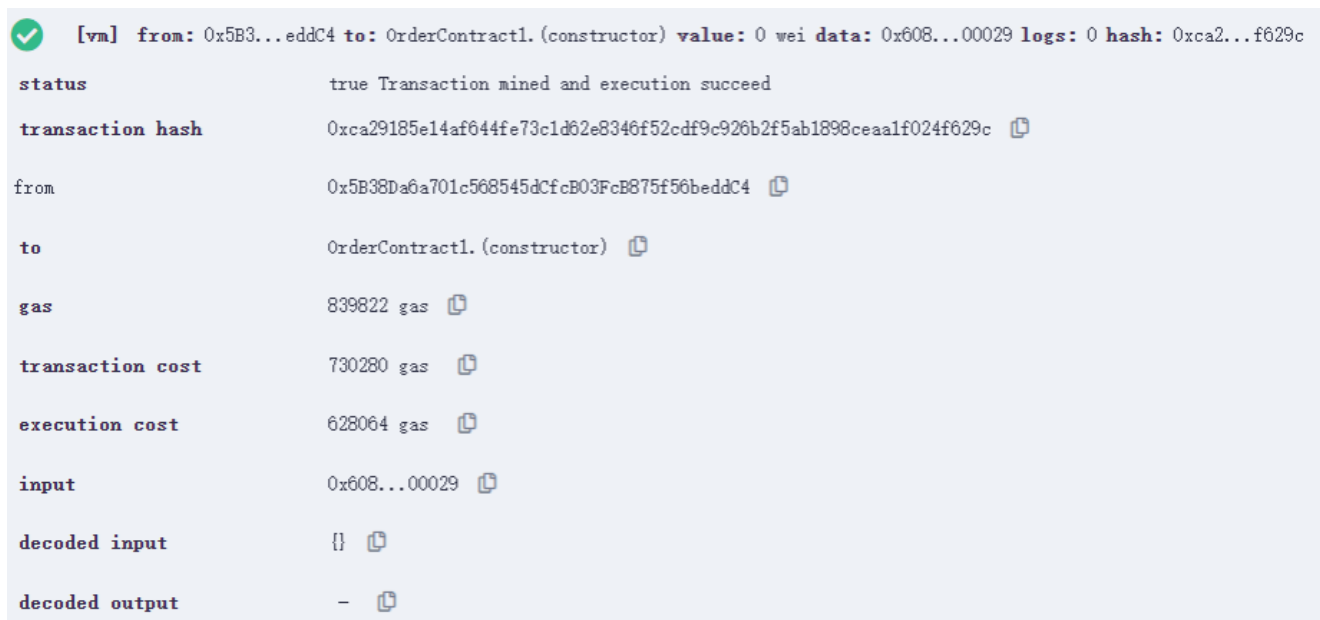


Figure 12. Detailed information of contract deployment.

### 5.5.3. Smart Contract Call

After deploying the smart contracts onto the blockchain, the contracts can interact with each other, call their functions, and record transactions and state changes. In this study, smart contracts were tested according to the multimodal transport business. Before testing the calls, each shipper's account started with a balance of 100 ether, while the smart contract account had a starting balance of 0 ether. Each transaction consumed a certain amount of ether and gas. First, carriers, orders, and alliance information were added through the order smart contract, as shown in Figure 13.

When the status of the order contract is 1, each shipper of the order transfers funds to the corresponding order smart contract. After the successful transfer, both accounts undergo changes, as shown in Figures 14 and 15.

The successful transfer is shown in Figure 16.

When the consignee confirms receipt, the order is completed, and the corresponding status value of the order smart contract changes to 4. Then, it transfers funds to the alliance partner smart contract. After the transfer, the account balance of the order smart contract becomes 0, while the alliance partner contract receives the corresponding amount, as shown in Figure 17.



Figure 13. Adding order information.

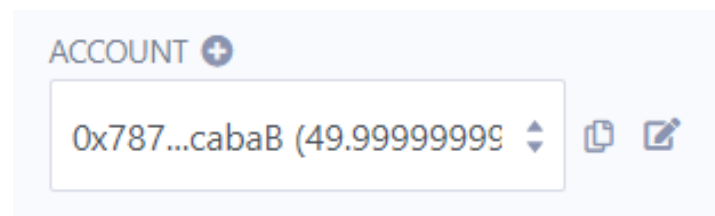


Figure 14. Changes in shipper's account.

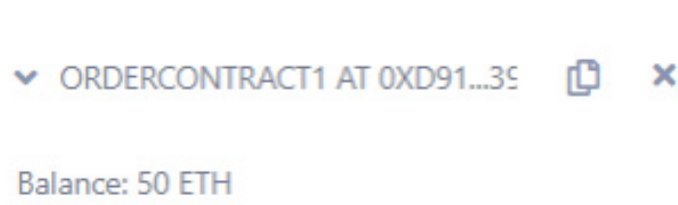


Figure 15. Changes in order smart contract account.

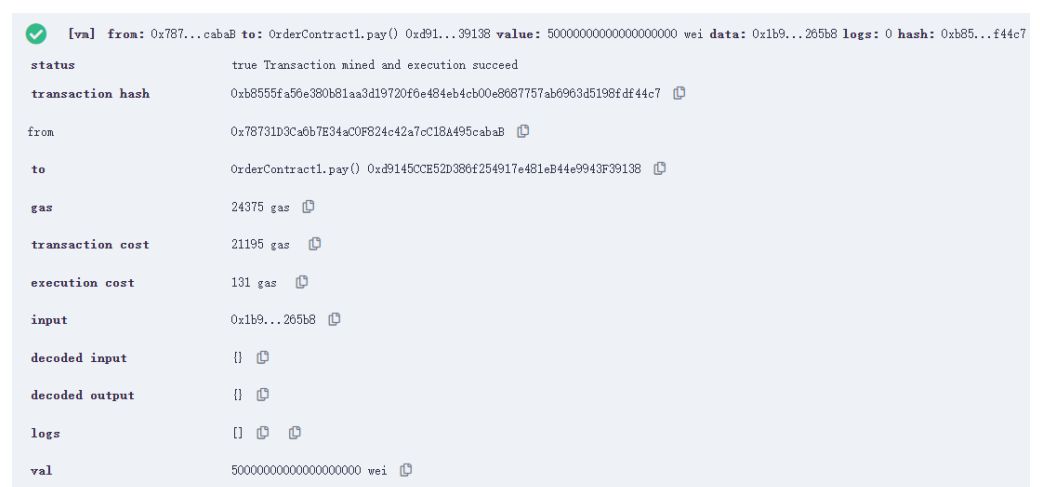


Figure 16. Shipper transferring funds to the order smart contract.

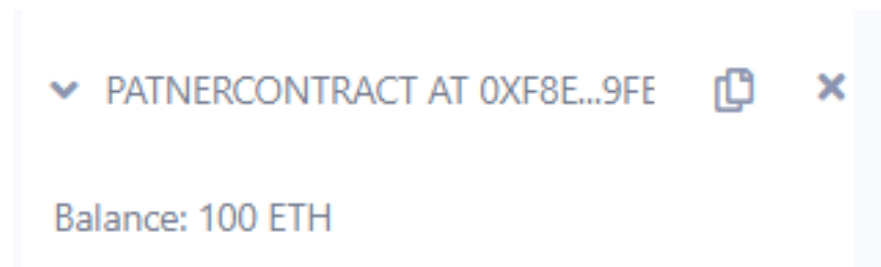


Figure 17. Changes in the alliance partner smart contract account.

The successful transfer can be seen in Figure 18.

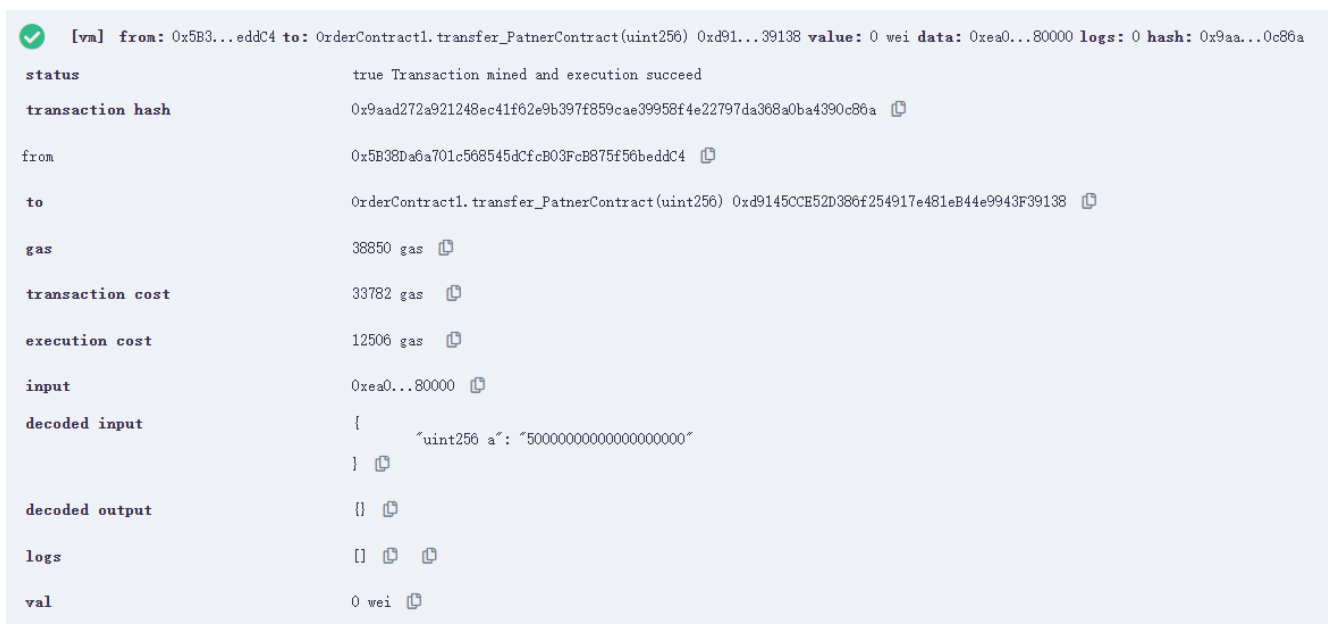


Figure 18. The transfer from the order smart contract to the alliance partner smart contract.

When all the order smart contracts contained in the alliance smart contract have a status of 4 and complete the transfer, the status value of the alliance partner smart contract changes to 3, and transfers are made to the carriers within the alliance, as shown in Figure 19.

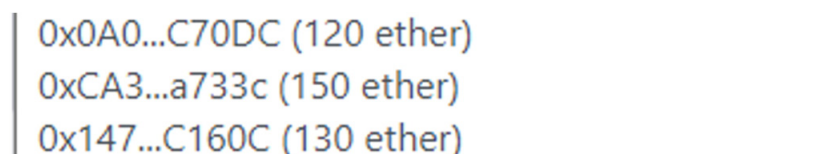


Figure 19. Carrier account changes.

## 6. Conclusions

This paper proposed the architecture of a multimodal transport blockchain platform and redesigned the business process. It established a blockchain-based “one-bill coverage system” collaboration model, provided collaboration strategies, and improved collaboration mechanisms. Furthermore, it designed and implemented smart contracts related to the “one-bill coverage system”. This study offers theoretical methods and scientific decision-making basis for the “one-bill coverage system” problem, promotes the standardization construction of multimodal transport-related systems, and provides new insights for its development.

The research contributions of this paper can be summarized as follows. First, it has enriched the application of blockchain smart contract theory and technology in the field

of multimodal electronic documents. Second, in view of the characteristics of multimodal electronic document collaboration business, the “one-bill coverage system” multiparty collaboration process of multimodal transport based on the blockchain platform is re-engineered, breaking the information island and process barriers in traditional multimodal transport. Third, it innovatively proposes a multiparty collaboration model of multimodal transport, and obtains a collaboration strategy by solving the model. In order to realize the automatic execution of the collaboration strategy on the blockchain platform, it uses the Solidity language to write relevant smart contracts on the Remix platform, which effectively improves the collaboration efficiency among the participants of multimodal transport.

This paper still has some shortcomings: the implementation of the “one-bill coverage system” in multimodal transport requires the active sharing of relevant transport data by all parties. However, some parties are not willing to share sensitive data related to their own interests. In the future, efforts in various areas such as policies and industry cooperation are needed to promote the true implementation of the “one-bill coverage system”. Smart contracts usually need to be complemented with front-end and blockchain underlying technologies to be implemented. Future research can combine front-end and back-end design and development to better implement the functions of smart contracts.

**Author Contributions:** Conceptualization, L.S. and X.Q.; methodology, D.Y. and Z.Z.; software, X.Q.; validation, Z.Z.; formal analysis, D.Y.; data curation, D.Y.; writing—original draft preparation, D.Y.; writing—review and editing, Z.J. All authors have read and agreed to the published version of the manuscript.

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