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Empty container leasing and channel coordination in a Dual-Channel container transportation service chain based on joint contracts

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ABSTRACT

In this paper, we study the empty container leasing decision and coordination problem of dual-channel container transportation service chain (DCCTSC) under stochastic demand in the presence of financial constraints of the carrier. First, we introduce the advance payment financing mode to solve the capital constraint problem of the carrier and analyze the optimal empty container leasing strategies under decentralized and centralized modes respectively. Then, we design a joint contract with advance payment financing parameters to coordinate the DCCTSC and discuss the conditions for contract enforceability. Finally, we verify the validity of the proposed model and coordination mechanism as well as the effects of contract and financing parameters on the DCCTSC through numerical examples. The results of the study show that the joint contract can effectively coordinate the DCCTSC and increase the total system profit by 5.23 % at most. The combination of contract parameters is flexible, and the adjustment of contract and financing parameters only changes the profit distribution between members and does not affect the coordination of the overall system

1. Introduction

In the traditional shipping market, carriers are the main providers of container transport services. Forwarders are intermediaries between carriers and consignors, providing value-added services. Carriers complete canvassing through forwarders, and consignors entrust forwarders to handle shipping procedures to meet their shipping needs. That means forwarders are the main canvassing subjects of traditional canvassing channel in the traditional container transportation service system (Tongzon, 2009). However, as the status of the carrier in the container transportation service chain continues to rise, to strive for more cargoes, the carrier has proactively established subsidiaries engaged in freight transportation to directly provide shipping services to consignors. For example, Maersk owns DAMCO Global Logistics, a subsidiary that canvassing for it, American President Lines (APL) owns APL Logistics, and China Ocean Shipping Company (COSCO) owns COSCO International Freight Company. In this way, a direct channel for carriers to canvass for cargoes is formed. Therefore, the development of carriers presents two trends: On the one hand, carriers choose suitable forwarders and enhance the ability of traditional channels to canvass for cargoes by strengthening the partnership with forwarders to encourage them to canvass for cargoes from the cross-economic hinterland of competitors to compensate for their own shortcomings, which is the basis for ensuring carriers development. On the other hand, carriers actively build their own direct cargo subsidiaries, effectively expand their direct economic hinterland and strengthen the canvassing ability of direct channels to provide convenient multimodal transport services for consignors in the hinterland (Xie, Liang, Ma, & Yan, 2017). The development of these two types of channels has given rise to the present development of the dual-channel container transportation service chain (DCCTSC).

Obviously, the DCCTSC has many advantages. For example, based on the close relationship between carriess and ports, the freight department of carriers can conveniently manage the loading and unloading, storage, and transfer of cargoes through direct channels, providing customers with excellent full-course services and shortening the transportation time. Traditional channels can not only expand the economic hinterland of carriers to canvass for cargoes but can also effectively reduce the competitive pressure of the freight forwarding industry through cooperation between carriers and forwarders. Although the DCCTSC has achieved complementarity in terms of cargo sources, there are still many problems in the actual integration and coordination process. Compared

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with single channel, the relationship between carriers and forwarders in the DCCTSC has undergone tremendous changes. First of all, carriers are the upstream of forwarders. Carriers and forwarders will give priority to their own interests, which will harm the overall interests of the container transportation service chain, resulting in a "double marginal effect". Secondly, carriers are also competitors of forwarder, that is, the relationship between carriers and forwarders is a horizontal parallel. At this time, carriers and forwarders are equal to customers but have independent interests, which will easily cause channel conflicts. This special relationship between channel members makes the contradictions in the interests of the members of the container transportation service chain more prominent. To solve the problems of the DCCTSC and better realize the seamless connection of the two channels and the advantages this approach delivers, it is necessary for the members of each channel to cooperate more closely. Therefore, how to use contracts to resolve conflicts in the DCCTSC so as to highlight the advantages of each channel and increase the benefits of the service chain as a whole and of each member is an urgent issue to be solved.

In order to meet the market demand, carriers and forwarders usually prepare a certain amount of empty containers through leasing before the demand occurs. So that after the demand occurs they can use the pre-prepared empty containers to load cargoes to complete the container transport. Generally speaking, the number of empty containers in a fixed shipping area for a fixed period of time is usually fixed. Therefore, an unreasonable amount of empty containers may cause carriers and forwarders to suffer from the risk of backlog or shortage of empty containers in a short period of time. The dual-channel scenario is also accompanied by instability in shipping demand. And because of the complex relationship of cooperation and competition between carriers and forwarders, information often has asymmetry, so the risk of waste of empty containers and the risk of loss of opportunity cost are greater in the DCCTSC, and the difficulty of empty container leasing decision of carriers and forwarders is higher, that is, the unreasonable allocation of resources is more likely to cause huge losses. Therefore, before the container transportation demand occurs, reasonable planning of empty container leasing quantity by carriers and forwarders is of extraordinary significance to the intensive use of empty containers as well as to enhance the overall revenue of each member and DCCTSC.

Furthermore, under the situation of increasingly fierce competition in the shipping market, when carriers choose the dual-channel canvassing mode, it means that they need to explore the market, then the potential market demand will increase and carriers need to lease more empty containers to meet the growing demand. In this case, the carrier's own capital is often not enough to support the whole operation process, which leads to the phenomenon of untimely supply of empty containers or insufficient quantity of empty containers, thus affecting the normal canvassing of downstream forwarders. Therefore, it is necessary to consider the financial constraints of carriers in the DCCTSC. Its importance is mainly reflected in: (1) To ensure that carriers make optimal operational decisions and avoid carriers from affecting customer satisfaction of direct channels or losing cooperative forwarders due to financial constraints. (2) To ensure that forwarders make optimal operational decisions and avoid the risk of interruption of forwarders' canvassing due to insufficient funds of carriers. (3) To provide a basis for the DCCTSC to achieve coordination and avoid carriers and forwarders from being unable to fulfil the contract due to insufficient funds of carriers, and thus unable to achieve coordination. When faced with greater financial pressure, carriers can choose to apply for loans from banks or accept advance payments provided by forwarders downstream in the container transport service chain to solve the problem of insufficient funds. In contrast to bank loans, advance financing is a type of internal supply chain financing, and its cost is lower, so this method is widely adopted by enterprises in the supply chain (Zhao & Huchzermeier, 2019). Similarly, if the DCCTSC is to be harmonised, the problem of insufficient funding for carriers must first be addressed. Forwarders use advance payment internal financing mode not only can quickly and inexpensively fill the gap of the carrier's funds, and will not cause the outflow of revenue from the DCCTSC system. In essence, a suitable contractual mechanism enables a DCCTSC considering prepayment financing to achieve the optimal state of the service chain system without financial constraints. In addition, carriers are in a relatively strong position in the container transportation service chain. Therefore, for the purpose of controlling cash flow risks, carriers can also require downstream forwarders to adopt the method of advance payment. In general, since the problem of financial constraints of carriers and coordination of DCCTSC has a wide practical background, it is an important research topic worthy of attention to design a scientific, reasonable and effective contract to achieve coordination of DCCTSC while considering advance payment financing.

Based on this, we combine the supply chain financing problem with the DCCTSC empty container decision and coordination problem in the presence of stochastic demand. Specifically, our research is divided into four steps. We first introduce the advance payment financing mode to solve the problem of carrier capital constraints. Then, based on the carrier being the leader, we analyze the optimal empty container inventory decision of the DCCTSC under the decentralized and centralized modes. Next, we design a reasonably joint contract coordination mechanism containing advance payment financing parameters, so that the sum of profits under decentralized decision of carriers and forwarders is equal to the optimal profit under centralized decision when contract parameters and financing parameters meet specific conditions, i.e., the DCCTSC achieves a coordinated state. Lastly, we analyze the conditions that need to be satisfied for the combination of contract parameters when each member is able to achieve Pareto improvement, i.e., how to make the joint contract enforceable.

The contributions of this paper can be summarized as follows: (1) We consider both the traditional canvassing channel and direct canvassing channel of carriers, and introduce the coordination problem existing in the traditional dual-channel supply chain into the container transportation service chain, i.e., we study the DCCTSC. By considering the cooperation and coordination between carriers and forwarders, we formulate the empty container decision that makes the DCCTSC system optimal as a whole, which provides new ideas for carriers and forwarders in canvassing and leasing empty containers. (2) We apply the supply chain contract coordination theory to the problem of empty container leasing and channel coordination between upstream and downstream subjects of DCCTSC. On the basis of the beneficial results of traditional supply chain collaboration management, we design a joint contract to study the theory related to the coordination of container transportation service chain by combining the characteristics of DCCTSC, which expands the application scope of the existing traditional supply chain contract coordination theory. (3) We study the problem of planning empty container resources in a decentralized system without a central planner. We consider from the perspective of external decision making, treating the participating collaborating subjects as independent individuals making empty container decisions separately, and achieve the overall optimization of empty containers by considering the synergy among the participating subjects in the DCCTSC.

2. Literature review

This paper reviews the literature relating to three main areas: dual-channel supply chains, maritime transport chains and supply chain contracts.

Much of the research on dual-channel supply chains over the last decade has been approached from the perspective of operational decisions such as pricing and inventory, most of which have focused on channel selection and channel coordination. Chiang (2010) analyzed the optimal inventory levels for the two channels when both intra-channel and inter-channel conflicts occur simultaneously, and coordinated the dual-channel supply chain when multiple conflicts coexist through a contract. Xiao and Shi (2016) examined the impact of the coordination state of a dual-channel supply chain on channel selection in the case of supply shortages, and explored the role of decentralization. Xu, Wang, et al. (2018) studied the pricing strategy of a multi-channel supply chain in a low-carbon environment and designed the corresponding contract to achieve Pareto improvement for the chain members. Finally, they provided suggestions for the government to formulate relevant environmental policies. Modak and Kelle (2019) designed special contracts to coordinate a dual-channel sales system under stochastic market demand with unknown distribution functions. They also provided managerial insights into the wholesale price decisions of internet channel and the selling price strategies of two channels. Zhang, Liu, and Niu (2020) explored the coordination of member profits in a dual-channel supply chain for dual-channel supply chain with salvage recycling and dual-channel supply chain with scrap recycling based on the type of returned product, and analyzed the impact of product quality on this type of supply chain. Asl-Najafi, Yaghoubi, and Zand (2021) discussed how to rationally allocate the quantity of products between the two channels when manufacturers' output is random and investigated how to coordinate the dual-channel supply chain through contracts when there is a shortage of output. Gao, Xiao, and Wei (2021) analyzed the decision-making steps of each member of the green dual-channel supply chain with the goal of maximizing environmental benefits and profits, and coordinated the profits of the chain members. Finally, guidance is provided for the government to guide each member of the supply chain to comply with environmental regulations. Zheng, Chu, and Jin (2021) classified closed-loop dual-channel supply chains into three categories based on recycling agents, and then designed price contracts consisting of wholesale prices, direct channel prices, and transfer prices to coordinate these three types of dual-channel supply chains, and analyzed the optimal recycling channels for manufacturers under different scenarios. Mu, Kang, and Zhang (2022) proposed an improved two-part credit contract considering asymmetric information for studying the operational planning and coordination of a dual-channel supply chain based on credit sales model under uncertain demand. The results showed that the improved contract can mitigate channel conflicts due to credit sales. Lin, Liu, Peng, and Lee (2023) solved a bi-objective optimization problem of production and distribution decisions in a multi-layered dual-channel supply chain by designing an improved algorithm combining the nondominated sorting genetic algorithm II and the lion pride algorithm. The results showed that their proposed altruistic pricing strategy effectively increased the revenue share of retailers and weakened the channel conflict in this multi-layer dual-channel system. Zhao and Li (2023) divided the market into regular and pre-sale markets, and then investigated the problem of coordinating a dual-channel supply chain that includes an advance sale phase and a regular sale phase, taking into account the factor of discounted sales. In addition, scholars have discussed the case of financial constraints. Zeng, Gong, and Xu (2019) studied the optimal inventory decisions of wholesalers in a dual-channel e-commerce supply chain with capital constraints for online retailers and analyzed the selection conditions for each of the traditional online channels and online direct channels. Zhen, Shi, Li, and Zhang (2020) explored the impact of third-party platform financing and retailer financing on the operational decisions of manufacturers in a dual-channel system with manufacturers' financial constraints. Pei, Li, and Liu (2022) addressed the equilibrium financing problem for manufacturers with capital constraints in a dual-channel supply chain under an uncertain demand scenario where only part of the demand distribution is known. Xu, Tang, Lin, and Lu (2022) realized the coordination of the dual-channel supply chain with four factors including channel preference, sales effort, supplier free-riding behavior and cross-channel return by contract, in the presence of financial constraints for retailers.

As shown in Table 1, we compare this study with the related literature on dual-channel supply chains. The abovementioned research on dual-channel supply chains is primarily concerns with channel design, channel conflict and coordination, and most of them are solved by contract coordination mechanism and game theory. The methods used and the results achieved in these works are mature in dealing with inventory conflicts between multiple channels and channel coordination, and these works also have similarities with the problems studied in this paper. For example, these early works laid the groundwork for this study in terms of contract design. In addition, some financing methods when members have financial constraints are of reference value. Therefore, we

Table 1
Comparisons between this study and the related literature regarding dual-channel supply chains.

Reference	Channel type	Chain member	Decision	Stochastic demand	Capital constraint	Contract coordination mechanism
Chiang (2010)	T & DO	A manufacturer, a retailer	Inventory and channel coordination	✓		✓
Xiao and Shi (2016)	T & DO	A manufacturer, a retailer	Channel selection			
Xu, Wang, et al. (2018)	T & DO	A manufacturer, a retailer	Pricing and channel coordination			✓
Modak and Kelle (2019)	T & DO	A manufacturer, a retailer	Pricing and channel coordination	✓		✓
Zhang et al. (2020)	T & DO	A manufacturer, a retailer	Pricing and channel coordination			✓
Asl-Najafi et al. (2021)	T & D	A manufacturer, a retailer	Channel selection and channel coordination			✓
Gao et al. (2021)	T & DO	A government, a manufacturer, a retailer	Pricing and channel coordination			✓
Zheng et al. (2021)	T & D	A manufacturer, a retailer	Channel selection and channel coordination			✓
Mu et al. (2022)	T & DO	A supplier, a retailer	Channel coordination	✓		✓
Lin et al. (2023)	T & DO	Multiple suppliers, a manufacturer, multiple retailers	Production and channel coordination	✓		
Zhao and Li (2023)	T & DO	A manufacturer, a retailer	Pricing and channel coordination			✓
Zeng et al. (2019)	TO & DO	A wholesaler, multiple online retailers	Inventory and channel selection	✓	✓	
Zhen et al. (2020)	T & DO	A manufacturer, a retailer	Financing		✓	
Pei et al. (2022)	T & DO	A manufacturer, a retailer	Pricing and financing	✓	✓	
Xu et al. (2022)	T & DO	A manufacturer, a retailer	Pricing and channel coordination		✓	✓
This study	T & D	A carrier, a forwarder	Inventory, financing and channel coordination	✓	✓	✓

*T: Traditional, TO: Traditional online, D: Direct, DO: Direct online.

extend traditional mature dual-channel supply chain research to the DCCTSC, which provides a new means for carriers and forwarders to reasonably plan empty container inventory, canvass through dual channels and achieve coordination between the two canvassing channels.

The second hot topic relevant to our research is maritime transport chain. Most relevant research focuses on operational decisions and capacity planning. Liu, Jiang, Liu, and Geng (2013) discussed the optimal leasing strategies based on call options and put options in terms of two types of situations: peak shipping season and low shipping season. Li and Zhang (2015) demonstrated that capacity reservation is a beneficial strategy for all members of a shipping system consisting of carriers and competing freight forwarders. Wang et al. (2020) discussed the integrated scheduling strategy of the port-centric maritime supply chain. There is relatively less literature focusing on port competition and liner alliances. Song, Lyons, Li, and Sharifi (2016) examined the best joint pricing decision of ports and shipping companies when ports has competition in the hinterland transportation and transshipment process. Wang, Zhuo, Niu, and He (2017) discussed who should canvass for cargoes to create a win–win scenario in the shipping supply chain when shipping companies form an alliance. Liu and Wang (2019) discussed the value of carrier alliances in different scenarios and designed effective contracts to coordinate maritime transport chains in the presence of carrier competition. Trapp, Harris, Rodrigues, and Sarkis (2020) considered cooperation and competition in the maritime market while considering environmental factors, and developed a joint competition planning model among multi-container retailers to evaluate the feasibility of cooperation and competition. Luo, Chang, and Xu (2021) introduced option contracts into the container transportation chain to study the horizontal coordination strategy among freight forwarders. On this basis, they proposed an option trading scheme and demonstrated that option trading can further promote the cooperation among forwarders. There are also researches that use empty containers as a decision variable to study the maritime transport chain. Li, Leung, Wu, and Liu (2007) devised a heuristic algorithm that shows how decision makers can allocate the right number of empty containers among multiple ports at the right time to reduce the average cost. Zheng, Sun, and Gao (2015) studied empty container allocation problem while taking into account the problem of coordination among liner companies. They proposed a two-stage optimization approach combining collective and inverse optimization to solve this combinatorial problem, and based on this, they weighed the subjective perceptions of customers in different ports regarding the value attached to transportation services. Myung (2017) designed a more effective integer planning model for empty container repositioning in hinterland transportation networks based on four classical empty container repositioning models proposed by predecessors. Lu, Lee, and Lee (2020) used a stochastic dynamic programming model to study the joint decision of pricing and empty container repositioning in a two-location shipping service with stochastic shipping demand. Mehrzadegan, Ghandehari, and Ketabi (2022) proposed a new slot allocation model with the goal of maximizing total profit in a limited period of time, which is used to plan liner company's full containers and empty containers, and thus influence the liner's transportation decisions.

As shown in Table 2, we compare this study with the related literature on maritime transport chain. As can be seen, firstly, the focus of these studies is on the operational and strategic decisions in a single-channel maritime service chain. For example, cooperation and integration among ports, shipping alliance strategies and performance evaluation, etc. Almost no literature considers both traditional canvassing channels and direct canvassing channels of carriers, which means that the research on dual-channel container shipping service chains is almost nonexistent. Secondly, the research on operational decision making in maritime service chain mainly focuses on empty container resource decision making. Most of these early works were internal resource combination optimization problems of a single subject, usually based on centralized mode considerations, using dynamic, linear or integer programming methods in operations research to formulate the objective function and constraints and build the corresponding mathematical model. They center on designing new heuristic algorithms or improving existing ones and using various simulation software to find the optimal or near-optimal solution of the model. At present, there is little literature on container resource management in a decentralized mode, and there is almost no research on the overall optimization of container resources by considering the collaboration among various participants from the perspective of container transportation service chain. In summary, we take the DCCTSC as the research object, from the perspective of considering the cooperation and coordination between the upstream and downstream members of the chain (i.e., the decentralized mode) to formulate the optimal empty container decision for the whole system, which can fill a part of the gap of this kind of research.

Supply chain contracts have been extensively studied by a vast number of scholars and some results have been achieved. Contracts connect the upstream and downstream node members of the supply chain and influence the revenue boundary of supply chain operation decisions. Typical supply chain contract mechanisms include: wholesale price contracts (Nouri, Hosseini-Motlagh, Nematollahi, & Sarker, 2018; Hosseini-Motlagh, Govindan, Nematollahi, & Jokar, 2019), revenue-sharing contracts (Zhao, Chen, & Gong, 2019; Adnan & Özelkan, 2020), buyback contracts (Zhao, Choi, Cheng, Sethi, & Wang, 2014; Farhat, Akbalik, Hadj-Alouane, & Sauer, 2019), and quantity discount contracts (Heydari, Govindan, & Jafari, 2017, Zissis, Saharidis, Aktas, & Ioannou, 2018). Since a reasonable contractual coordination mechanism is the key to solving channel problems, some other scholars have examined how to coordinate channel conflicts in dual-channel supply chains using various types of traditional contract mechanisms. Chen,

Table 2
Comparisons between this study and the related literature regarding maritime transport chains.

Reference	Channel structure		Organization		Demand	
	Single-channel	Dual-channel	Centralized mode	Decentralized mode	Determining demand	Stochastic demand
Liu et al. (2013)	✓			✓		✓
Li and Zhang (2015)	✓			✓	✓	
Wang et al. (2020)	✓		✓			✓
Song et al. (2016)	✓			✓		✓
Wang et al. (2017)	✓			✓	✓	
Liu and Wang (2019)	✓			✓	✓	
Trapp et al. (2020)	✓		✓			✓
Luo et al. (2021)	✓			✓		✓
Li et al. (2007)	✓		✓			✓
Zheng et al. (2015)	✓		✓		✓	
Myung (2017)	✓		✓			✓
Lu et al. (2020)	✓		✓			✓
Mehrzadegan et al. (2022)	✓		✓			✓
This study		✓		✓		✓

Zhang, and Sun (2012) examined pricing decisions while considering the coordination between channels and further discussed the conditions under which manufacturers and retailers would prefer a dual-channel mode of operation. Xu, Dan, Zhang, and Liu (2014) discussed the pricing strategies of dual-channel supply chains under decentralized and centralized modes respectively, taking into account risk aversion factors, and analyzed how risk resilience would affect the pricing strategies under different modes, and thus how it affects the coordination process. Feng, Govindan, and Li (2017) studied the recycling supply chain of waste electronic devices, proposed a dual-channel scheme with parallel online and offline recycling, and designed an effective contract to coordinate this dual recycling channel. From the perspective of environmental protection, Xu, Qi, et al. (2018) explored the impact of the government's supervision of carbon emissions on the two-channel supply chains, and applied the price discount contract to online and traditional channels separately, and finally obtained the optimal coordination scheme by comparison. In the context of uncertain manufacturer output and stochastic customer demand, Zhu, Wen, Ji, and Qiu (2020) combined with the risk aversion behavior of downstream members of the supply chain to discuss whether joint contract can successfully coordinate such dual-channel supply chains and gave the conditions that need to be satisfied to achieve Pareto improvement under the decentralized mode. Xu, Zhang, and He (2020) considered a new factor, that is, the power of e-commerce platforms to expand the consumer market. They integrate this factor with the traditional dual-channel supply chain coordination problem to explore how this factor influences each member to achieve a coordinated state and demonstrated it with an actual case.

As shown in Table 3, we compare this study with the related literature on supply chain contracts. Regarding the research on supply chain contracts, scholars have usually extended the basic contract models from the dimensions of demand curve fluctuation, multi-stage decision making, and information asymmetry, and designed various derived and improved contract models or joint contract models according to various practical application scenarios to improve supply chain performance and revenue. However, most of these changes have been studied in traditional product supply chains, and few studies have applied contract coordination theory to issues such as empty container leasing and dual-channel coordination in container service supply chains in the context of shipping. This study not only applies the contract coordination theory to the coordination problem of the DCCTSC, but also considers the financial constraints of carriers on this basis, which expands the application scenario of contract coordination theory.

3. Problem description

In this article, we discuss the coordination of the DCCTSC. Consider a container transportation service chain that canvasses for cargoes through a dual-channel system, in which there are a carrier and a forwarder. The carrier prepares empty containers by leasing from the container leasing company to meet the freight demand in the market. The carrier occupies the dominant position in the DCCTSC. On the one hand, the carrier collects the freight demand in the market through the forwarder to complete canvassing, which is called the traditional channel. On the other hand, the carrier canvasses for cargoes directly through its own freight subsidiary, which is the direct channel. In the traditional channel, the carrier is upstream of the forwarder and the relationship between them is cooperative. When the direct channel is considered, the relationship between the carrier and the forwarder has changed from a single cooperative to a coexistence of cooperation and competition. We assume that the market demand is random, and the market demand is divided into traditional channel demand and direct channel demand according to different channels. Due to the existence of channel competition in the DCCTSC, customers will transfer between the two channels according to the specific supply and demand conditions of the channels. When the carrier has capital constraints, the forwarder takes advance payments to fill its financial gap. Fig. 1 illustrates an overview of the DCCTSC.

The subscripts f and t represent the forwarder and the carrier respectively. Table 4 lists the variables and parameters we use in this paper.

The parameters in the above table need to satisfy $p_f > w > c_f > s_f$ and $p_t > c_t > s_t$, which ensures that both the carrier and the forwarder are profitable. When customer demand switching is not considered, the traditional channel and the direct channel face random demand $\widehat{Df}$ and $\widehat{Dt}$ respectively, and they are independent of each other. Their probability density functions and cumulative distribution functions are denoted as $f(x)$, $g(y)$ and $F(x)$, $G(y)$.We assume that the distribution functions are continuously differentiable and increasing. When considering customer demand switching, there are two scenarios. First, when the traditional channel is short of containers, consignors will switch to the direct channel at a ratio of λ_f. Second, when the direct channel is short of containers, customers will switch to the traditional channel at a ratio of λ_t. The actual demand functions of the two channels after considering the customer demand switching between channels can be written as $D_f = \widehat{Df} + \lambda_t(\widehat{Dt} - q_t)^+$ and $D_t = \widehat{Dt} + \lambda_f\left(\widehat{Df} - q_f\right)^+$, respectively. The empty containers leased by the carrier or forwarder will give priority to meeting the demands of their own channel and then consider whether there are remaining empty containers that can meet the demands transferred from the other channel, i.e., $\left(p_f - s_f + g_f\right) \geqslant \lambda_f\left(p_t - s_t + g_t\right)$ and $\left(p_t - s_t + g_t\right)\rangle\lambda_t\left(p_f - s_f + g_f\right)$.

Table 3
Comparisons between this study and the related literature regarding supply chain contracts.

Reference	Supply chain type		Channel structure		Contract type	
	Traditional product supply chain	Maritime supply chain	Single-channel	Dual-channel	Single contract	Joint contract
Nouri et al. (2018)	✓		✓		✓	
Hosseini-Motlagh et al. (2019)	✓		✓		✓	
Zhao et al. (2019)	✓		✓		✓	
Adnan and Özelkan (2020)	✓		✓		✓	
Zhao et al. (2014)	✓		✓		✓	
Farhat et al. (2019)	✓		✓		✓	
Heydari et al. (2017)	✓		✓		✓	
Zissis et al. (2018)	✓		✓		✓	
Chen et al. (2012)	✓			✓	✓	
Xu et al. (2014)	✓			✓	✓	
Feng et al. (2017)	✓			✓		✓
Xu, Qi, et al. (2018)	✓			✓	✓	
Zhu et al. (2020)	✓			✓		✓
Xu et al. (2020)	✓			✓		✓
This study		✓		✓		✓

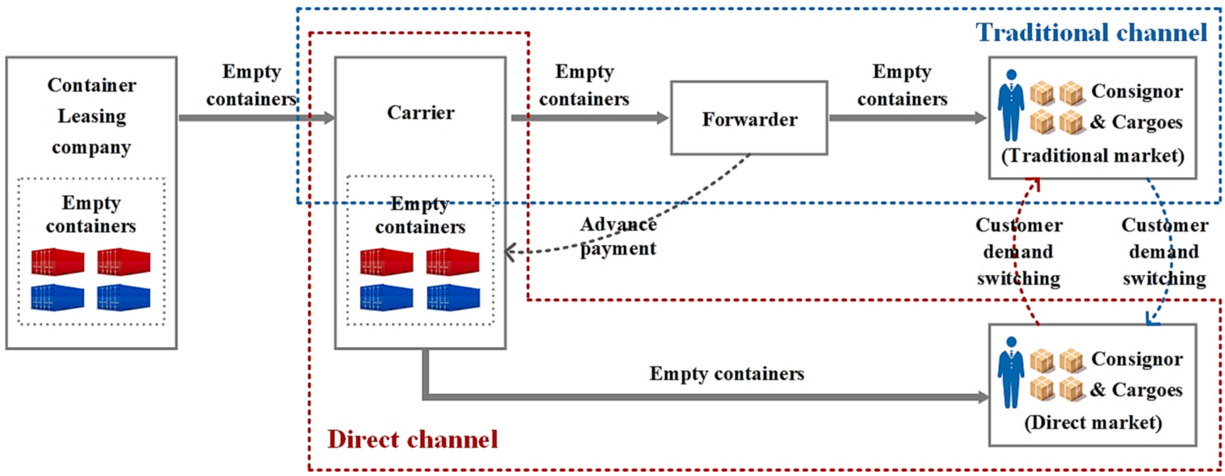

Fig. 1. Structure of the DCCTSC.

Table 4
Notations.

Notation	Explanation
Variables:	
$D\hat{f}$	The demand of traditional channel when demand switching is not considered
$D\hat{t}$	The demand of direct channel when demand switching is not considered
D_f	The demand of traditional channel when considering demand switching
D_t	The demand of direct channel when considering demand switching
q_f	The quantity of empty containers leased by the forwarder in the traditional channel
q_t	The quantity of empty containers leased by the carrier in the direct channel
Parameters:	
Π_f^0	The profit of the forwarder in the decentralized mode
Π_t^0	The profit of the carrier in the decentralized mode
Π_f	The profit of the forwarder under the improved revenue sharing and buyback joint contract
Π_t	The profit of the carrier under the improved revenue sharing and buyback joint contract
Π_c	The profit of the DCCTSC in the centralized mode
p_f	The unit canvassing price for the forwarder in the traditional channel
p_t	The unit canvassing price for the carrier in the direct channel
w	The unit wholesale price of empty containers ordered by the forwarder from the carrier
c_f	The unit leasing cost of empty containers for the carrier in the traditional channel
c_t	The unit leasing cost of empty containers for the carrier in the direct channel
s_f	The unit salvage value of empty containers for the forwarder in the traditional channel
s_t	The unit salvage value of empty containers for the carrier in the direct channel
g_f	The unit penalty cost of empty containers for the forwarder in the traditional channel
g_t	The unit penalty cost of empty containers for the carrier in the direct channel
λ_f	The transfer rate of customers switching from the traditional channel to the direct channel
λ_t	The transfer rate of customers switching from the direct channel to the traditional channel
r_t	The price discount offered by the carrier to the forwarder
B	Funds owned by the carrier
L	The scale of financing provided to the carrier by the forwarder

When the carrier has capital constraints, i.e., $B < c_f q_f + c_t q_t$, insufficient funds will affect the quantity of empty containers leased and thus undermine the interests of all members of the container transport service chain. In this case, the dominant carrier will adopt forwarder advance payment financing to solve its capital shortage problem. Therefore, the situation studied in this paper is as follows: When the forwarder adopts the advance payment method, the carrier gives it a certain price discount r_t, and $0 \leqslant r_t \leqslant (w - c_f)/c_f$. In addition, it is assumed that the forwarder can not only meet the demand of its own channel but also ensure that the carrier with capital constraints has sufficient funds to lease empty containers, i.e., $B \geqslant \left[c_f q_f + c_t q_t - w q_f/(1+r_t)\right]^+$.

The operation process of the whole DCCTSC is as follows: First, at the beginning of the service lead time t_0, the carrier determines the number of empty containers q_t to lease in the direct channel based on the forecast of market demand, and the forwarder determines the number of empty containers q_f to lease in the traditional channel according to q_t and pays the advance payment $L = c_f q_f + c_t q_t - B$ to the carrier. After receiving the advance payment, the carrier pays the container leasing company the total leasing fee for the empty containers required for the two channels and obtains $q_f + q_t$ empty containers. At the beginning of the selling season t_1, the carrier first delivers empty containers $(1+r_t)L/w$ to the forwarder, who then leases the remaining required empty containers from the carrier at wholesale price w. We illustrate decision sequence of the carrier and the forwarder in Fig. 2 (service lead time: from t_0 to t_1, selling season: from t_1 to t_2). We build the decentralized and centralized models of the DCCTSC based on such operational process respectively. Among them, the decentralized model is to treat the carrier and the forwarder as two independent individuals making separate empty container decisions in the absence of a central planner. The centralized model is to consider the carrier and the forwarder as a whole, and this whole acts as the central planner to make the overall appropriate empty container decision.

4. Model formulation

In this section, we first analyze the decision makers' respective profit-maximizing empty container decisions in the decentralized mode, and then determine the optimal decision that makes whole optimal in the centralized mode as the best benchmark.

4.1. Decentralized model

In this section, we discuss the empty container leasing model of the DCCTSC in the decentralized mode. When considering customer demand switching between channels, there are six demand cases for the two channels, as shown in Fig. 3.

Let Q_f denote the actual demand satisfied by the forwarder in the traditional channel: $Q_f = E\min\left\{q_f, D_f\right\}$. Let I_f denote the extra empty containers of the forwarder: $I_f = E\left(q_f - D_f\right)^+$. Let U_f denote the un-

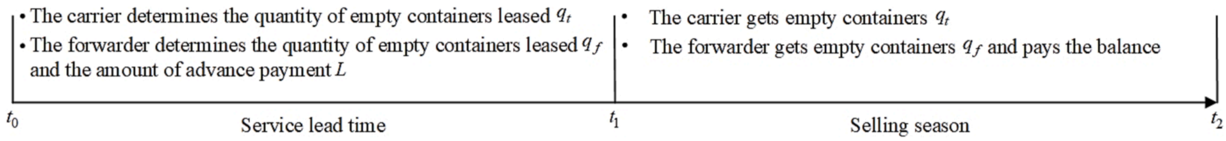

Fig. 2. The decision sequence of the carrier and the forwarder.

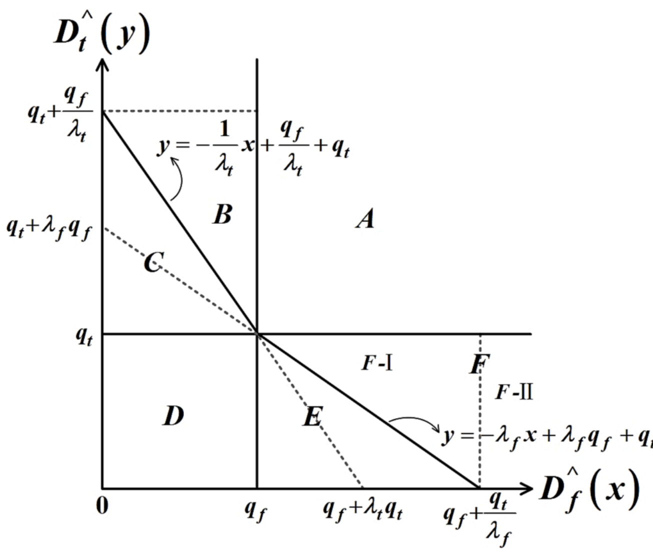

Fig. 3. The demand distribution of the forwarder and carrier with customer demand switching.

satisfied demand of the forwarder: $U_f = E\left(D_f - q_f\right)^+$. For the carrier, we define the actual satisfied demand, extra empty containers and unsatisfied demand as $Q_t = E\min\{q_t, D_t\}$, $I_t = E(q_t - D_t)^+$, and $U_t = E(D_t - q_t)^+$, respectively.

For the six demand cases shown in Fig. 3, the value of each parameter is shown in Table 5. We use case E as an example to show how these values are set. In case E, we have $\widehat{Df} > q_f$, so the actual demand of the forwarder can be obtained as $D_f = \widehat{Df} = x > q_f$; thus, it is easy to obtain $Q_f = q_f$, $I_f = 0$, and $U_f = D_f - q_f = x - q_f$. Similarly, it can be seen from the figure that $\widehat{Dt} < q_t$, so the actual demand of the carrier is $D_t = \widehat{Dt} + \lambda_f\left(\widehat{Df} - q_f\right) = y + \lambda_f\left(x - q_f\right)$. Additionally, since case E satisfies $y < -\lambda_f x + \lambda_f q_f + q_t$, we can obtain $q_t > y + \lambda_f x - \lambda_f q_f = D_t$, and then it is easy to obtain $Q_t = D_t = y + \lambda_f\left(x - q_f\right)$, $I_t = q_t - D_t = q_t - y - \lambda_f\left(x - q_f\right)$, and $U_t = 0$.

In the decentralized model, the revenue of the forwarder comes from the retail revenue of the traditional channel, the salvage value of the extra empty containers and the price discount due to the advance payment adopted by the forwarder, and the costs are mainly the goodwill penalty cost caused by out of stock and the order cost of empty containers. The revenue of the carrier consists of the retail revenue of the direct channel, the salvage value of the remaining empty containers and the wholesale revenue of the traditional channel, and the main costs include the empty container leasing cost of two channels and the financing cost incurred by providing price discount. Thus, the profit function of the forwarder and carrier in the decentralized mode can be described as:

$$\Pi_f^0(q_f, q_t) = p_f E\min(q_f, D_f) + s_f E(q_f - D_f)^+ - g_f E(D_f - q_f)^+ - wq_f + r_t\left(c_f q_f + c_t q_t - B\right) \tag{1}$$

$$\Pi_t^0(q_f, q_t) = p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+ + wq_f - \left(c_f q_f + c_t q_t\right) - r_t\left(c_f q_f + c_t q_t - B\right) \tag{2}$$

Proposition 1. *In the DCCTSC considering advance payment financing provided by the forwarder, there exists $q_t^{0*} = \underset{q_t^0 \in S}{\arg\max}\, \Pi_t^0\left(q_t^0\right)$ such that the optimal empty container leasing quantity of the forwarder and carrier is denoted as $\left(q_f^{0*}, q_t^{0*}\right)$.*

We obtain the first-order derivative and the second-order derivative of the forwarder's profit function based on Leibniz's law as follows:

$$\begin{aligned}\frac{\partial \Pi_f^0(q_f, q_t)}{\partial q_f} = &-(p_f - s_f)\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx - (p_f - s_f)\int_0^{q_f} \\ &\times \int_{q_t}^{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t} f(x)g(y)dydx + g_f\int_{q_f}^{\infty}\int_0^{q_t} f(x)g(y)dydx + g_f\int_{q_f}^{\infty} \\ &\times \int_{q_t}^{\infty} f(x)g(y)dydx + g_f\int_0^{q_f} \\ &\times \int_{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t}^{\infty} f(x)g(y)dydx - w + p_f + r_t c_f\end{aligned} \tag{3}$$

$$\begin{aligned}\frac{\partial^2 \Pi_f^0(q_f, q_t)}{\partial q_f^2} = &-(p_f - s_f + g_f)\int_0^{q_t} f(q_f)g(y)dy - \frac{1}{\lambda_t}(p_f - s_f \\ &+ g_f)\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx\end{aligned} \tag{4}$$

It is clear that $\frac{\partial^2 \Pi_f^0(q_f, q_t)}{\partial q_f^2} \leqslant 0$, i.e., the profit of forwarder Π_f^0 is strictly

Table 5
Values of parameters in different cases.

	Q_f	Q_t	I_f	I_t	U_f	U_t
Case A	q_f	q_t	0	0	$x + \lambda_t(y - q_t) - q_f$	$y + \lambda_f\left(x - q_f\right) - q_t$
Case B	q_f	q_t	0	0	$x + \lambda_t(y - q_t) - q_f$	$y - q_t$
Case C	$x + \lambda_t(y - q_t)$	q_t	$q_f - x - \lambda_t(y - q_t)$	0	0	$y - q_t$
Case D	x	y	$q_f - x$	$q_t - y$	0	0
Case E	q_f	$y + \lambda_f\left(x - q_f\right)$	0	$q_t - y - \lambda_f\left(x - q_f\right)$	$x - q_f$	0
Case F	q_f	q_t	0	0	$x - q_f$	$y + \lambda_f\left(x - q_f\right) - q_t$

concave in q_f. Let $\frac{\partial \Pi_f^0(q_f, q_t)}{\partial q_f} = 0$ to get the forwarder's optimal number of empty containers q_f^{0*} to lease. Let $q_f^{0*} = q_f(q_t)$ be the optimal response function of the forwarder; then, the profit of the carrier is $\Pi_t^0\left(q_f, q_t\right) = \Pi_t^0\left(q_f(q_t), q_t\right)$.

By differentiating $\Pi_t^0\left(q_f, q_t\right)$ with respect to q_t, we obtain the following equation:

$$\frac{d\Pi_t^0\left(q_f, q_t\right)}{dq_t} = \frac{\partial \Pi_t^0\left(q_f, q_t\right)}{\partial q_f}\frac{dq_f}{dq_t} + \frac{\partial \Pi_t^0\left(q_f, q_t\right)}{\partial q_t} \tag{5}$$

Since $\left.\frac{d\Pi_t^0(q_f, q_t)}{dq_t}\right|_{q_f=0} = p_t - c_t(1+r_t) + (1+\lambda_f)g_t > 0$, $\left.\frac{d\Pi_t^0(q_f, q_t)}{dq_t}\right|_{q_f=\infty} = p_t - c_t(1+r_t) - (p_t - s_t) = s_t - c_t(1+r_t) < 0$ and $\frac{d\Pi_t^0(q_f, q_t)}{dq_t}$ is continuous, according to the Zero theorem, there is at least one solution such that $\frac{d\Pi_t^0(q_f, q_t)}{dq_t} = 0$. Let S be the set of q_t^0 satisfying $\frac{d\Pi_t^0(q_f, q_t)}{dq_t} = 0$. Therefore, there exists $q_t^{0*} = \underset{q_t^0 \in S}{\arg\max}\,\Pi_t^0\left(q_t^0\right)$ such that the optimal empty container leasing quantity in the DCCTSC is denoted as $\left(q_f^{0*}, q_t^{0*}\right)$.

Corollary 1. *For* $\forall q_t$, $\frac{dq_f}{dq_t} < 0$ *and* $\left|\frac{dq_f}{dq_t}\right| \leqslant \lambda_t$.

$$\begin{aligned}\frac{\partial \Pi_c\left(q_f, q_t\right)}{\partial q_f} = & -\left(p_f - s_f\right)\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx - \left(p_f - s_f\right)\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t} f(x)g(y)dydx + g_f\int_{q_f}^{\infty}\int_0^{q_t} f(x)g(y)dydx + g_f\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx \\ & + g_f\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t}^{\infty} f(x)g(y)dydx - \lambda_f(p_t - s_t)\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x + \lambda_f q_f + q_t} f(x)g(y)dydx + \lambda_f g_t\int_{q_f + \frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t} f(x)g(y)dydx + \lambda_f g_t\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}}\int_{-\lambda_f x + \lambda_f q_f + q_t}^{q_t} f(x)g(y)dydx \\ & + \lambda_f g_t\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx + p_f - c_f\end{aligned} \tag{7}$$

$$\begin{aligned}\frac{\partial \Pi_c\left(q_f, q_t\right)}{\partial q_t} = & -\lambda_t\left(p_f - s_f\right)\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t} f(x)g(y)dydx + \lambda_t g_f\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t}^{\infty} f(x)g(y)dydx + \lambda_t g_f\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx - (p_t - s_t)\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx - (p_t \\ & - s_t)\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x + \lambda_f q_f(q_t) + q_t} f(x)g(y)dydx + g_t\int_0^{q_f}\int_{q_t}^{\infty} f(x)g(y)dydx + g_t\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx + g_t\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}}\int_{-\lambda_f x + \lambda_f q_f + q_t}^{q_t} f(x)g(y)dydx \\ & + g_t\int_{q_f + \frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t} f(x)g(y)dydx + p_t - c_t\end{aligned} \tag{8}$$

Corollary 1 shows that when the carrier increases the quantity of empty containers leased in the direct channel, the corresponding optimal empty container leasing quantity of the forwarder will decrease, and the rate of decrease is less than the rate at which consignors switch from the direct channel to the traditional channel, i.e., λ_t. In addition, according to Eq. (3), it is easy to obtain that when q_t approaches infinity, q_f will approach the optimal solution $F^{-1}\left(\frac{p_f - w + r_t c_f + g_f}{p_f - s_f + g_f}\right)$ of the newsvendor model in the traditional channel. According to Corollary 1, we know that q_f is a decreasing function of q_t. Therefore, for any q_t, $q_f(q_t) \geqslant F^{-1}\left(\frac{p_f - w + r_t c_f + g_f}{p_f - s_f + g_f}\right)$. In other words, in the case of advance payment financing, the carrier's dual-channel method of canvassing will increase the empty container leasing quantity of the forwarder in the traditional channel. Proof see Appendix A.

4.2. Centralized model

In this section, we discuss the empty container leasing model of the DCCTSC in the centralized mode. In the decentralized mode, due to double marginalization and the conflicts between channels among members of the DCCTSC, the benefits of the DCCTSC unable to reach the optimum level of the system. In the centralized mode, the carrier and the forwarder are considered as a whole, and it plays the role of a central planner that centrally considers the empty container leasing strategy of the carrier and the forwarder. In this case, the carrier and forwarder will jointly pursue the overall profit maximization of the container transportation service chain to reach the optimum level of the system. The expected profit function of the entire system in the centralized mode can be expressed as:

$$\begin{aligned}\Pi_c\left(q_f, q_t\right) = & \, p_f E\min\left(q_f, D_f\right) + s_f E\left(q_f - D_f\right)^+ - g_f E\left(D_f - q_f\right)^+ \\ & + p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+ - \left(c_f q_f + c_t q_t\right)\end{aligned} \tag{6}$$

Proposition 2. $\Pi_c\left(q_f, q_t\right)$ *is jointly concave in* q_f *and* q_t.

We differentiate $\Pi_c\left(q_f, q_t\right)$ with respect to q_f and q_t as follows:

Then, by calculating the second-order derivatives, we can know that $\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_f^2} < 0$, $\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t^2} < 0$ and $\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_f^2}\cdot\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t^2} - \frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_f \partial q_t}\cdot\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t \partial q_f} > 0$. Therefore, there exists a set of optimal empty container leasing values for both traditional and direct channels, which maximize the profit of the DCCTSC system. The optimal empty container leasing quantity $\left(q_f^{c*}, q_t^{c*}\right)$ satisfies $\frac{\partial \Pi_c(q_f, q_t)}{\partial q_f} = 0$ and $\frac{\partial \Pi_c(q_f, q_t)}{\partial q_t} = 0$. The detailed proof of Proposition 2 is given in the Appendix A.

Corollary 2. *In the centralized model,* $\Pi_c\left(q_f^{c*}, q_t^{c*}\right) \geqslant \Pi_f^0\left(q_f^{0*}, q_t^{0*}\right) + \Pi_t^0\left(q_f^{0*}, q_t^{0*}\right)$ *always holds.*

$\left(q_f^{c^*}, q_t^{c^*}\right)$ is a set of optimal empty container leasing values that make the total profit of the system maximum, and applying it to Eq. (6), we can easily get $\Pi_f^0\left(q_f^{c^*}, q_t^{c^*}\right) + \Pi_t^0\left(q_f^{c^*}, q_t^{c^*}\right) = \Pi_c\left(q_f^{c^*}, q_t^{c^*}\right)$. As can be seen from the Proposition 2, Π_c is a strictly concave function, while $\left(q_f^{0^*}, q_t^{0^*}\right)$ is a different set of values from $\left(q_f^{c^*}, q_t^{c^*}\right)$, so $\Pi_c\left(q_f^{c^*}, q_t^{c^*}\right) \geqslant \Pi_f^0\left(q_f^{0^*}, q_t^{0^*}\right) + \Pi_t^0\left(q_f^{0^*}, q_t^{0^*}\right)$ is definitely valid.

It is only true that $\Pi_c\left(q_f^{c^*}, q_t^{c^*}\right) = \Pi_f^0\left(q_f^{0^*}, q_t^{0^*}\right) + \Pi_t^0\left(q_f^{0^*}, q_t^{0^*}\right)$ is established when $q_f^{0^*} = q_f^{c^*}$ and $q_t^{0^*} = q_t^{c^*}$. This means that when the forwarder competes with the carrier, if their empty container leasing quantity does not achieve the level in the centralized mode, then the sum of their profits must be smaller than the whole system profit in the centralized mode. In other words, if the forwarder can coordinate with the carrier to make their respective empty container leasing quantities reach the optimal empty container leasing level in the centralized mode, then the sum of their profits can be continuously rose to the maximum amount of profit in the centralized mode.

5. Cooperation and coordination mechanism

To achieve the coordination of the DCCTSC, we consider an improved revenue sharing and buyback combination contract $\{w, \varphi_1, \varphi_2, b\}$ led by the carrier. The carrier leases empty containers to the forwarder at wholesale price w before the selling season and compensates forwarders for unused surplus empty containers at buyback price b after the selling season. Moreover, after the selling season, the carrier obtains φ_2 of the direct channel revenue and $1-\varphi_1$ of the traditional channel revenue, while the forwarder obtains φ_1 of the traditional channel revenue and $1-\varphi_2$ of the direct channel revenue.

The implementation mechanism of the improved revenue sharing and buyback joint contract is as follows: First, before the carrier leases empty containers, the members of the DCCTSC determine the optimal empty container leasing quantity $\left(q_f^{c^*}, q_t^{c^*}\right)$ according to Eq. (7) and Eq. (8). Second, the forwarder and the carrier use Eq. (12) and Eq. (13) to determine the relationship between contract parameters according to $q_f^{c^*}$, $q_t^{c^*}$ and r_t given by the carrier and determine the appropriate values of φ_1 and b through negotiation to achieve a reasonable distribution of profits. Third, after receiving the advance payment $L = c_f q_f + c_t q_t - B$ from the forwarder, the carrier leases $q_f + q_t$ empty containers from the container leasing company. Fourth, the forwarder obtains empty containers q_f and pays the balance $w\left[q_f - (1+r_t)L/w\right]$ to the carrier at wholesale price w. Finally, at the end of the selling season, the carrier determines the buyback amount $bE\left(q_f - D_f\right)^+$ based on the number of unused empty containers fed back by the forwarder and calculates the actual amount T that needs to be paid to the forwarder, $T = T_{tf} - T_{ft}$, where

$T_{tf} = (1-\varphi_2)\left[p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+\right] + bE\left(q_f - D_f\right)^+$ and $T_{ft} = (1-\varphi_1)\left[p_f E\min\left(q_f, D_f\right) + s_f E\left(q_f - D_f\right)^+ - g_f E\left(D_f - q_f\right)^+\right]$.

Under the improved revenue sharing and buyback joint contract, the anticipated profit of the forwarder can be described as below:

$$\begin{aligned}\Pi_f\left(q_f, q_t\right) = {} & \varphi_1\left[p_f E\min\left(q_f, D_f\right) + s_f E\left(q_f - D_f\right)^+ \right. \\ & \left. - g_f E\left(D_f - q_f\right)^+\right] + (1-\varphi_2)\left[p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ \right. \\ & \left. - g_t E(D_t - q_t)^+\right] + bE\left(q_f - D_f\right)^+ - wq_f + r_t\left(c_f q_f + c_t q_t - B\right)\end{aligned} \tag{9}$$

According to Eq. (9), the optimal empty container leasing quantity q_f^* of the forwarder in the traditional channel satisfies $\frac{\partial \Pi_f(q_f, q_t)}{\partial q_f} = 0$. Let $q_f^* = q_f(q_t)$ be the optimal response function of the forwarder, and let the expected profit of the carrier be $\Pi_t\left(q_f, q_t\right) = \Pi_t\left(q_f(q_t), q_t\right)$, we have:

$$\begin{aligned}\Pi_t\left(q_f(q_t), q_t\right) = {} & \varphi_2\left[p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ \right. \\ & \left. - g_t E(D_t - q_t)^+\right] + (1-\varphi_1)\left[p_f E\min\left(q_f, D_f\right) \right. \\ & + s_f E\left(q_f - D_f\right)^+ \\ & \left. - g_f E\left(D_f - q_f\right)^+\right] - bE\left(q_f - D_f\right)^+ + wq_f - \left(c_f q_f \right. \\ & \left. + c_t q_t\right) - r_t\left(c_f q_f + c_t q_t - B\right)\end{aligned} \tag{10}$$

According to the Stackelberg countermeasures principle, the optimal empty container leasing quantity q_t^* of the carrier in the direct channel satisfies the following equation:

$$\frac{d\Pi_t\left(q_f, q_t\right)}{dq_t} = \frac{\partial \Pi_t\left(q_f, q_t\right)}{\partial q_f}\frac{dq_f}{dq_t} + \frac{\partial \Pi_t\left(q_f, q_t\right)}{\partial q_t} = 0 \tag{11}$$

Proposition 3. *In the DCCTSC based on the improved revenue sharing and buyback joint contract, if the contract parameters $\{w, \varphi_1, \varphi_2, b\}$ meet the following conditions, the DCCTSC can achieve coordination.*

$$\begin{aligned}\varphi_2 = {} & 1 - \varphi_1 + \frac{b\beta_2}{(p_f - s_f + g_f)\beta_2 - g_f\int_{q_t}^{\infty} g(y)\mathrm{d}y} \\ & + \frac{c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1}\left[\varphi_1 + r_t - \frac{b\beta_2}{(p_f - s_f + g_f)\beta_2 - g_f\int_{q_t}^{\infty} g(y)\mathrm{d}y}\right]\end{aligned} \tag{12}$$

$$\begin{aligned}w = {} & (\varphi_1 + r_t)\left[c_f + \frac{p_f + g_f - (p_f - s_f + g_f)\alpha_1 - c_f}{p_t + g_t - (p_t - s_t + g_t)\beta_1}\cdot c_t\right] \\ & + \frac{b\beta_2\left[p_f + g_f - (p_f - s_f + g_f)\alpha_1 - c_f\right]}{(p_f - s_f + g_f)\beta_2 - g_f\int_{q_t}^{\infty} g(y)\mathrm{d}y}\cdot\left[1 - \frac{c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1}\right] + b\alpha_1\end{aligned} \tag{13}$$

To facilitate further analysis, we assume:

$$\alpha_1 = \int_0^{q_f}\int_0^{q_t} f(x)g(y)\mathrm{d}y\mathrm{d}x + \int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t} f(x)g(y)\mathrm{d}y\mathrm{d}x$$

$$\alpha_2 = \int_{q_f}^{q_f + \frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x + \lambda_f q_f + q_t} f(x)g(y)\mathrm{d}y\mathrm{d}x$$

$$\beta_1 = \int_0^{q_f}\int_0^{q_t} f(x)g(y)\mathrm{d}y\mathrm{d}x + \int_{q_f}^{q_f + \frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x + \lambda_f q_f + q_t} f(x)g(y)\mathrm{d}y\mathrm{d}x$$

$$\beta_2 = \int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t} f(x)g(y)\mathrm{d}y\mathrm{d}x$$

Therefore, the first-order derivatives of $\Pi_c\left(q_f, q_t\right)$, $\Pi_f\left(q_f, q_t\right)$ and

$\Pi_t\left(q_f, q_t\right)$ are as follows:

$$\frac{\partial \Pi_c\left(q_f, q_t\right)}{\partial q_f} = p_f - c_f + g_f + \lambda_f g_t \int_{q_f}^{\infty} f(x)dx - \left(p_f - s_f + g_f\right)\alpha_1 - \lambda_f\left(p_t - s_t + g_t\right)\alpha_2 \tag{14}$$

$$\frac{\partial \Pi_c\left(q_f, q_t\right)}{\partial q_t} = p_t - c_t + g_t + \lambda_t g_f \int_{q_t}^{\infty} g(y)dy - \left(p_t - s_t + g_t\right)\beta_1 - \lambda_t\left(p_f - s_f + g_f\right)\beta_2 \tag{15}$$

$$\frac{\partial \Pi_f\left(q_f, q_t\right)}{\partial q_f} = \varphi_1\left[p_f + g_f - \left(p_f - s_f + g_f\right)\alpha_1\right] - (1-\varphi_2)\lambda_f\left[\left(p_t - s_t + g_t\right)\alpha_2 - g_t \int_{q_f}^{\infty} f(x)dx\right] + b\alpha_1 - w + r_t c_f \tag{16}$$

$$\frac{\partial \Pi_t\left(q_f, q_t\right)}{\partial q_f} = (1-\varphi_1)\left[p_f + g_f - \left(p_f - s_f + g_f\right)\alpha_1\right] - \varphi_2\lambda_f\left[\left(p_t - s_t + g_t\right)\alpha_2 - g_t \int_{q_f}^{\infty} f(x)dx\right] - b\alpha_1 + w - (1+r_t)c_f \tag{17}$$

$$\frac{\partial \Pi_t\left(q_f, q_t\right)}{\partial q_t} = \varphi_2\left[p_t + g_t - \left(p_t - s_t + g_t\right)\beta_1\right] - (1-\varphi_1)\lambda_t\left[\left(p_f - s_f + g_f\right)\beta_2 - g_f \int_{q_t}^{\infty} g(y)dy\right] - b\lambda_t\beta_2 - (1+r_t)c_t \tag{18}$$

It is assumed that the optimal quantity of empty containers to lease of the carrier and forwarder after contract coordination can reach the empty container leasing level in the centralized mode, i.e., $q_f^* = q_f^{c*}$ and $q_t^* = q_t^{c*}$. According to $\frac{\partial \Pi_c(q_f,q_t)}{\partial q_f} = 0$ and $\frac{\partial \Pi_f(q_f,q_t)}{\partial q_f} = 0$, we can obtain $\frac{\partial \Pi_t(q_f,q_t)}{\partial q_f} = 0$. Then, substituting Eq. (11), we can obtain $\frac{d\Pi_t(q_f,q_t)}{dq_t} = \frac{\partial \Pi_t(q_f,q_t)}{\partial q_t}$. Therefore, under the improved revenue sharing and buyback joint covenant, the optimal empty container leasing quantity $\left(q_f^*, q_t^*\right)$ satisfies the conditions $\frac{\partial \Pi_f(q_f,q_t)}{\partial q_f} = 0$ and $\frac{\partial \Pi_t(q_f,q_t)}{\partial q_t} = 0$. In equating Eq. (14), Eq. (15), Eq. (16) and Eq. (18) to zero, the following equations can be obtained:

$$\lambda_f = \frac{p_f + g_f - \left(p_f - s_f + g_f\right)\alpha_1 - c_f}{\left(p_t - s_t + g_t\right)\alpha_2 - g_t \int_{q_f}^{\infty} f(x)\mathrm{d}x} \tag{19}$$

$$\lambda_t = \frac{p_t + g_t - \left(p_t - s_t + g_t\right)\beta_1 - c_t}{\left(p_f - s_f + g_f\right)\beta_2 - g_f \int_{q_t}^{\infty} g(y)\mathrm{d}y} \tag{20}$$

$$w = \varphi_1\left[p_f + g_f - \left(p_f - s_f + g_f\right)\alpha_1\right] - (1-\varphi_2)\lambda_f\left[\left(p_t - s_t + g_t\right)\alpha_2 - g_t \int_{q_f}^{\infty} f(x)\mathrm{d}x\right] + b\alpha_1 + r_t c_f \tag{21}$$

$$\varphi_2 = \frac{(1-\varphi_1)\lambda_t\left[\left(p_f - s_f + g_f\right)\beta_2 - g_f \int_{q_t}^{\infty} g(y)\mathrm{d}y\right] + b\lambda_t\beta_2 + (1+r_t)c_t}{p_t + g_t - \left(p_t - s_t + g_t\right)\beta_1} \tag{22}$$

By combining equations (19) ~ (22) and simplifying, we can obtain Proposition 3. Proof see Appendix.

Proposition 3 indicates that in the carrier-led improved revenue sharing and buyback joint contract, if the contract parameters $\{w, \varphi_1, \varphi_2, b\}$ simultaneously satisfy Eq. (12) and Eq. (13), the optimal quantity of empty container to lease of the carrier and forwarder can achieve the level in the centralized mode, thus achieving coordination. Simultaneously, since there is a linear function relationship between contract parameters, any one of them can be represented by the other two parameters. Therefore, by adjusting some contract parameters, it is possible to achieve a reasonable distribution of profits of the DCCTSC. Taking the corresponding relationship between $\{\varphi_1, b\}$ and $\{w, \varphi_2\}$ as an example, under the condition that the price discount coefficient r_t is given, the carrier can achieve control over the sharing coefficient φ_2 and wholesale price w in the direct channel by regulating the sharing coefficient φ_1 and the buyback price b in the traditional channel to further the division of profits in the DCCTSC.

6. Pareto improvement analysis

Although the parameters of the improved joint revenue sharing and buyback contract can ensure that the DCCTSC achieves coordination when it satisfies Proposition 3, to make the contract implementable (i.e., each member of the DCCTSC can accept the contract), it is necessary to ensure that the profits obtained by the carrier and forwarder after accepting the contract are greater than the profits in the decentralized mode, i.e., a win–win situation is achieved.

Proposition 4. *Under the coordination of the improved revenue sharing and buyback joint contract, when the buyback price b is determined, the conclusions are as follows:*

(i) When $\frac{\partial \Delta\Pi_f}{\partial \varphi_1} > 0$, take $\underline{\varphi_1} = \max\left(0, \varphi_1^f\right)$ and $\overline{\varphi_1} = \min\left(\varphi_1^t, 1\right)$. If $\underline{\varphi_1} < \overline{\varphi_1}$, and then when $\varphi_1 \in \left[\underline{\varphi_1}, \overline{\varphi_1}\right]$, each member of the DCCTSC can achieve a Pareto improvement.

(ii) When $\frac{\partial \Delta\Pi_f}{\partial \varphi_1} < 0$, take $\underline{\varphi_1} = \max\left(0, \varphi_1^t\right)$ and $\overline{\varphi_1} = \min\left(\varphi_1^f, 1\right)$. If $\underline{\varphi_1} < \overline{\varphi_1}$, and then when $\varphi_1 \in \left[\underline{\varphi_1}, \overline{\varphi_1}\right]$, each member of the DCCTSC can achieve a Pareto improvement.

Where φ_1^f and φ_1^t are the values when $\Delta\Pi_f = 0$ and $\Delta\Pi_t = 0$, respectively.

Substituting q_f^{c*} and q_t^{c*} calculated in the centralized mode into the profit functions of the carrier and forwarder under the joint contract, the profits of the carrier and forwarder after contract coordination are obtained as $\Pi_f\left(q_f^{c*}, q_t^{c*}\right)$ and $\Pi_t\left(q_f^{c*}, q_t^{c*}\right)$. Let Π_f^{0*} and Π_t^{0*} denote the expected profits of the carrier and forwarder in the decentralized mode. Then, $\Pi_f\left(q_f^{c*}, q_t^{c*}\right) - \Pi_f^{0*} \geqslant 0$ and $\Pi_t\left(q_f^{c*}, q_t^{c*}\right) - \Pi_t^{0*} \geqslant 0$ should be satisfied when the members of the DCCTSC achieve a Pareto improvement. We assume that $\Delta\Pi_f = \Pi_f\left(q_f^{c*}, q_t^{c*}\right) - \Pi_f^{0*}$ and $\Delta\Pi_t = \Pi_t\left(q_f^{c*}, q_t^{c*}\right) - \Pi_t^{0*}$, there are:

$$\Delta\Pi_f = (\varphi_1 - 1)\left[p_f E\min\left(q_f, D_f\right) + s_f E\left(q_f - D_f\right)^+ - g_f E\left(D_f - q_f\right)^+\right] + (1-\varphi_2)\left[p_t E\min\left(q_t, D_t\right) + s_t E\left(q_t - D_t\right)^+ - g_t E\left(D_t - q_t\right)^+\right] + bE\left(q_f - D_f\right)^+ \tag{23}$$

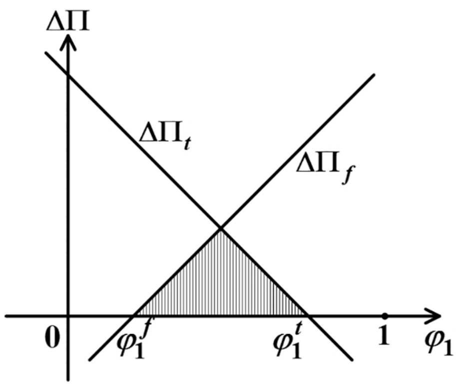

Fig. 4. Pareto improvement interval when $\frac{\partial \Delta\Pi_f}{\partial \varphi_1} > 0$.

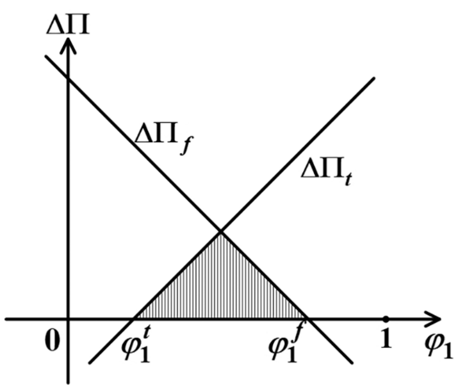

Fig. 5. Pareto improvement interval when $\frac{\partial \Delta\Pi_f}{\partial \varphi_1} < 0$.

Table 6
Empty container leasing quantity and profits under different decisions.

Different decisions	Wholesale price w	Optimal empty container leasing quantity		Profit		
		q_f	q_t	Π_f	Π_t	Π_c
Centralized model	/	1264	525	508,019		
Decentralized model	400	1345	715	409,066	92,132	501,198
	420	1243	713	383,384	119,829	503,213
	440	1169	711	359,363	144,081	503,444
	460	1110	710	336,616	166,037	502,653
	480	1060	710	314,929	186,221	501,150
	500	1015	711	294,166	204,927	499,094
	520	975	712	274,232	222,342	496,575
	540	938	714	255,059	238,592	493,651
	560	903	716	236,595	253,764	490,359
	580	870	719	218,801	267,923	486,724
	600	839	722	201,647	281,115	482,762

$$\Delta\Pi_t = (\varphi_2 - 1)[p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+] + (1 - \varphi_1)\left[p_f E\min(q_f, D_f) + s_f E(q_f - D_f)^+ - g_f E(D_f - q_f)^+\right] - bE(q_f - D_f)^+ \tag{24}$$

Differentiating $\Delta\Pi_f$ and $\Delta\Pi_t$ with respect to φ_1 generates the following equations:

$$\begin{aligned}\frac{\partial \Delta\Pi_f}{\partial \varphi_1} = {} & \left[p_f E\min(q_f, D_f) + s_f E(q_f - D_f)^+ \right.\\ & \left. - g_f E(D_f - q_f)^+\right] + \frac{p_t + g_t - (p_t - s_t + g_t)\beta_1 - c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1}[p_t E\min(q_t, D_t) \\ & + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+]\end{aligned} \tag{25}$$

$$\begin{aligned}\frac{\partial \Delta\Pi_t}{\partial \varphi_1} = {} & -\left[p_f E\min(q_f, D_f) + s_f E(q_f - D_f)^+ \right.\\ & \left. - g_f E(D_f - q_f)^+\right] - \frac{p_t + g_t - (p_t - s_t + g_t)\beta_1 - c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1}[p_t E\min(q_t, D_t) \\ & + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+]\end{aligned} \tag{26}$$

It is easy to obtain that $\frac{\partial \Delta\Pi_f}{\partial \varphi_1} = -\frac{\partial \Delta\Pi_t}{\partial \varphi_1}$. When $\frac{\partial \Delta\Pi_f}{\partial \varphi_1} > 0$, take $\underline{\varphi_1} = \max\left(0, \varphi_1^f\right)$ and $\overline{\varphi_1} = \min(\varphi_1^t, 1)$. If $\underline{\varphi_1} < \overline{\varphi_1}$, then $\varphi_1^f < \varphi_1^t$ and $\left[\underline{\varphi_1}, \overline{\varphi_1}\right]$, $[0,1] \neq \varnothing$. Therefore, as shown in Fig. 4, when $\varphi_1 \in \left[\underline{\varphi_1}, \overline{\varphi_1}\right]$, each member of the DCCTSC can achieve a Pareto improvement. Similarly, when $\frac{\partial \Delta\Pi_f}{\partial \varphi_1} < 0$, take $\underline{\varphi_1} = \max\left(0, \varphi_1^t\right)$ and $\overline{\varphi_1} = \min\left(\varphi_1^f, 1\right)$. If $\underline{\varphi_1} < \overline{\varphi_1}$, then $\varphi_1^t < \varphi_1^f$ and $\left[\underline{\varphi_1}, \overline{\varphi_1}\right]$, $[0,1] \neq \varnothing$. Therefore, as shown in Fig. 5, when $\varphi_1 \in \left[\underline{\varphi_1}, \overline{\varphi_1}\right]$, each member of the DCCTSC can achieve a Pareto improvement.

7. Numerical analysis

In order to verify the conclusions of the above sections and further analyze the model, a numerical example is given. The parameters used in our study are extracted by studying related literature of Liu et al. (2013) and Xie et al. (2017), and modified appropriately to fit our study. We assume that D_f and D_t are normally distributed, where $x \sim N(600, 400)$ and $y \sim N(300, 400)$. The basic parameters are set as follows: $p_f = 1000$, $c_f = 400$, $s_f = 100$, $g_f = 100$, $\lambda_f = 0.5$, $p_t = 800$, $c_t = 400$, $s_t = 100$, $g_t = 150$ and $\lambda_t = 0.6$.

7.1. Numerical results

We take $r_t = 0.05$ and $B = 40000$, and set the wholesale price w of empty containers for the forwarder in the decentralized mode without contract coordination to an arithmetic progression with a common difference of 20. Under different wholesale prices, the optimal empty container leasing quantity and the profit of the forwarder and the carrier are shown in Table 6. As can be seen in Table 6, the optimal empty container leasing quantity of the carrier in the decentralized mode is higher than the level of empty containers leased in the centralized mode for different wholesale prices of empty containers. The optimal empty container leasing quantity of the forwarder is partly lower than that in the centralized mode, and the other part is higher than the leasing level in the centralized mode. In terms of profit, as the wholesale price of empty containers rises, the profit of the forwarder has gradually decreased, while the profit of the carrier has continuously increased. However, regardless of the value of w, the sum of system profits in the decentralized mode is lower than the total profits in the centralized mode.

Then, after coordinating the DCCTSC through a joint contract with

Table 7
Empty container leasing quantity and profits under contract coordination.

Different decisions	Wholesale price w	Optimal empty container leasing quantity		Profit		
		q_f	q_t	Π_f	Π_t	Π_c
Centralized model	/	1264	525	508,019		
Contract coordination	400	1264	525	412,113	95,906	508,019
	420	1264	525	384,738	123,281	508,019
	440	1264	525	361,925	146,094	508,019
	460	1264	525	341,122	166,896	508,019
	480	1264	525	318,310	189,709	508,019
	500	1264	525	295,497	212,521	508,019
	520	1264	525	277,247	230,771	508,019
	540	1264	525	258,997	249,021	508,019
	560	1264	525	245,310	262,709	508,019
	580	1264	525	227,060	280,959	508,019
	600	1264	525	203,208	304,811	508,019

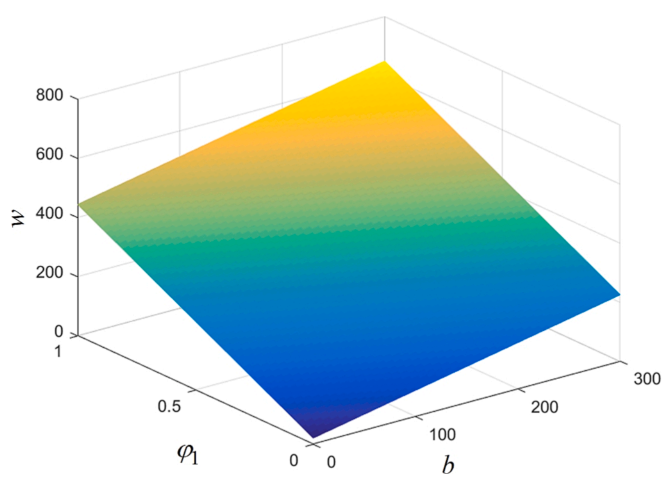

Fig. 6. The relationship among φ_1, b and w.

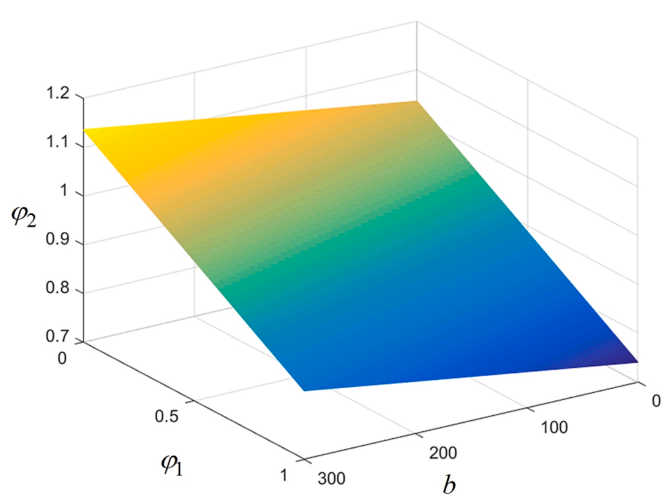

Fig. 7. The relationship among φ_1, b and φ_2.

appropriate contract parameters, i.e., the values of contract parameters satisfy the conditions in Proposition 3, we calculate the optimal empty container leasing quantity of the forwarder and the carrier as well as the profit, and the results are shown in Table 7. Table 7 shows that the optimal empty container leasing quantity for both the forwarder and the carrier can reach the level of the centralized mode after using the contract for coordination. And the sum of the profit of the forwarder and the carrier is also exactly equal to the total profit in the centralized mode.

In addition, by comparing Tables 6 and 7, it can be found that, on the one hand, the sum of the profits of the forwarder and the carrier after the joint contract coordination is higher than the sum of the profits of both under the decentralized mode. Taking $w = 600$ as an example, the sum of profit of the forwarder and the carrier under decentralized mode drops to the lowest value of 482762, while the sum of profit of both after contract coordination reaches the optimal value of 508,019 for centralized decision making, and the total profit of the system increases by 5.23 %. On the other hand, the profits of each of the forwarder and the carrier under the joint contract exceed the respective levels before coordination. It can be seen that the improved joint revenue sharing and buyback contract can achieve a Pareto improvement in the profitability of the forwarder and the carrier.

7.2. Sensitivity analysis and discussions

In the next, some sensitivity analysis regarding the contract parameters w, φ_1, φ_2 and b and the financing parameters r_t and B, are conducted to show the effect of changes in different parameters on the model.

7.2.1. Changes in contract parameters

Since the contract parameters w, φ_1, φ_2 and b are mutually constrained and have a corresponding relationship in the DCCTSC model, we take parameters φ_1 and b as an example when discussing the contract parameter changes and their impact on the container transportation service chain. We take $r_t = 0.05$ and assume that other parameters are constant and analyze the relationship between φ_1, b and w, and φ_1, b and φ_2. The results are shown in Fig. 6 and Fig. 7.

Fig. 6 and Fig. 7 present a sensitivity analysis of the sharing coefficient φ_1 and the buyback price b, which verifies Proposition 3. When the coordination of the DCCTSC is achieved, there is a linear functional relationship between the parameters of the joint contract with one-to-one correspondence. Fig. 6 and Fig. 7 show that when the buyback price b remains unchanged, with an increase in φ_1, the wholesale price w shows an increasing trend, while the sharing coefficient φ_2 shows a

Table 8
Relationship between contract parameters and profits of members in DCCTSC.

φ_1	$b = 20$		$b = 60$		b = 100	
	Π_f	Π_t	Π_f	Π_t	Π_f	Π_t
0.2	75,504	432,515	53,188	454,831	30,872	477,147
0.3	121,129	386,890	98,813	409,206	76,497	431,522
0.4	166,754	341,265	144,438	363,581	122,122	385,897
0.5	212,379	295,640	190,063	317,956	167,747	340,272
0.6	258,004	250,015	235,688	272,331	213,372	294,647
0.7	303,629	204,390	281,313	226,706	258,997	249,021
0.8	349,254	158,765	326,938	181,081	304,622	203,396
0.9	394,879	113,140	372,563	135,456	350,247	157,771

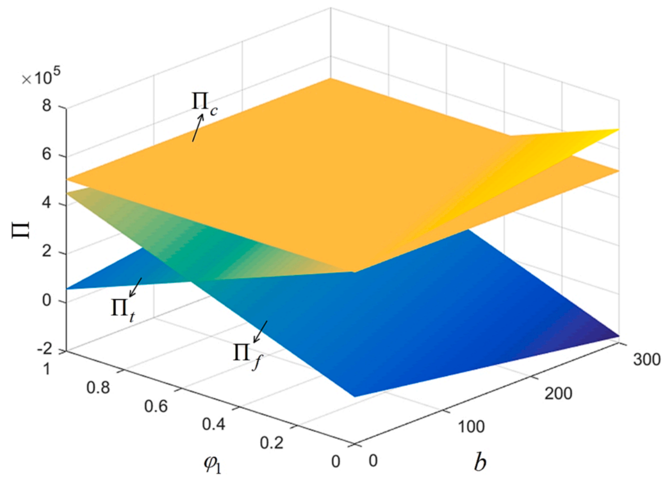

Fig. 8. The relationship between contract parameters and $\Pi_c/\Pi_f/\Pi_t$.

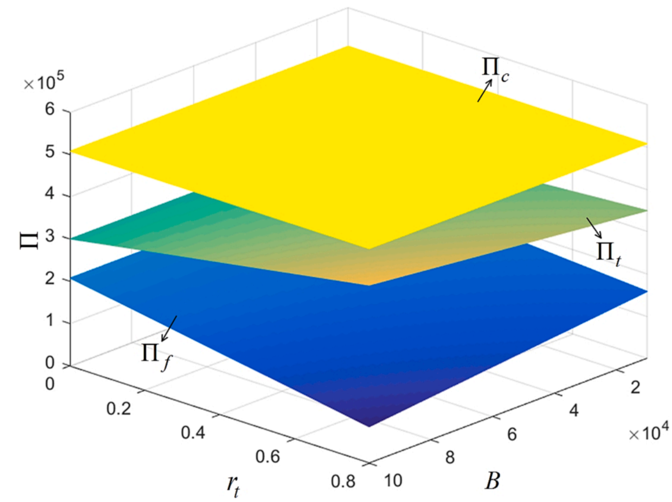

Fig. 9. The relationship between financing parameters and $\Pi_c/\Pi_f/\Pi_t$.

Table 9
Relationship between financing parameters and profits of members in DCCTSC.

r_t	$B = 40000$		$B = 60000$		$B = 80000$	
	Π_f	Π_t	Π_f	Π_t	Π_f	Π_t
0.05	213,362	294,657	212,362	295,657	211,362	296,657
0.1	208,772	299,246	206,772	301,246	204,772	303,246
0.15	204,183	303,836	201,183	306,836	198,183	309,836
0.2	199,594	308,425	195,594	312,425	191,594	316,425
0.25	195,004	313,014	190,004	318,014	185,004	323,014
0.3	190,415	317,604	184,415	323,604	178,415	329,604
0.35	185,826	322,193	178,826	329,193	171,826	336,193
0.4	181,236	326,782	173,236	334,782	165,236	342,782
0.45	176,647	331,372	167,647	340,372	158,647	349,372
0.5	172,058	335,961	162,058	345,961	152,058	355,961

decreasing trend. This is because an increase in the sharing coefficient phi will increase the marginal profit of the forwarder and reduce the marginal profit of the carrier, which will further lead to an increase in the number of empty containers leased by the forwarder in the traditional channel and a decrease in the number of empty containers leased by the carrier in the direct channel. To maintain the coordinated state of the service chain, the carrier will readjust the empty container leasing quantity of the two channels to the optimal leasing level by increasing the wholesale price and reducing the proportion of revenue sharing from the direct channel. Similarly, when the sharing coefficient φ_1 remains constant, increasing the buyback price b will produce a similar effect to φ_1, which will not be detailed here.

We take $r_t = 0.05$ and $B = 40000$, and assume that other parameters remain unchanged, and on this basis, we analyze the impact of contract parameters φ_1 and b on the total profit of the DCCTSC and the profit of each member, as shown in Table 8.

From Table 8, it can be seen that when the buyback price b is fixed, the profit of the forwarder tends to increase with the increase of the sharing coefficient φ_1, while the profit of the carrier tends to decrease. When the sharing coefficient φ_1 is constant, as the buyback price b increases, the profit of the forwarder tends to decrease, while the profit of the carrier tends to increase. With the change in the sharing coefficient φ_1 and buyback price b, although the profits of the forwarder and carrier are changing, the profit of the forwarder and the carrier always satisfies the equation $\Pi_f + \Pi_t = \Pi_c = 508019$, i.e., the total profit of this DCCTSC is always at the optimal level under supply chain coordination. This means that the improved revenue sharing and buyback joint contract enable the coordination of the DCCTSC. And the adjustment of contract parameters φ_1 and b only changes the profit distribution among the members of the DCCTSC and does not affect the coordination of the overall system. In practice, the determination of contract parameters φ_1 and b mainly depends on the bargaining power of both sides of the container transportation service chain. Fig. 8 visualizes how the variation of the revenue sharing coefficient φ_1 and the buyback price b distributes the profits of DCCTSC between the forwarder and the carrier.

7.2.2. Changes in financing parameters

Then, we take $\varphi_1 = 0.6$ and $b = 100$ and assume that other parameters remain unchanged, and on this basis, we analyze the impact of financing parameters r_t and B on the total profit of the DCCTSC and the profit of each member, as shown in Table 9.

As seen from Table 9, the changes in the price discount coefficient r_t and the initial capital B of the carrier also do not affect the coordination status of this DCCTSC and only play a role in the redistribution of profits among the members of the container transportation service chain. When the initial capital B of the carrier is fixed, with an increase in the price discount coefficient r_t, the profit of the forwarder demonstrates a declining trend, while the profit of the carrier shows an upward trend. Although the carrier can alleviate its capital shortage through advance payment financing, an increase in r_t will reduce the marginal profit of the carrier and increase the marginal profit of the forwarder, which will further lead to a decline in the number of empty containers leased by the carrier in the direct channel and an increase in the number of empty containers leased by the forwarder in the traditional channel. To

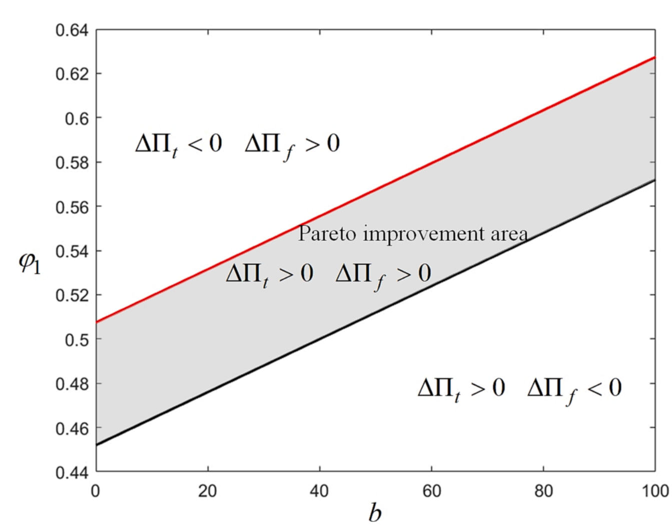

Fig. 10. Pareto improvement analysis of the profits of the DCCTSC members.

maintain the optimal level of empty container leasing when the service chain is coordinated, the carrier will increase the wholesale price and reduce the proportion of revenue in the direct channel shared with the forwarder, but this process will cause the profit of the forwarder to be encroached on by the carrier. When the price discount coefficient r_t remains unchanged, with a decrease in the initial capital B of the carrier, the profit of the carrier indicates a decreasing trend, while the profit of the forwarder shows an increasing trend. The greater the amount of advance payment paid by the forwarder to the carrier, the more benefits it enjoys from price discounts. Therefore, the profit of the forwarder increases as the carrier's capital gap increases. In addition, combined with the above analysis, it can be seen that when the carrier's capital gap is smaller and the price discount is higher, the profits of the forwarder and carrier will show a trend of accelerated decline and accelerated rise, respectively, which can be verified by comparing the changes in the respective profit of the forwarder and the carrier in Table 9. Fig. 9 visualizes how the variation of the price discount coefficient r_t and the initial capital B of the carrier affect the allocation of the profits of DCCTSC between the carrier and the forwarder, and the trend of the carrier's and forwarder's profits with the changes in the price discount coefficient and the initial capital.

7.2.3. Pareto improvement analysis

We take the financing parameters $r_t = 0.05$ and $B = 40000$, the wholesale price $w = 600$ in the decentralized mode and assume that other parameters remain unchanged. Then, the optimal number of empty containers to lease and the maximum profit of the forwarder and carrier in the decentralized mode can be obtained as $q_f^{0*} = 838.5856$, $q_t^{0*} = 722.2944$, $\Pi_f^0 = 201650$ and $\Pi_t^0 = 281110$. We analyze whether each member of the container transportation service chain can achieve a Pareto improvement, and the results are shown in Fig. 10.

It can be seen from Fig. 10 that when the combination of contract parameters $\{\varphi_1, b\}$ falls in the gray area below the red line and above the black line, the DCCTSC achieves coordination and realizes a Pareto improvement in the profit of each member of the container transportation service chain. At the same time, the combination of contract parameters to achieve supply chain coordination and Pareto improvement is also flexible, that is, any $\{\varphi_1, b\}$ falling in the gray area can further increase the profit of the carrier and forwarder relative to before coordination. In summary, Proposition 4 can be verified.

8. Conclusion

In this paper, under random market demand and shortage of funds for the carrier, we studied the problem of empty container decision and coordination in a DCCTSC. First, we introduced the advance payment financing mode to solve the capital constraint problem of the carrier and discussed the optimal empty container leasing strategies of the carrier and the forwarder under decentralized and centralized decision-making, respectively. Further, we designed an improved revenue sharing and buyback joint contract mechanism containing advance payment financing parameters and investigated the coordination of the contract. Finally, through the analysis of numerical examples, we confirmed the effectiveness of the coordination mechanism of DCCTSC proposed in this paper, analyzed the impact of contract parameters and financing parameters on the carrier, the forwarder and the whole system, and judged the feasibility of Pareto improvement of each member's profit. The results of the study show that the expected profits of the forwarder and the carrier in the decentralized mode always fall short of the profits in the centralized mode. The optimal empty container leasing quantity of the forwarder is a decreasing function of the empty container leasing quantity of the carrier in the direct channel. The carrier canvass for cargoes through the DCCTSC system can improve the empty container leasing level of the forwarder in the traditional channel. When the joint contract is introduced to coordinate the DCCTSC, the total profit of this DCCTSC is always at the optimal level under service chain coordination, i.e., it achieves the profit level in the centralized mode. At this point, as long as the contract parameters are set appropriately, the profits of the forwarder, the carrier and the entire dual-channel system are higher than those before coordination. There is a linear function of one-to-one correspondence between the parameters of the joint contract. When the buyback price remains unchanged, with an increase in traditional channel revenue sharing coefficient, the wholesale price shows an increasing trend, while the direct channel sharing coefficient shows a decreasing trend. Similarly, when the traditional channel sharing coefficient is constant, as the buyback price rises, the wholesale price continues to rise, while the direct channel revenue sharing coefficient continues to fall. The adjustment of contract parameters and financing parameters only changes the profit distribution among the members of the service chain and does not affect the coordination of the overall system. Furthermore, when the combination of contract parameters is within a certain range, the DCCTSC can realize the Pareto improvement of each member's profit while being in a coordinated state, i.e., achieve a win–win situation. And the combination of contract parameters also has a certain degree of flexibility.

Our study focuses on the direct canvassing channel of the carrier, which is less discussed in the current literature, and merges it with the traditional canvassing channel to form a DCCTSC, filling the research gap of the maritime transport chain in terms of dual-channel systems. We study the empty container decision of the maritime transport chain in a decentralized manner, where each member makes decisions alone as an independent individual. Unlike most previous empty container resource planning problems under centralized decision making, which is closer to reality. We consider the situation where the carrier has financial constraints and design a more flexible joint contract with advance payment financing parameters. The proposed contract mechanism enriches the methodological system of contract coordination and broadens the scope of application of contract coordination theory at the methodological level, and helps enterprises achieve effective management of DCCTSC at the practical level.

Based on the above research findings, we propose several managerial implications:

(1) Carriers in the DCCTSC environment often face greater financial pressure, forwarder advance payment financing mode can avoid the risk of insufficient funds of carriers leading to untimely supply of empty containers and interruption of canvassing, so that the risk is shared between carriers and forwarders. This is an important way for carriers to solve their capital constraint problems.
(2) Carriers can coordinate the optimal empty container leasing level of both members of the DCCTSC to reach the level of empty containers in the optimal state of the dual-channel system according to the implementation mechanism of the improved joint revenue sharing and buyback contract containing advance payment financing parameters, thus achieving the goal of maximizing the overall profit of the DCCTSC. This provides a concrete and operable method for carriers to realize effective management of DCCTSC and cooperation between carriers and forwarders.
(3) This paper provides a scientific rationale for the enforceability of an improved revenue sharing and buyback joint contract. The carrier and forwarder can negotiate a range of values for the combination of contract parameters so that both parties can achieve Pareto improvements in their allocated profits. At this point, the improved revenue sharing and buyback joint contract has an implementable basis.
(4) Forwarders and carriers in the DCCTSC can more flexibly allocate profits between them through improved revenue sharing and buyback joint contract. The advantage of joint contract compared with single contract is that carriers and forwarders can allocate the system profit more flexibly by negotiating the value of the

combination of contract parameters, while the single contract can only achieve profit allocation through the adjustment of individual parameter, and because of this, the joint contract is more flexible.

There are still some expandable aspects for future research. In this paper, we only discuss the situation where the carrier is in the dominant position, and future research could consider what conditions the contract parameters should satisfy when the forwarder is in the dominant position. Furthermore, we suppose that demand obeys a normal distribution. In practice, the demand of carriers and forwarders may be correlated. How to study the channel coordination of the DCCTSC on the basis of demand relevance should be further discussed. Finally, this paper considers a DCCTSC composed of two independent subjects in a single cycle, and future research can consider more complex container service supply chain systems, such as studying the coordination of more than two participating subjects with each other in multiple cycles.

CRediT authorship contribution statement

Tian Luo: Conceptualization, Methodology, Validation, Formal analysis, Software, Writing – original draft. **Daofang Chang:** Supervision, Project administration, Funding acquisition. **Zhenyu Xu:** Resources, Investigation. **Xiaoyuan Hu:** Writing – review & editing, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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Appendix A

Proof of Proposition 1

According to the different cases of demand for the DCCTSC, Eq. (1) and Eq. (2) can be expressed as follows:

$$\begin{aligned}\Pi_f^0(q_f,q_t) &= p_f q_f\left[1-\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx\right]\\ &-(p_f-s_f)\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}\left[q_f-x-\lambda_t(y-q_t)\right]f(x)g(y)dydx\\ &+s_f q_f\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx+(p_f-s_f)\int_0^{q_f}\int_0^{q_t} xf(x)g(y)dydx\\ &-g_f\left\{\int_{q_f}^{\infty}\int_0^{q_t}(x-q_f)f(x)g(y)dydx+\int_{q_f}^{\infty}\int_{q_t}^{\infty}\left[x+\lambda_t(y-q_t)-q_f\right]f(x)g(y)dydx\right.\\ &\left.+\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}^{\infty}\left[x+\lambda_t(y-q_t)-q_f\right]f(x)g(y)dydx\right\}-wq_f+r_t(c_fq_f+c_tq_t-B)\end{aligned} \tag{A1}$$

$$\begin{aligned}\Pi_t^0(q_f,q_t) &= p_t q_t\left[1-\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx\right]\\ &-(p_t-s_t)\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x+\lambda_f q_f+q_t}\left[q_t-y-\lambda_f(x-q_f)\right]f(x)g(y)dydx\\ &+s_t q_t\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx+(p_t-s_t)\int_0^{q_f}\int_0^{q_t} yf(x)g(y)dydx\\ &-g_t\left\{\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_{-\lambda_f x+\lambda_f q_f+q_t}^{q_t}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx\right.\\ &+\int_{q_f+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx\\ &+\int_{q_f}^{\infty}\int_{q_t}^{\infty}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx\\ &\left.+\int_0^{q_f}\int_{q_t}^{\infty}(y-q_t)f(x)g(y)dydx\right\}+wq_f-c_fq_f-c_tq_t-r_t(c_fq_f+c_tq_t-B)\end{aligned} \tag{A2}$$

By differentiating $\Pi_t^0(q_f,q_t)$ with respect to q_t, we obtain the following equation:

$$\frac{d\Pi_t^0(q_f,q_t)}{dq_t}=\frac{\partial\Pi_t^0(q_f,q_t)}{\partial q_f}\frac{dq_f}{dq_t}+\frac{\partial\Pi_t^0(q_f,q_t)}{\partial q_t} \tag{A3}$$

Among them,

$$\frac{\partial\Pi_t^0(q_f,q_t)}{\partial q_f} = -\lambda_f(p_t-s_t)\int_{q_f(q_t)}^{q_f(q_t)+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x+\lambda_f q_f(q_t)+q_t} f(x)g(y)dydx$$
$$+\lambda_f g_t\int_{q_f(q_t)+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t} f(x)g(y)dydx + \lambda_f g_t\int_{q_f(q_t)}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx \tag{A4}$$
$$+\lambda_f g_t\int_{q_f(q_t)}^{q_f(q_t)+\frac{q_t}{\lambda_f}}\int_{-\lambda_f x+\lambda_f q_f(q_t)+q_t}^{q_t} f(x)g(y)dydx + w - c_f(1+r_t)$$

$$\frac{\partial\Pi_t^0(q_f,q_t)}{\partial q_t} = -(p_t-s_t)\int_0^{q_f(q_t)}\int_0^{q_t} f(x)g(y)dydx$$
$$-(p_t-s_t)\int_{q_f(q_t)}^{q_f(q_t)+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x+\lambda_f q_f(q_t)+q_t} f(x)g(y)dydx + g_t\int_0^{q_f(q_t)}\int_{q_t}^{\infty} f(x)g(y)dydx$$
$$+g_t\int_{q_f(q_t)+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t} f(x)g(y)dydx + g_t\int_{q_f(q_t)}^{q_f(q_t)+\frac{q_t}{\lambda_f}}\int_{-\lambda_f x+\lambda_f q_f(q_t)+q_t}^{q_t} f(x)g(y)dydx \tag{A5}$$
$$+g_t\int_{q_f(q_t)}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx + p_t - c_t(1+r_t)$$

We substitute Eq. (A.2) and (A.3) into Eq. (A.1) and simplify it as follows:

$$\frac{d\Pi_t^0(q_f,q_t)}{dq_t} = -(p_t-s_t)\int_0^{q_f(q_t)}\int_0^{q_t} f(x)g(y)dydx$$
$$-(p_t-s_t)\left[1+\lambda_f\frac{dq_f(q_t)}{dq_t}\right]\int_{q_f(q_t)}^{q_f(q_t)+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x+\lambda_f q_f(q_t)+q_t} f(x)g(y)dydx$$
$$+(1+\lambda_f)g_t\int_{q_f(q_t)+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t} f(x)g(y)dydx + (1+\lambda_f)g_t\int_{q_f(q_t)}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx \tag{A6}$$
$$+(1+\lambda_f)g_t\int_{q_f(q_t)}^{q_f(q_t)+\frac{q_t}{\lambda_f}}\int_{-\lambda_f x+\lambda_f q_f(q_t)+q_t}^{q_t} f(x)g(y)dydx$$
$$+g_t\int_0^{q_f(q_t)}\int_{q_t}^{\infty} f(x)g(y)dydx + p_t - c_t(1+r_t) + \left[w - c_f(1+r_t)\right]\frac{dq_f(q_t)}{dq_t}$$

$$\therefore \left.\frac{d\Pi_t^0(q_f,q_t)}{dq_t}\right|_{q_f=0} = p_t - c_t(1+r_t) + (1+\lambda_f)g_t > 0 \tag{A7}$$

$$\left.\frac{d\Pi_t^0(q_f,q_t)}{dq_t}\right|_{q_f=\infty} = p_t - c_t(1+r_t) - (p_t-s_t) = s_t - c_t(1+r_t) < 0 \tag{A8}$$

Since $\frac{d\Pi_t^0(q_f,q_t)}{dq_t}$ is continuous, according to the Zero theorem, there is at least one solution such that $\frac{d\Pi_t^0(q_f,q_t)}{dq_t} = 0$. Let S be the set of q_t^0 satisfying $\frac{d\Pi_t^0(q_f,q_t)}{dq_t} = 0$. Therefore, there exists $q_t^{0*} = \underset{q_t^0\in S}{\arg\max}\,\Pi_t^0(q_t^0)$ such that the optimal quantity of empty containers to lease in the DCCTSC is denoted as $\left(q_f^{0*}, q_t^{0*}\right)$.

Proof of Corollary 1

$$\mu(q_f,q_t) = \frac{\partial\Pi_f^0(q_f,q_t)}{\partial q_f} = -(p_f-s_f)\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx$$

Let $-(p_f-s_f)\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t} f(x)g(y)dydx + g_f\int_{q_f}^{\infty}\int_0^{q_t} f(x)g(y)dydx$ $+g_f\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx + g_f\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}^{\infty} f(x)g(y)dydx - w + p_f + r_t c_f$, according to the implicit function derivation rule, we can obtain $\frac{dq_f}{dq_t} = -\frac{\frac{\partial\mu(q_f,q_t)}{\partial q_t}}{\frac{\partial\mu(q_f,q_t)}{\partial q_f}}$, where:

$$\frac{\partial\mu(q_f,q_t)}{\partial q_t} = -(p_f - s_f + g_f)\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)\mathrm{d}x \tag{A9}$$

$$\frac{\partial\mu(q_f,q_t)}{\partial q_f} = -(p_f - s_f + g_f)\int_0^{q_t} f(q_f)g(y)\mathrm{d}y$$
$$-\frac{1}{\lambda_t}(p_f - s_f + g_f)\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)\mathrm{d}x \tag{A10}$$

Thus, we can obtain:

$$\frac{dq_f}{dq_t} = -\frac{\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx}{\int_0^{q_t} f(q_f)g(y)dy + \frac{1}{\lambda_t}\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx} < 0 \tag{A11}$$

$$\left|\frac{dq_f}{dq_t}\right| = \frac{\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx}{\int_0^{q_t} f(q_f)g(y)dy + \frac{1}{\lambda_t}\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx} \leqslant \frac{\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx}{\frac{1}{\lambda_t}\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx} = \lambda_t \tag{A12}$$

In addition, according to Eq. (3), it is easy to obtain:

$$\lim_{q_t\to\infty}\frac{\partial\Pi_f^0(q_f,q_t)}{\partial q_f} = -(p_f - s_f)\int_0^{q_f} f(x)dx + g_f\int_{q_f}^{\infty} f(x)dx - w + p_f + r_t c_f = -(p_f - s_f)F(q_f) + g_f[1 - F(q_f)] - w + p_f + r_t c_f$$
$$= p_f - w + r_t c_f + g_f - (p_f - s_f + g_f)F(q_f) \tag{A13}$$

Let $\lim_{q_t\to\infty}\frac{\partial\Pi_f^0(q_f,q_t)}{\partial q_f} = 0$, and we can obtain $q_f = F^{-1}\left(\frac{p_f - w + r_t c_f + g_f}{p_f - s_f + g_f}\right)$. Therefore, when q_t approaches infinity, q_f will approach the optimal solution $F^{-1}\left(\frac{p_f - w + r_t c_f + g_f}{p_f - s_f + g_f}\right)$ of the newsvendor model in the traditional channel.

Proof of Proposition 2

Eq. (6) can be written as follows:

$$\begin{aligned}
\Pi_c(q_f,q_t) &= p_f q_f + p_t q_t - (p_f q_f - s_f q_f + p_t q_t - s_t q_t)\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx \\
&-(p_f - s_f)\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t}\left[q_f - x - \lambda_t(y - q_t)\right]f(x)g(y)dydx \\
&+(p_f - s_f)\int_0^{q_f}\int_0^{q_t} xf(x)g(y)dydx - g_f\int_{q_f}^{\infty}\int_0^{q_t}(x - q_f)f(x)g(y)dydx \\
&-g_f\int_{q_f}^{\infty}\int_{q_t}^{\infty}\left[x + \lambda_t(y - q_t) - q_f\right]f(x)g(y)dydx \\
&-g_f\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t}^{\infty}\left[x + \lambda_t(y - q_t) - q_f\right]f(x)g(y)dydx \\
&-(p_t - s_t)\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x + \lambda_f q_f + q_t}\left[q_t - y - \lambda_f(x - q_f)\right]f(x)g(y)dydx \\
&+(p_t - s_t)\int_0^{q_f}\int_0^{q_t} yf(x)g(y)dydx \\
&-g_t\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}}\int_{-\lambda_f x + \lambda_f q_f + q_t}^{q_t}\left[y + \lambda_f(x - q_f) - q_t\right]f(x)g(y)dydx \\
&-g_t\int_{q_f + \frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t}\left[y + \lambda_f(x - q_f) - q_t\right]f(x)g(y)dydx \\
&-g_t\int_{q_f}^{\infty}\int_{q_t}^{\infty}\left[y + \lambda_f(x - q_f) - q_t\right]f(x)g(y)dydx \\
&-g_t\int_0^{q_f}\int_{q_t}^{\infty}(y - q_t)f(x)g(y)dydx - c_f q_f - c_t q_t
\end{aligned} \tag{A14}$$

The second-order derivatives of Π_c are calculated as below:

$$\begin{aligned}
\frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_f^2} &= -\left[(p_f - s_f + g_f) - \lambda_f(p_t - s_t + g_t)\right]\int_0^{q_t} f(q_f)g(y)dx - \lambda_f g_t f(q_f) - \frac{1}{\lambda_t}(p_f - s_f + g_f)\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx - \lambda_f^2(p_t - s_t \\
&+ g_t)\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}} f(x)g(-\lambda_f x + \lambda_f q_f + q_t)dx \\
&< 0
\end{aligned} \tag{A15}$$

$$\begin{aligned}\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t^2} = & -\left[(p_t - s_t + g_t) - \lambda_t(p_f - s_f + g_f)\right]\int_0^{q_f} f(x)g(q_t)dx - \lambda_t q_f g(q_t) - \lambda_t(p_f - s_f + g) \int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx - (p_t - s_t + g_t)\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}} f(x)g(\\ & -\lambda_f x + \lambda_f q_f + q_t)dx \\ & < 0\end{aligned} \tag{A16}$$

$$\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_f \partial q_t} = \frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t \partial q_f} = -(p_f - s_f + g_f)\int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)dx - \lambda_f(p_t - s_t + g_t)\int_{q_f}^{q_f + \frac{q_t}{\lambda_f}} f(x)g(-\lambda_f x + \lambda_f q_f + q_t)dx < 0 \tag{A17}$$

Let $A = \int_0^{q_f} f(x)g\left(-\frac{1}{\lambda_t}x + \frac{q_f}{\lambda_t} + q_t\right)\mathrm{d}x$, $B = \int_{q_f}^{q_f + \frac{q_t}{\lambda_f}} f(x)g(-\lambda_f x + \lambda_f q_f + q_t)\mathrm{d}x$, we have:

$$\begin{aligned}\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_f^2} &= -\left[(p_f - s_f + g_f) - \lambda_f(p_t - s_t + g_t)\right]\int_0^{q_t} f(q_f)g(y)dx \\ &\quad -\lambda_f g_t f(q_f) - \frac{1}{\lambda_t}(p_f - s_f + g_f)A - \lambda_f^2(p_t - s_t + g_t)B \\ &< -\frac{1}{\lambda_t}(p_f - s_f + g_f)A - \lambda_f^2(p_t - s_t + g_t)B < 0\end{aligned} \tag{A18}$$

$$\begin{aligned}\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t^2} &= -\left[(p_t - s_t + g_t) - \lambda_t(p_f - s_f + g_f)\right]\int_0^{q_f} f(x)g(q_t)dx \\ &\quad -\lambda_t q_f g(q_t) - \lambda_t(p_f - s_f + g_f)A - (p_t - s_t + g_t)B \\ &< -\lambda_t(p_f - s_f + g_f)A - (p_t - s_t + g_t)B < 0\end{aligned} \tag{A19}$$

$$\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_f \partial q_t} = \frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t \partial q_f} = -(p_f - s_f + g_f)A - \lambda_f(p_t - s_t + g_t)B < 0 \tag{A20}$$

$$\begin{aligned}\therefore \frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_f^2}\cdot\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t^2} &> \left[\frac{1}{\lambda_t}(p_f - s_f + g_f)A + \lambda_f^2(p_t - s_t + g_t)B\right] \\ &\quad \cdot\left[\lambda_t(p_f - s_f + g_f)A + (p_t - s_t + g_t)B\right] \\ &= (p_f - s_f + g_f)^2A^2 + \frac{1}{\lambda_t}(p_f - s_f + g_f)(p_t - s_t + g_t)AB \\ &\quad +\lambda_f^2\lambda_t(p_f - s_f + g_f)(p_t - s_t + g_t)AB + \lambda_f^2(p_t - s_t + g_t)^2B^2 \\ &= (p_f - s_f + g_f)^2A^2 + \lambda_f^2(p_t - s_t + g_t)^2B^2 \\ &\quad +\frac{1}{\lambda_t}\left[(p_f - s_f + g_f)(p_t - s_t + g_t)AB + \lambda_f^2\lambda_t^2(p_f - s_f + g_f)(p_t - s_t + g_t)AB\right] \\ &= (p_f - s_f + g_f)^2A^2 + \lambda_f^2(p_t - s_t + g_t)^2B^2 \\ &\quad +\frac{1}{\lambda_t}\left(1 + \lambda_f^2\lambda_t^2\right)(p_f - s_f + g_f)(p_t - s_t + g_t)AB\end{aligned} \tag{A21}$$

$$\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_f \partial q_t}\cdot\frac{\partial^2 \Pi_c(q_f, q_t)}{\partial q_t \partial q_f} = (p_f - s_f + g_f)^2A^2 + \lambda_f^2(p_t - s_t + g_t)^2B^2 + 2\lambda_f(p_f - s_f + g_f)(p_t - s_t + g_t)AB \tag{A22}$$

$$\therefore \left|H(q_f,q_t)\right| = \begin{vmatrix} \frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_f^2} & \frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_f\partial q_t} \\ \frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_t\partial q_f} & \frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_t^2} \end{vmatrix}$$

$$\begin{aligned} &= \frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_f^2}\cdot\frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_t^2} - \frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_f\partial q_t}\cdot\frac{\partial^2\Pi_c(q_f,q_t)}{\partial q_t\partial q_f} \\ &> (p_f - s_f + g_f)^2A^2 + \lambda_f^2(p_t - s_t + g_t)^2B^2 \\ &+\frac{1}{\lambda_t}\left(1+\lambda_f^2\lambda_t^2\right)(p_f - s_f + g_f)(p_t - s_t + g_t)AB \\ &-\Big[(p_f - s_f + g_f)^2A^2 + \lambda_f^2(p_t - s_t + g_t)^2B^2 \\ &+ 2\lambda_f(p_f - s_f + g_f)(p_t - s_t + g_t)AB\Big] \\ &= \frac{1}{\lambda_t}\left(1+\lambda_f^2\lambda_t^2\right)(p_f - s_f + g_f)(p_t - s_t + g_t)AB \\ &-2\lambda_f(p_f - s_f + g_f)(p_t - s_t + g_t)AB \\ &= \frac{1}{\lambda_t}(p_f - s_f + g_f)(p_t - s_t + g_t)AB\left[1+\lambda_f^2\lambda_t^2 - 2\lambda_f\lambda_t\right] \\ &= \frac{1}{\lambda_t}(p_f - s_f + g_f)(p_t - s_t + g_t)AB(1-\lambda_f\lambda_t)^2 > 0 \end{aligned} \tag{A23}$$

$\therefore$ This Hessian matrix is negative definite.

Proof of Proposition 3

Eq. (9) can be expressed as below:

$$\begin{aligned} \Pi_f(q_f,q_t) &= \varphi_1\Bigg\{p_fq_f\left[1-\int_0^{q_f}\int_0^{q_t}f(x)g(y)dydx\right] + s_fq_f\int_0^{q_f}\int_0^{q_t}f(x)g(y)dydx \\ &-(p_f - s_f)\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}\left[q_f - x - \lambda_t(y-q_t)\right]f(x)g(y)dydx \\ &+(p_f - s_f)\int_0^{q_f}\int_0^{q_t}xf(x)g(y)dydx - g_f\int_{q_f}^{\infty}\int_0^{q_t}(x-q_f)f(x)g(y)dydx \\ &-g_f\int_{q_f}^{\infty}\int_{q_t}^{\infty}\left[x+\lambda_t(y-q_t)-q_f\right]f(x)g(y)dydx \\ &-g_f\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}^{\infty}\left[x+\lambda_t(y-q_t)-q_f\right]f(x)g(y)dydx\Bigg\} \\ &+(1-\varphi_2)\Bigg\{p_tq_t\left[1-\int_0^{q_f}\int_0^{q_t}f(x)g(y)dydx\right] + s_tq_t\int_0^{q_f}\int_0^{q_t}f(x)g(y)dydx \\ &-(p_t - s_t)\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_fx+\lambda_fq_f+q_t}\left[q_t - y - \lambda_f(x-q_f)\right]f(x)g(y)dydx \\ &+(p_t - s_t)\int_0^{q_f}\int_0^{q_t}yf(x)g(y)dydx \\ &-g_t\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_{-\lambda_fx+\lambda_fq_f+q_t}^{q_t}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx \\ &-g_t\int_{q_f+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx \\ &-g_t\int_{q_f}^{\infty}\int_{q_t}^{\infty}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx \\ &-g_t\int_0^{q_f}\int_{q_t}^{\infty}(y-q_t)f(x)g(y)dydx\Bigg\} + b\Bigg\{\int_0^{q_f}\int_0^{q_t}(q_f-x)f(x)g(y)dydx \\ &+\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}\left[q_f - x - \lambda_t(y-q_t)\right]f(x)g(y)dydx\Bigg\} \\ &-wq_f + r_t(c_fq_f + c_tq_t - B) \end{aligned} \tag{A24}$$

Differentiating $\Pi_f(q_f,q_t)$ with respect to q_f generates the following equation:

$$
\begin{aligned}
\frac{\partial \Pi_f(q_f,q_t)}{\partial q_f} &= \varphi_1\Bigg\{p_f-(p_f-s_f)\Bigg[\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx \\
&+\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t} f(x)g(y)dydx\Bigg]+g_f\Bigg[\int_{q_f}^{\infty}\int_0^{q_t} f(x)g(y)dydx \\
&+\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx+\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}^{\infty} f(x)g(y)dydx\Bigg]\Bigg\} \\
&-(1-\varphi_2)\lambda_f\Bigg\{(p_t-s_t)\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x+\lambda_f q_f+q_t} f(x)g(y)dydx \\
&-g_t\Bigg[\int_{q_f+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t} f(x)g(y)dydx+\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_{-\lambda_f x+\lambda_f q_f+q_t}^{q_t} f(x)g(y)dydx \\
&+\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx\Bigg]\Bigg\}+b\Bigg[\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx \\
&+\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t} f(x)g(y)dydx\Bigg]-w+r_tc_f
\end{aligned}
\tag{A25}
$$

Eq. (10) can be written as follows:

$$
\begin{aligned}
\Pi_t(q_f(q_t),q_t) &= \varphi_2\Bigg\{p_tq_t\Bigg[1-\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx\Bigg] \\
&+s_tq_t\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx+(p_t-s_t)\int_0^{q_f}\int_0^{q_t} yf(x)g(y)dydx \\
&-(p_t-s_t)\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x+\lambda_f q_f+q_t}\left[q_t-y-\lambda_f(x-q_f)\right]f(x)g(y)dydx \\
&-g_t\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_{-\lambda_f x+\lambda_f q_f+q_t}^{q_t}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx \\
&-g_t\int_{q_f+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx \\
&-g_t\int_{q_f}^{\infty}\int_{q_t}^{\infty}\left[y+\lambda_f(x-q_f)-q_t\right]f(x)g(y)dydx \\
&-g_t\int_0^{q_f}\int_{q_t}^{\infty}(y-q_t)f(x)g(y)dydx\Bigg\} \\
&+(1-\varphi_1)\Bigg\{p_fq_f\Bigg[1-\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx\Bigg]+s_fq_f\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx \\
&-(p_f-s_f)\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}\left[q_f-x-\lambda_t(y-q_t)\right]f(x)g(y)dydx \\
&+(p_f-s_f)\int_0^{q_f}\int_0^{q_t} xf(x)g(y)dydx-g_f\int_{q_f}^{\infty}\int_0^{q_t}(x-q_f)f(x)g(y)dydx \\
&-g_f\int_{q_f}^{\infty}\int_{q_t}^{\infty}\left[x+\lambda_t(y-q_t)-q_f\right]f(x)g(y)dydx \\
&-g_f\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}^{\infty}\left[x+\lambda_t(y-q_t)-q_f\right]f(x)g(y)dydx\Bigg\} \\
&-b\Bigg\{\int_0^{q_f}\int_0^{q_t}(q_f-x)f(x)g(y)dydx \\
&+\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}\left[q_f-x-\lambda_t(y-q_t)\right]f(x)g(y)dydx\Bigg\} \\
&+wq_f-(c_fq_f+c_tq_t)-r_t(c_fq_f+c_tq_t-B)
\end{aligned}
\tag{A26}
$$

Differentiating $\Pi_t(q_f,q_t)$ with respect to q_f and q_t generates the following equation:

$$\begin{aligned}
\frac{\partial \Pi_t(q_f,q_t)}{\partial q_f} &= (1-\varphi_1)\Bigg\{p_f-(p_f-s_f)\Bigg[\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx \\
&+\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t} f(x)g(y)dydx\Bigg]+g_f\Bigg[\int_{q_f}^{\infty}\int_0^{q_t} f(x)g(y)dydx \\
&+\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx+\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}^{\infty} f(x)g(y)dydx\Bigg]\Bigg\} \\
&-\varphi_2\lambda_f\Bigg\{(p_t-s_t)\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x+\lambda_f q_f+q_t} f(x)g(y)dydx \\
&-g_t\Bigg[\int_{q_f+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t} f(x)g(y)dydx+\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_{-\lambda_f x+\lambda_f q_f+q_t}^{q_t} f(x)g(y)dydx \\
&+\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx\Bigg]\Bigg\}-b\Bigg[\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx \\
&+\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t} f(x)g(y)dydx\Bigg]+w-(1+r_t)c_f
\end{aligned} \tag{A27}$$

$$\begin{aligned}
\frac{\partial \Pi_t(q_f,q_t)}{\partial q_t} &= \varphi_2\Bigg\{p_t-(p_t-s_t)\Bigg[\int_0^{q_f}\int_0^{q_t} f(x)g(y)dydx \\
&+\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_0^{-\lambda_f x+\lambda_f q_f+q_t} f(x)g(y)dydx\Bigg]+g_t\Bigg[\int_0^{q_f}\int_{q_t}^{\infty} f(x)g(y)dydx \\
&+\int_{q_f+\frac{q_t}{\lambda_f}}^{\infty}\int_0^{q_t} f(x)g(y)dydx+\int_{q_f}^{q_f+\frac{q_t}{\lambda_f}}\int_{-\lambda_f x+\lambda_f q_f+q_t}^{q_t} f(x)g(y)dydx \\
&+\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx\Bigg]\Bigg\}-(1-\varphi_1)\lambda_t\Bigg\{(p_f-s_f)\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t} f(x)g(y)dydx \\
&-g_f\Bigg[\int_{q_f}^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx+\int_0^{q_f}\int_{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t}^{\infty} f(x)g(y)dydx\Bigg]\Bigg\} \\
&-b\lambda_t\int_0^{q_f}\int_{q_t}^{-\frac{1}{\lambda_t}x+\frac{q_f}{\lambda_t}+q_t} f(x)g(y)dydx-(1+r_t)c_t
\end{aligned} \tag{A28}$$

According to the assumptions of α_1, α_2, β_1, and β_2, we have:

$$\begin{aligned}
\frac{\partial \Pi_c(q_f,q_t)}{\partial q_f} &= -(p_f-s_f)\alpha_1+g_f(1-\alpha_1)-\lambda_f(p_t-s_t)\alpha_2 \\
&+\lambda_f g_t\Bigg[\int_{q_f}^{\infty}\int_0^{\infty} f(x)g(y)dydx-\alpha_2\Bigg]+p_f-c_f \\
&= p_f-c_f+g_f+\lambda_f g_t\int_{q_f}^{\infty}\int_0^{\infty} f(x)g(y)dydx \\
&-(p_f-s_f+g_f)\alpha_1-\lambda_f(p_t-s_t+g_t)\alpha_2 \\
&= p_f-c_f+g_f+\lambda_f g_t\int_{q_f}^{\infty} f(x)dx-(p_f-s_f+g_f)\alpha_1-\lambda_f(p_t-s_t+g_t)\alpha_2
\end{aligned} \tag{A29}$$

$$\begin{aligned}
\frac{\partial \Pi_c(q_f,q_t)}{\partial q_t} &= -\lambda_t(p_f-s_f)\beta_2+\lambda_t g_f\Bigg[\int_0^{\infty}\int_{q_t}^{\infty} f(x)g(y)dydx-\beta_2\Bigg] \\
&-(p_t-s_t)\beta_1+g_t(1-\beta_1)+p_t-c_t \\
&= p_t-c_t+g_t+\lambda_t g_f\int_{q_t}^{\infty} g(y)dy-(p_t-s_t+g_t)\beta_1-\lambda_t(p_f-s_f+g_f)\beta_2
\end{aligned} \tag{A30}$$

$$\begin{aligned}\frac{\partial\Pi_f(q_f,q_t)}{\partial q_f} &= \varphi_1\left[p_f-(p_f-s_f)\alpha_1+g_f(1-\alpha_1)\right]\\ -(1-\varphi_2)\lambda_f&\left\{(p_t-s_t)\alpha_2-g_t\left[\int_{q_f}^{\infty}\int_0^{\infty}f(x)g(y)dydx-\alpha_2\right]\right\}+b\alpha_1-w+r_tc_f\\ &= \varphi_1\left[p_f+g_f-(p_f-s_f+g_f)\alpha_1\right]\\ -(1-\varphi_2)\lambda_f&\left[(p_t-s_t+g_t)\alpha_2-g_t\int_{q_f}^{\infty}\int_0^{\infty}f(x)g(y)dydx\right]+b\alpha_1-w+r_tc_f\\ &= \varphi_1\left[p_f+g_f-(p_f-s_f+g_f)\alpha_1\right]\\ -(1-\varphi_2)\lambda_f&\left[(p_t-s_t+g_t)\alpha_2-g_t\int_{q_f}^{\infty}f(x)dx\right]+b\alpha_1-w+r_tc_f\end{aligned}\tag{A31}$$

$$\begin{aligned}\frac{\partial\Pi_t(q_f,q_t)}{\partial q_f} &= (1-\varphi_1)\left[p_f-(p_f-s_f)\alpha_1+g_f(1-\alpha_1)\right]\\ -\varphi_2\lambda_f&\left\{(p_t-s_t)\alpha_2-g_t\left[\int_{q_f}^{\infty}\int_0^{\infty}f(x)g(y)dydx-\alpha_2\right]\right\}-b\alpha_1+w-(1+r_t)c_f\\ &= (1-\varphi_1)\left[p_f+g_f-(p_f-s_f+g_f)\alpha_1\right]\\ -\varphi_2\lambda_f&\left[(p_t-s_t+g_t)\alpha_2-g_t\int_{q_f}^{\infty}\int_0^{\infty}f(x)g(y)dydx\right]-b\alpha_1+w-(1+r_t)c_f\\ &= (1-\varphi_1)\left[p_f+g_f-(p_f-s_f+g_f)\alpha_1\right]-\varphi_2\lambda_f[(p_t-s_t+g_t)\alpha_2\\ &\quad -g_t\int_{q_f}^{\infty}f(x)dx\Big]-b\alpha_1+w-(1+r_t)c_f\end{aligned}\tag{A32}$$

$$\begin{aligned}\frac{\partial\Pi_t(q_f,q_t)}{\partial q_t} &= \varphi_2[p_t-(p_t-s_t)\beta_1+g_t(1-\beta_1)]\\ -(1-\varphi_1)\lambda_t&\left\{(p_f-s_f)\beta_2-g_f\left[\int_0^{\infty}\int_{q_t}^{\infty}f(x)g(y)dydx-\beta_2\right]\right\}-b\lambda_t\beta_2-(1+r_t)c_t\\ &= \varphi_2[p_t+g_t-(p_t-s_t+g_t)\beta_1]\\ -(1-\varphi_1)\lambda_t&\left[(p_f-s_f+g_f)\beta_2-g_f\int_0^{\infty}\int_{q_t}^{\infty}f(x)g(y)dydx\right]-b\lambda_t\beta_2-(1+r_t)c_t\\ &= \varphi_2[p_t+g_t-(p_t-s_t+g_t)\beta_1]-(1-\varphi_1)\lambda_t\left[(p_f-s_f+g_f)\beta_2-g_f\int_{q_t}^{\infty}g(y)dy\right]\\ &\quad -b\lambda_t\beta_2-(1+r_t)c_t\end{aligned}\tag{A33}$$

Since the optimal empty container leasing quantity q_t^* of the carrier in the direct channel satisfies $\frac{d\Pi_t(q_f,q_t)}{dq_t}=\frac{\partial\Pi_t(q_f,q_t)}{\partial q_f}\frac{dq_f}{dq_t}+\frac{\partial\Pi_t(q_f,q_t)}{\partial q_t}=0$, and according to $\frac{\partial\Pi_c(q_f,q_t)}{\partial q_f}=0$ and $\frac{\partial\Pi_f(q_f,q_t)}{\partial q_f}=0$, we know that $\frac{\partial\Pi_t(q_f,q_t)}{\partial q_f}=0$. Therefore, the optimal empty container leasing quantity $\left(q_f^*,q_t^*\right)$ satisfies the conditions $\frac{\partial\Pi_f(q_f,q_t)}{\partial q_f}=0$ and $\frac{\partial\Pi_t(q_f,q_t)}{\partial q_t}=0$.

From $\frac{\partial\Pi_c(q_f,q_t)}{\partial q_f}=0$, we obtain:

$$\lambda_f=\frac{p_f+g_f-(p_f-s_f+g_f)\alpha_1-c_f}{(p_t-s_t+g_t)\alpha_2-g_t\int_{q_f}^{\infty}f(x)\mathrm{d}x}\tag{A34}$$

From $\frac{\partial\Pi_c(q_f,q_t)}{\partial q_t}=0$, we obtain:

$$\lambda_t=\frac{p_t+g_t-(p_t-s_t+g_t)\beta_1-c_t}{(p_f-s_f+g_f)\beta_2-g_f\int_{q_t}^{\infty}g(y)\mathrm{d}y}\tag{A35}$$

From $\frac{\partial\Pi_f(q_f,q_t)}{\partial q_f}=0$, we obtain:

$$w=\varphi_1\left[p_f+g_f-(p_f-s_f+g_f)\alpha_1\right]-(1-\varphi_2)\lambda_f\left[(p_t-s_t+g_t)\alpha_2-g_t\int_{q_f}^{\infty}f(x)\mathrm{d}x\right]+b\alpha_1+r_tc_f\tag{A36}$$

From $\frac{\partial\Pi_t(q_f,q_t)}{\partial q_t}=0$, we obtain:

$$\varphi_2 = \frac{(1-\varphi_1)\lambda_t\left[\left(p_f - s_f + g_f\right)\beta_2 - g_f\int_{q_t}^{\infty} g(y)dy\right] + b\lambda_t\beta_2 + (1+r_t)c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1} \tag{A37}$$

By combining Eq. (A.29) ~ Eq. (A.32), we obtain:

$$\varphi_2 = 1 - \varphi_1 + \frac{b\beta_2}{\left(p_f - s_f + g_f\right)\beta_2 - g_f\int_{q_t}^{\infty} g(y)dy} + \frac{c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1}\left[\varphi_1 + r_t - \frac{b\beta_2}{\left(p_f - s_f + g_f\right)\beta_2 - g_f\int_{q_t}^{\infty} g(y)dy}\right] \tag{A38}$$

$$w = (\varphi_1 + r_t)\left[c_f + \frac{p_f + g_f - \left(p_f - s_f + g_f\right)\alpha_1 - c_f}{p_t + g_t - (p_t - s_t + g_t)\beta_1}\cdot c_t\right] + \frac{b\beta_2\left[p_f + g_f - \left(p_f - s_f + g_f\right)\alpha_1 - c_f\right]}{\left(p_f - s_f + g_f\right)\beta_2 - g_f\int_{q_t}^{\infty} g(y)dy}\cdot\left[1 - \frac{c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1}\right] + b\alpha_1 \tag{A39}$$

Proof of Proposition 4

Substituting the value of φ_2 into Eq. (23) and Eq. (24), we obtain:

$$\begin{aligned}\Delta\Pi_f = {} & (\varphi_1 - 1)\left[p_f E\min\left(q_f, D_f\right) + s_f E\left(q_f - D_f\right)^+ - g_f E\left(D_f - q_f\right)^+\right] \\ & + \left\{\varphi_1 - \frac{b\beta_2}{\left(p_f - s_f + g_f\right)\beta_2 - g_f\int_{q_t}^{\infty} g(y)dy} - \frac{c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1}\cdot\left[\varphi_1 + r_t - \frac{b\beta_2}{\left(p_f - s_f + g_f\right)\beta_2 - g_f\int_{q_t}^{\infty} g(y)dy}\right]\right\} \\ & \cdot\left[p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+\right] + bE\left(q_f - D_f\right)^+\end{aligned} \tag{A40}$$

$$\begin{aligned}\Delta\Pi_t = {} & \left\{-\varphi_1 + \frac{b\beta_2}{\left(p_f - s_f + g_f\right)\beta_2 - g_f\int_{q_t}^{\infty} g(y)dy} + \frac{c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1}\cdot\left[\varphi_1 + r_t - \frac{b\beta_2}{\left(p_f - s_f + g_f\right)\beta_2 - g_f\int_{q_t}^{\infty} g(y)dy}\right]\right\} \\ & \cdot\left[p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+\right] - bE\left(q_f - D_f\right)^+ \\ & + (1 - \varphi_1)\left[p_f E\min\left(q_f, D_f\right) + s_f E\left(q_f - D_f\right)^+ - g_f E\left(D_f - q_f\right)^+\right]\end{aligned} \tag{A41}$$

$$\begin{aligned}\therefore\frac{\partial\Delta\Pi_f}{\partial\varphi_1} = {} & \left[p_f E\min\left(q_f, D_f\right) + s_f E\left(q_f - D_f\right)^+ - g_f E\left(D_f - q_f\right)^+\right] \\ & + \frac{p_t + g_t - (p_t - s_t + g_t)\beta_1 - c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1} \\ & \cdot\left[p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+\right]\end{aligned} \tag{A42}$$

$$\begin{aligned}\frac{\partial\Delta\Pi_t}{\partial\varphi_1} = {} & -\left[p_f E\min\left(q_f, D_f\right) + s_f E\left(q_f - D_f\right)^+ - g_f E\left(D_f - q_f\right)^+\right] \\ & - \frac{p_t + g_t - (p_t - s_t + g_t)\beta_1 - c_t}{p_t + g_t - (p_t - s_t + g_t)\beta_1} \\ & \cdot\left[p_t E\min(q_t, D_t) + s_t E(q_t - D_t)^+ - g_t E(D_t - q_t)^+\right]\end{aligned} \tag{A.43}$$

It is easy to obtain that $\frac{\partial\Delta\Pi_f}{\partial\varphi_1} = -\frac{\partial\Delta\Pi_t}{\partial\varphi_1}$.

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