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Efficient rail-water intermodal transportation network using game theory

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ABSTRACT

In rail-water combined transport, maintaining a fair and equitable distribution of income is crucial for sustaining the cooperative relationship between railway and waterway transportation, which forms the bedrock for efficient combined railway and waterway operations. To achieve this, a cooperative game model is proposed that encompasses both railway and waterway transportation. The model considers the structural relationship between transport routes, dividing their operational cooperation into two modes: intermodal transportation and shared transportation. Two allocation methods are introduced to address this: one based on the contribution of the transport network and the other utilizing the modified Shapley value method. An in-depth analysis of the revenue allocation scheme is provided. The results of the calculations demonstrate that the cooperative revenue allocation model is effective in fairly and reasonably distributing the cooperative revenue, thereby ensuring the ongoing collaboration between railroads and waterways.

Keywords: Rail-water combined transport; Profit distribution; Route structure; Cooperative game

1. Introduction

Intermodal transportation refers to a mode of transportation where imported and exported goods are transported by rail to coastal seaports and then further transported by ships. Due to its efficiency, cost-effectiveness, and environmental advantages, intermodal transportation has become one of the most promising modes of transportation in China's future development.

Research on intermodal transportation has primarily focused on problem investigation, scheduling optimization, and pricing management. Ge et al. [1] and Matei et al. [2] conducted surveys on the current situation and theoretical directions of sea-rail intermodal transportation in China and proposed improvement suggestions regarding institutional and practical gaps. Vasco conducted a comprehensive analysis of the pros and cons of integrating railway transportation with other modes such as highway, waterway, and aviation. Additionally, he suggested a transfer technology to enhance the efficiency of multimodal transportation services when switching between transportation modes. Furthermore, energy consumption in railway transportation was also studied as part of the research [3]. Beuthe et al. [4] conducted a study in a specific region, where 10 different types of goods were transported within a multimodal transport network. In this study, he devised a comprehensive traffic demand allocation model that took into account all possible routes and transportation modes. The research also introduced a combined approach that considered both direct and cross demand elasticity coefficients for three transportation modes: railway, highway, and water transportation.

In the area of scheduling optimization for intermodal transportation, several scholars have made significant contributions. Fan et al. [5] introduced a learning-forgetting mechanism to update algorithms and optimize the energy consumption of intermodal transportation. Their work aimed to improve the efficiency of energy usage in this

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mode of transportation. Han et al. [6] proposed a mixed-data index evaluation model based on the hesitant fuzzy multi-attribute decision-making method. This model can be used to evaluate and compare different aspects of intermodal transportation, taking into account multiple attributes. Chang [7] developed an optimization study by formulating a multi-objective, multi-commodity flow problem with time windows and concave costs. This model was specifically tailored to address the challenges of the international multimodal transportation route selection problem. To deal with the complexity of the problem, relaxation and decomposition techniques were employed to break it down into manageable components. Ziliaskopoulos and Wardell [8] introduced a path optimization algorithm designed for multimodal transportation networks. They tested and confirmed the efficiency and complexity of the algorithm in handling delays that occur during multimodal transportation processes and cross operations. Regarding the pricing issue, Algaba et al. [9] combined service scheduling with freight rate allocation and constructed a branch pricing algorithm considering the constraints of container transit time and fuel consumption. Their research aimed to find an optimal pricing strategy that takes into account time and fuel-related factors. Nowak et al. [10] examined the correlation between the carrier's route and profits within the framework of a quantity discount contract. Their study explored how pricing and route decisions can impact carrier profits. Wang and Meng [11] delved into the optimal pricing issue for terminal enterprises considering congestion-related factors. They aimed to find pricing strategies that account for congestion and its effects on terminal operations. Zheng and Luo [12] formulated integration models for the shipping market, considering the effects of transportation economies of scale and competition from service substitution. Their work explored the game relationship between different carriers and multimodal service providers.

Cooperative game theory has proven to be a valuable tool for analyzing the dynamics of intermodal transportation supply chains. Zhang et al. [13] applied game analysis to study optimal pricing and revenue in the cold chain logistics process. By using game theory, they were able to gain insights into the pricing strategies and revenue generation in the cold chain logistics domain. In another study, Zhang et al. [14] examined the optimal decisions of manufacturers and retailers under both Stackelberg and cooperative game scenarios. This analysis provided a deeper understanding of the interactions between manufacturers and retailers in the supply chain. Hua et al. [15] compared a single model (advertising only) with a joint model (advertising and recycling pricing) in a two-tier reverse supply chain. Their goal was to determine optimal pricing and advertising strategies. The use of game theory in this context allowed them to identify the most effective strategies in the reverse supply chain. Taleizadeh et al. [16] extended the two-tier supply chain and employed three coordination contracts to improve the performance of the supply chain. They addressed the issue of profit allocation in supply chains using the Shapley value method. This research offered valuable insights into enhancing supply chain coordination and cooperation. On the other hand, Demir et al. [17] considered the uncertainty of travel time in the green multimodal transport service network. They designed the multimodal transportation route decision for multiple commodities using the sample average approximation method. Their study examined the multimodal transportation plan under various objective constraints related to travel time and demand uncertainty. While existing research on multimodal transport has predominantly focused on optimizing operational planning for various solutions in transportation, loading, and unloading, there is limited literature analyzing the competition between multi-modal operators and other carriers from the perspective of multi-party games [17]. This area presents a promising opportunity for further research and understanding the dynamics of competition among different players in the multimodal transportation domain.

When it comes to route selection for intermodal transportation, much of the research has been focused on optimizing transportation networks. Zhang et al. [18] proposed a railway-centric multimodal route selection model, which took into account time penalty costs and damage compensation costs. By considering these factors, their model aimed to find more efficient and reliable routes for intermodal transportation. Li et al. [19] argued that distributed system computing could better meet the requirements of multi-mode path queries and conducted experiments to verify the scalability of the algorithm on large graphs. This approach seeks to improve the efficiency of finding optimal routes in complex transportation networks. Xu and Rong [20] tackled multimodal route optimization by calculating interchange times between different transportation modes and transportation times between nodes. By considering these aspects, their research aimed to identify routes that minimize transit times and improve the overall efficiency of intermodal transportation.

In light of the current situation and existing research, China's policy guidance for the development of intermodal transportation rightly highlights key areas such as the establishment of enterprise alliances, infrastructure improvement, informatization, and scheduling optimization. Container intermodal transportation has experienced significant growth. However, some challenges have emerged, particularly related to increased costs for enterprises due to infrastructure upgrades, informatization efforts, and scheduling optimization. A crucial aspect that requires attention is the fair and reasonable distribution of profits among participating entities in the enterprise alliances. The value contributed by different enterprises to the alliance can vary significantly, and this calls for a well-balanced profit distribution mechanism. Without a fair allocation of profits, the stability of cooperation may be jeopardized, leading to the withdrawal of participating entities and subsequent loss of benefits for all involved. Addressing this issue becomes critical for sustaining and fostering the development of intermodal transportation.

To tackle the profit distribution challenge, this paper proposes to explore the use of cooperative game theory as a foundation for research. By considering railway companies and water transport companies as participants in the cooperative game, the paper aims to investigate and develop a profit distribution mechanism for intermodal transportation. Utilizing cooperative game theory can provide valuable insights into devising a fair and reasonable profit-sharing scheme among the participants, leading to more stable and beneficial cooperation within the enterprise alliances. Ultimately, this research can offer important theoretical references for policymakers and stakeholders in promoting the continued growth and development of intermodal transportation in China. By addressing the crucial issue of profit distribution, the paper can contribute to fostering a collaborative and sustainable environment that benefits all participants in the intermodal transportation sector.

2. Problem description

Given a directed transportation network, let V be the set of nodes v in the network, $V = (1, 2, \ldots, v)$; U be the set of carriers u in the network, $U = (1, 2, \ldots, u)$, and $L \subset V \times V \times U$ be the set of routes l carried by each carrier between any two nodes in the network, $L = (1, 2, \ldots, l)$. Let R be the set of travel paths r in the network, $R = (1, 2, \ldots, r)$, where each path r is composed of a sequence of adjacent transferable routes l, that is, $r_{ij} = \sum_{ij} l$.

Specifically, when there are multiple feasible routes or paths between two nodes i and j, customers based on complete rationality, select travel routes according to their own needs and external factors. The probability of selecting a specific path is denoted as $q(l)$.

Based on the above, the profit function for carriers u on operating routes l can be defined by Eq. (1):

$$f(u,l) = q(l)p(i,j)t(u) + b - C_u \tag{1}$$

The profit function for carriers u on travel routes r can be defined by Eq. (2):

$$f(u,r) = \sum_{l \in r} f(u,l) \tag{2}$$

The total profit function for carriers u on the transportation network N can be defined by Eq. (3):

$$f(u) = \sum_{r \in R} f(u,r) \tag{3}$$

The premise of cooperative transportation is that participating carriers can obtain more profits through cooperation. In this paper, the set of carriers U from the railway and waterway are considered as participants in the alliance, and a cooperative game model (U, F) is constructed. The profit function f for each carrier satisfies the Eq. (4):

$$f : 2^{|U|} \to R \tag{4}$$

In Eq. (4), assuming that there are two coalitions in the set of cooperative alliances, denoted as S and M, $S \subset M \subseteq U | \{i\}$, satisfying the Eq. (5):

$$f(\varnothing) = 0 \tag{5}$$

$$f(u) \geq \sum_{u \in U} f(u) \tag{6}$$

$$f(S \cup \{i\}) - f(S) \leq (M \cup \{i\}) - f(M) \tag{7}$$

The cooperation alliance between railway and water transport exhibits convexity, meaning that the larger the alliance, the higher the cooperative benefits. Carriers can create new cooperative surplus value by joining the cooperation alliance. Therefore, it is feasible to establish this cooperative transportation alliance.

3. Model construction

In the transportation network composed of railways and waterways, depending on whether the transportation routes have a connecting or parallel relationship within the network, cooperative transportation can be divided into intermodal transportation (IT) mode and common transportation mode.

3.1. Revenue allocation model for intermodal transportation mode

Intermodal transportation (IT) mode refers to transportation completed by different routes. As shown in Fig. 1, the arrows indicate the direction of travel paths $r = (l_1, l_2)$. Logistics depart from Node 1, pass through Node 2, and proceed to Node 3. The logistics transportation on this path requires the joint use of route $l_1 = (1, 2, u_1)$ operated by carrier u_1 and route $l_2 = (2, 3, u_2)$ operated by carrier u_2 to complete the transportation cooperatively. In the IT mode, upstream carriers on the transportation chain contribute to the logistics revenue obtained by downstream carriers and should receive additional revenue sharing. Similarly, under different scenarios, revenue allocation should be adjusted. The revenue allocation expression is given by Eq. (8):

$$\phi_1(u,l) = \begin{cases} f(u,l) + \theta f(u',l'), l = l_1 \\ (1-\theta) f(u,l), l = l_2 \\ (1-\theta)\left[f(u,l) + \theta f(u',l')\right], l = l_3 \end{cases} \tag{8}$$

3.2. Revenue allocation model for shared transportation mode

Shared transportation (ST) mode refers to having multiple routes available for customers to choose from along the travel path. As shown in Fig. 2, the arrows indicate the direction of travel paths. When traveling from Nodes 1 to 2, customers have the option to choose either route $l_1 = (1, 2, u_1)$ operated by carrier u_1 or route $l_2 = (1, 2, u_2)$ operated by carrier to complete their travel.

In the cooperative transportation alliance formed by different routes, the members jointly undertake the logistics transportation tasks between network nodes. To determine

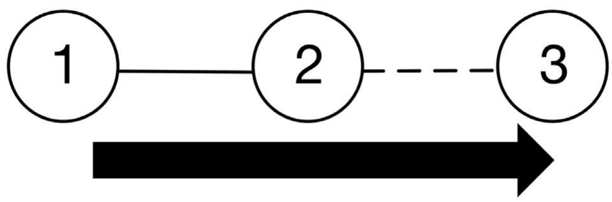

Fig. 1. Intermodal transportation mode. Solid lines represent the route of u_1, while dashed lines represent the route of u_2.

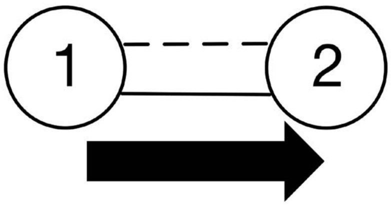

Fig. 2. Shared transportation mode. Solid lines represent the route of u_1, while dashed lines represent the route of u_2.

the allocation of cooperative benefits, this paper constructs a revenue allocation model based on the Shapley value correction.

The Shapley value method is a mathematical approach proposed by Lloyd S. Shapley, an American Economist, in 1953, to address the problem of alliance benefit allocation in multi-person cooperation. This allocation method is neither based on equal distribution among alliance members nor on the proportion of investment costs of each member. Instead, it allocates based on the importance of each member in generating economic benefits during the cooperation project within the alliance.

Let's denote a set $I = \{1, 2, \ldots, N\}$ representing the set of N individuals. If there exists a real-valued function $v(s)$ for any subset I (representing any combination of n individuals in the set), satisfying the axioms:

$$v(\varnothing) = 0 \tag{9}$$

$$v(s_1 \cup s_2) \geq v(s_1) + v(s_2) \tag{10}$$

$$s_1 \cap s_2 = \varnothing (s_1, s_2 \subseteq I) \tag{11}$$

where $v(s)$ is called a characteristic function defined on I, which represents the benefits of cooperation. Eqs. (1) and (2) embody the system thinking that the whole is greater than the sum of its parts, indicating that establishing a cooperative alliance can generate the maximum cooperative benefit is denoted as $v(I)$. Based on cooperation I, the share that more benefits without harming individual interests. When all members choose to cooperate, the i-th partner should receive from the maximum cooperative benefit $v(I)$ is denoted as $\psi_i(v)$. Therefore, the allocation of the cooperative problem is represented as: $\Phi(v) = (\varphi_1(v), \varphi_2(v), \ldots \varphi_n(v))$.

Obviously, the success of this cooperation must satisfy by Eqs. (12) and (13):

$$\sum_{i=1}^{n} \varphi_i(v) = v(I) \tag{12}$$

$$\varphi_i(v) \geq v(i), i = 1,2,\ldots,n \tag{13}$$

Under cooperation I, the allocation of benefits for each partner determined by the Shapley value method is given by:

$$\varphi_i(v) = \sum_{s \in s_i} w(|s|)\left[v(s) - v\left(\frac{s}{i}\right)\right], i = 1,2,\ldots,n \tag{14}$$

$$w(|s|) = \frac{(n-|s|)!(|s|-1)!}{n!} \tag{15}$$

where $s(i)$ represents all subsets of the set I that include the cooperating partners i, $|s|$ represents the number of elements in the subset s, n represents number of elements in the set I, and $w(|s|)$ is the weighting factor.

In this paper, we introduce a correction factor to adjust the allocation of cooperative benefits, avoiding the issue of equal distribution in the original Shapley value model. The expression for revenue allocation:

$$\phi_2(u,l) = \sum_{S \subset U} \frac{|S|!(|U_r| - |S| - 1)!}{|U_r|!}\left[f(S \cup \{l\}) - f(s)\right] + \left(\frac{\lambda_u}{\sum_{u \in U_r} \lambda_u} - \frac{1}{|U_r|}\right) f(U_r) \tag{16}$$

where λ_u represents the correction factor, $\frac{\lambda_u}{\sum_{u \in U_r} \lambda_u} - \frac{1}{|U_r|}$ is the difference between the comprehensive evaluation value of the cooperating participants u' and the average value of the alliance. The calculation λ_u formula for the correction factor is given by:

$$\lambda_u = (w_1, w_2, \ldots, w_n)(\alpha_1, \alpha_2, \ldots, \alpha_n)^T \tag{17}$$

where w_i represents the weight of the i-th influencing factor, and $\sum_{i=1}^{3} w_i = 1$, α represents the comprehensive evaluation value of the i-th influencing factor. In the context of intermodal transportation, issues such as vessel schedules and container weight ratios often arise, posing risks to the on-time delivery and service provision for shippers. Additionally, the presence of independent information systems and non-standardized container types increases the complexity of container handling, leading to higher operating costs for carriers. For carriers, providing intermodal services increases workload, poses challenges, and entails certain risks.

Analyzing the current problems faced by intermodal transportation in China and considering relevant policies, this paper selects contribution coefficient, operating costs, and risk sharing as the influencing factors in intermodal transportation.

The total revenue $f'(u)$ of each operator after allocation in the transportation network is the sum of intermodal transportation revenue, undistributed revenue, and shared transportation revenue, given by:

$$f'(u) = \sum_{r \in R_u} \phi_1(u,r) + \sum_{r' \in R_u} \phi_1(u,r') - \sum_{l \in L} \phi_1(u,l) + \sum_{l \in L} \phi_2(u,l) \tag{18}$$

where r' represents the travel route independently operated by carrier u, and $R_u = \{r, r'\}$.

4. Case study analysis

4.1. Case parameters

Considering the demand for empty containers, this paper presents a transportation network $N = (4.3.5)$ as shown in Fig. 3, where three transportation service companies operate different routes. Solid lines u_1 represent routes operated by a water transport company, dashed lines u_2 represent routes operated by another water transport company, and dotted lines u_3 represent routes operated by a railway company.

For the convenience of calculation and in line with reality, let's assume the container water transport price u_1, u_2 is 2 yuan/(TEU/km), the water transport cost c_1 = 500/km, c_2 = 600 yuan/km, the container railway price u_3 = 3 yuan/(TEU/km), and the railway operating cost c_3 = 700 yuan/km. The allocation parameter for the intermodal transportation mode is denoted as θ = 0.2, and the correction parameters for each company in the shared transportation mode:

$$\begin{aligned}&\left(a_1,a_2,a_3\right)_{u_1}^T=\left(0.6,0.2,0.4\right)^T,\\&\left(a_1,a_2,a_3\right)_{u2}^T=\left(0.2,0.4,0.3\right)^T,\\&\left(a_1,a_2,a_3\right)_{u3}^T=\left(0.6,0.2,0.4\right)^T\end{aligned} \quad (19)$$

where $(w_1,w_2,w_3)=(0.3,0.3,0.4)$, and $\lambda_{u_1}=0.4, \lambda_{u_2}=0.3, \lambda_{u_3}=0.3$. The government provides a subsidy of b = 1,000 yuan/km for each transportation route.

In a general transportation network, logistics flow in both directions. However, for simplicity and without loss of generality, we will consider only one direction, specifically the flow of containers from nodes with lower numbers to nodes with higher numbers. In this case, we have a total of 19 feasible paths in the system.

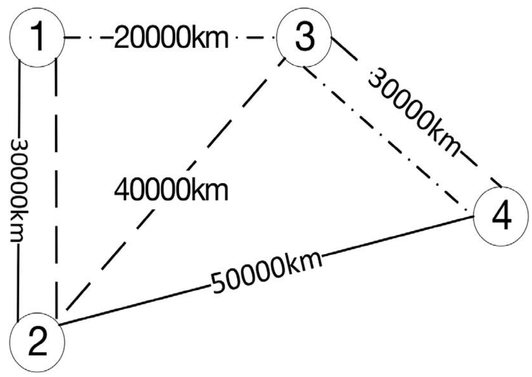

Fig. 3. Transportation network.

The probability $q(r) = 1/n$ of multiple paths being chosen for each node, n represents the number of available paths between nodes. The logistics demand between nodes is equally distributed among feasible paths. Assuming that each path carries 1,000 TEU, the total inflow of goods into the system is 19,000 TEU. The cost of external transfers in the network is considered infinite, meaning that if different carriers do not cooperate on a specific path, the logistics cannot be completed. It is assumed that customers on that path leave the intermodal transportation system due to lack of service. The feasible routes and their corresponding profits in the example network are shown in Table 2. In the cooperative game, each transportation company has three strategies to choose from: operate independently, cooperate pairwise, or cooperate with all partners. The revenue for each strategy is shown in Table 3. It can be observed that cooperation between railways and railway carriers can expand the alliance's revenue. This cooperative game is a convex game, with the characteristic that a larger alliance leads to greater cooperative benefits. Cooperation is sustainable, and the game core is not empty, with the Shapley value lying within the core [6].

4.2. Profit allocation

In the intermodal transportation network of railway and water transport, both the intermodal transportation mode and shared transportation mode coexist. When determining the profit allocation sequence for each transportation company, it is considered that parallel routes in the shared transportation mode participate in the transportation chain as a whole. Therefore, the profit allocation for the intermodal transportation mode is conducted first, followed by the profit allocation for the shared transportation mode. The specific allocation process is as follows:

Step 1: Calculate the profit situation for each transportation company when no allocation is made and allocate the profit to the routes in the network, as shown in Table 4.

Step 2: Calculate the profit allocation for the routes under the intermodal transportation mode. By considering the number of participating operators on each route, it can be determined that there are 7 routes that adopt the intermodal transportation mode, namely routes 4, 6, 7, 9, 10, 13, and 16. Based on the profit allocation method proposed in

Table 1
Parameter assumptions

Order number	Symbol	Symbol description
1	R_u	Set of paths in the travel routes where carriers u are involved in completing the transportation.
2	U_r	Set of carriers involved in the travel routes r.
3	c_u	Unit operating cost of carriers u on the paths in the transportation network.
4	$P(i, j)$	Total volume of container flow between nodes i and j.
5	$t(u)$	Transportation price set by carriers u for operating routes l between nodes i and j.
6	b	Subsidy revenue received by carriers u for operating routes l on the line.
7	P	Benefits of the cooperative alliance.
8	A	Overall factor productivity.

Table 2
Profits on each route in the transportation network

Travel	Routes r	Carriers	$f(u_1)$/10,000 yuan	$f(u_2)$/10,000 yuan	$f(u_3)$/10,000 yuan	Routes profits $f(r)$/10,000 yuan
1-2	r_1	u_1	7,500	0	0	7,500
	r_2	u_2	0	7200	0	7,200
1-2-3	r_3	u_2	0	16800	0	16,800
	r_4	u_1, u_2	7,500	9600	0	17,100
1-2-4	r_5	u_1	20,000	0	0	20,000
	r_6	u_1, u_2	12,500	7200	0	19,700
1-2-3-4	r_8	u_2	0	24000	0	24,000
	r_9	u_2, u_3	0	16800	9,900	26,700
	r_{10}	u_1, u_2, u_3	7,500	9600	9,900	27,000
1-3	r_{11}	u_3	0	0	6,600	6,600
1-3-4	r_{12}	u_3	0	9600	9,900	19,500
	r_{13}	u_2, u_3	0	7200	6,600	13,800
2-3	r_{14}	u_2	0	9600	0	9,600
2-3-4	r_{15}	u_2	0	16800	0	16,800
	r_{16}	u_2, u_3	0	9600	9,900	19,500
2-4	r_{17}	u_1	12,500	0	0	12,500
3-4	r_{18}	u_2	0	7200	0	7,200
	r_{19}	u_3	0	0	9,900	9,900
Total	19	3	7,500	158400	69,300	302,700

Table 3
Profits on each route under different strategies in cooperative game

Cooperative strategy	u_1	u_2	u_3	u_1, u_2	u_1, u_3	u_2, u_3	u_1, u_2, u_3
Profit $f(u)$/10,000 yuan	40,000	81,600	33,000	182,700	73,000	174,600	302,700

Table 4
Profits of each operator without redistribution

Carriers	Profit of operating route l(in units of 10,000 yuan)					Carrier profits $f(u)$/10,000 yuan
	(1,2)	(1,3)	(2,3)	(2,4)	(3,4)	
u_1	37,500	0	0	37,500	0	75,000
u_2	36,000	0	86,400	0	36,000	158,400
u_3	0	19,800	0	0	49,500	63,900
Route profits/10,000 yuan	73,500	19,800	86,400	37,500	85,500	302,700

Section 1 of this paper for the intermodal transportation mode, allocate the profit for these routes. The allocation results are then integrated back into the transportation network routes, resulting in the profit situation for each operator after the intermodal transportation mode profit allocation, as shown in Table 5.

Step 3: Calculate the profit allocation for the routes under the shared transportation mode. The routes (1, 2) and (3, 4) are operated through cooperation between carriers u_1, u_2 and u_3, respectively. Taking route (1, 2) as an example, the individual profits for carriers, operating independently are 175 and 257.28 million·yuan, respectively, while the additional profit generated from cooperation is 415.32 million yuan. Table 6 shows the calculation process for the Shapley value correction of operator u_1 on route (1, 2), and it can be seen that the total profit for operator u_1 is 16.273 million·yuan. Similarly, the profits for operator u_2 on routes (1, 2) and (3, 4) are 10.903 and 6.62 million·yuan, respectively, and the profit for operator u_3 on route (3, 4) is 4.72 million·yuan. Thus, the profit allocation for each operator in the cooperative transportation alliance is completed, as shown in Table 7.

5. Results

The establishment of a cooperative transportation alliance is aimed at increasing profits and ensuring the fair allocation of benefits among all participants. The results presented in Table 7 show that after adopting the cooperative

Table 5
Distribution of profits among carriers in intermodal transportation

Carriers	Profit of operating route l(in units of 10,000 yuan)					Carrier profits $f(u)$/10,000 yuan
	(1,2)	(1,3)	(2,3)	(2,4)	(3,4)	
u_1	43,944	0	0	35,000	0	78,944
u_2	40,816	0	85,020	0	33,120	158,956
u_3	0	21,240	0	0	43,560	64,800
Route profits/10,000 yuan	84,760	21,240	85,020	35,000	76,680	302,700

Table 6
Distribution of profits among carriers in cooperative transportation

Carriers	Profit of operating route l(in units of 10,000 yuan)					Carrier profits $f(u)$/10,000 yuan
	(1,2)	(1,3)	(2,3)	(2,4)	(3,4)	
u_1	40,976	0	0	35,000	0	75,976
u_2	43,784	0	85,020	0	35,610	164,414
u_3	0	21,240	0	0	41,070	62,310
Route profits/10,000 yuan	84,760	21,240	85,020	35,000	76,680	302,700

Table 7
Comparison of profits for each carrier before and after cooperative transportation

Carriers	Operating route	Participating paths	Non-cooperative	Cooperative (Undistributed)	Cooperative (distributed)
u_1	2	7	40,000	75,000	75,976
u_2	3	13	81,600	158,400	164,414
u_3	2	7	33,000	63,900	62,310
Total	5	19	11,8600	302,700	302,700

transportation mode, the total profit has significantly increased to 302,700 yuan, representing a growth of 155.23% compared to operating independently. This substantial profit increase aligns with the primary objective of the cooperative transportation alliance.

It is notable that Carrier u_2 experienced the largest profit increase of 101.49%. This is because Carrier u_2 operates three routes that contribute to completing 13 travel paths, accounting for 68.42% of the total paths in the transportation network. As the most significant contributor in the alliance, Carrier u_2 benefits the most from the cooperative mode.

In the cooperative transportation model, downstream routes transfer a portion of their profits to upstream routes to maintain the alliance. As a result, Carrier u_1 and Carrier u_3 operate the same number of routes and participate in the same number of paths after cooperation. In the current direction, Carrier u_3 experienced a profit increase of 88.81%, slightly lower than the 89.94% increase for Carrier u_1. However, in two-way transportation, the profit increase situation will be reversed, achieving a balanced profit distribution. This balanced distribution of profits helps to maintain the cooperative alliance and ensures that all participants are equally incentivized to continue their cooperation.

Overall, the research findings demonstrate the potential benefits of cooperative transportation alliances in increasing profits for participating carriers. Additionally, the results indicate the importance of carefully considering the allocation of benefits to achieve a fair and sustainable cooperative transportation model. By optimizing profit distribution, cooperative transportation alliances can foster a stable and mutually beneficial environment for all participants.

6. Conclusion

By applying cooperative game theory, the integration of railway and water transport has successfully transformed the previous competitive relationship between carriers into a more collaborative and profit-sharing alliance. The maintenance and sustainability of such a cooperative alliance depend on the establishment of a fair and reasonable mechanism for allocating the benefits generated through cooperation. This paper introduces the structural relationship between routes into the construction of a profit allocation model based on cooperative game theory.

The case study results demonstrate the effectiveness of the proposed model in ensuring that carriers with higher contribution levels receive a greater share of the profits. The model also achieves a balanced allocation of profits between transportation flows in both directions. Furthermore, the allocation results can be easily adjusted by changing the weights, showcasing the model's versatility, rationality, and fairness in accommodating different scenarios and preferences.

The use of cooperative game theory has proven instrumental in fostering cooperation and enhancing the intermodal transportation system's overall efficiency and profitability. Through the application of this theoretical framework, the competitive dynamics have been replaced by a more harmonious and mutually beneficial profit-sharing relationship among carriers.

Moving forward, policymakers and stakeholders in the intermodal transportation industry can draw valuable insights from this research to promote and encourage further collaboration and the establishment of cooperative alliances. By ensuring a fair and reasonable allocation of benefits, such alliances are more likely to endure and flourish, ultimately contributing to the continued growth and development of intermodal transportation in China.

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Data availability statement

There are no available data associated with the manuscript.

Conflicts of interest

The authors declare no conflicts of interest.

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