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# Strategic port competition in multimodal network development considering shippers' choice

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***Abstract****:* Ports are developing dry ports in overlapping hinterland to gain competitive edges and relieve congestion. However, the impact of sequential port competition in multimodal network design where two ports sequentially locate dry ports considering dry port capacity is under-investigated. The possible correlation of inland transport routes to a port due to unobserved attributes and parameter calibration are overlooked in shippers' choice model. We formulate a nested logit model to describe the joint choice of shippers on port, transport mode and dry port considering dry port service and range, custom clearance time, reliability, freight shipment size, and ship call frequency using calibrated parameters based on data collected by revealed preference and stated preference techniques. A Stackelberg game theoretical model is established for the two ports, and two algorithms are adapted to obtain Stackelberg equilibrium solution. We find that inland transport cost, inland transit and custom clearance time are more appreciated in multimodal transport than in road transport. Reliability and large-scale freight shipment are key factors for choosing multimodal transport. When the dry port location strategy of one port in Stackelberg equilibrium is its only dominant strategy in Nash game, Stackelberg equilibrium solution would be the same as pure Nash equilibrium solution. Leader port's dry port location strategy in Stackelberg equilibrium could be different from its dominant strategies in Nash game. Dry port location strategy could be affected by port service charge and waiting time.

***Keywords***: Stackelberg game; Dry port; Discrete choice model; Multimodal transport; Competitive location

## 1. Introduction

Ports are developing towards hinterland actions and investments with an aim of supporting their core business (Acciaro et al., 2017; Monios and Wilmsmeier, 2012). In recent years, the slower pace of global economy growth has coincided with a slowdown in international trade. Global shipping alliances have introduced larger vessels to benefit from economies of scale at sea. To strengthen the competitive position as ports of call, container ports actively make investments to improve port-hinterland connectivity (Notteboom et al., 2017). Moreover, congestion, limited capacity and the generation of additional traffic require ports to develop modern hinterland freight distribution network (Notteboom and Rodrigue, 2005). In view of shippers, inland transport cost plays a vital role in choosing which port to visit. Under the regionalization phase of port development, the inland distribution segment of supply chain forms an important target for reducing logistics cost and improving effciency (Notteboom and Rodrigue, 2005). These support the development outside of ports based on multimodal transport (Nebot et al., 2017; Crainic et al., 2015).

The immense pressure on developing multimodal network in hinterland has demanded and promoted the development of dry ports (Notteboom and Rodrigue, 2005). As defined by Leveque and Roso (2002), a dry port is an inland intermodal terminal directly connected to port(s) by high transport capacity, where customers can leave/pick up their standard units as if directly to a port. A fully-fledged dry port offers services that are usually available at ports, such as transshipment, consolidation, storage, customs clearance, depot of empty containers, maintenance and repair of containers and additional valued-added logistics services (Roso et al., 2009). Export cargoes are first consolidated at a dry port before transported to a port by train or barge. Import cargoes arriving at a port are first transported to a dry port by train or barge and then transferred to trucks for movement to destinations (Teye et al., 2017).

A number of dry ports are planned and invested by ports in overlapping hinterland (Wilmsmeier et al., 2011). For ports in a multi-port gateway region (Notteboom, 2010), efficient multimodal transport is paramount to control hinterland links (Monios and Wilmsmeier, 2013). Thus many ports invest in dry ports for the purpose of relieving operational burden at the capacity constrained port and capturing more cargoes from hinterland (Chang et al., 2018). Nevertheless, having multiple dry ports within a catchment area may enhance competition among dry ports, which may be detrimental to dry port efficiency and restrict the transformation of port resources into economic superiority (Chang et al., 2018; Wu and Yang, 2018). Thus, when designing multimodal transport network, a port must consider the strategies of its competitors (Xu et al., 2018).

The choice behavior of shippers is another important feature that should be taken into consideration in multimodal transport network design in hinterland. Shippers generate freight transportation demand and participate in the organization of how their freight should be moved (Crainic et al.,2018). A hinterland transport chain is a transport route over which cargo exported from the hinterland is transported by a multimodal carrier from the exporter in the network to port or to dry port and then to port (the import market is reverse) (Talley and Ng, 2017). After building a multimodal transport network in hinterland, each shipper has a choice of using multimodal or road alone transport route for the movement of his/her cargo to a port. In order for cargo to be exported from (or imported into) the hinterland, shippers must be willing to involve in cargo importation into (or cargo exportation from) the hinterland (Talley and Ng, 2017). Thus, hinterland transport chain choice behavior of shippers may directly influence the cargo flow over hinterland distribution network.

Another important feature in multimodal transport network design concerns the existence of capacity constraint. Dry ports are hub nodes where services such as consolidation, sorting, storage and transshipment between traffic modes are provided (Roso et al., 2009). The capacity of a dry port may be restricted to the maximum volume of handling, storage and circulating process (Zeng et al., 2011). Additional cargoes may not be served at a dry port after reaching its maximum capacity. This may limit the multimodal transport volume to a port. It is more realistic to operate a multimodal transport network considering dry port capacity constraint.

Some studies have investigated simultaneous port competition in multimodal network design based on Nash game-theoretical models without dry port capacity constraint (Xu et al., 2018; Zhang et al., 2018). However, sequential port competition in multimodal network design considering dry port capacity constraint is under-investigated. Nash port competition in multimodal network design assumes that each port chooses its dry port location strategy simultaneously without knowing the decision outcome of its rivals in advance. Besides, there may exist many Nash equilibrium solutions, which makes it hard to predict the behavior of competitors. In reality, ports may not always design their multimodal transport networks simultaneously. It is also possible for ports to enter multimodal transport market in a sequential order. For instance, after Rizhao port constructed a dry port in Linyi in 2008, Qingdao port constructed a dry port in Houma in 2009 (Notteboom and Yang, 2017). After Dalian port established a dry port in Shenyang, Yingkou port also established its dry port there. After Yingkou port established a dry port in Tongliao, Dalian port followed that. In a sequential competition environment, the leader (the one that makes initial decision) considers the impact of his/her decision outcome on that of the follower (the other player). The follower knows the decision outcome of the leader before choosing his/her own strategy. The feasible and best strategy of the follower are dependent on leader's decision outcome. To refine Nash equilibrium solutions and predict the equilibrium solution when ports design multimodal network in a sequence way, there is a need to study the effect of sequential port competition in multimodal network design considering dry port capacity constraint.

Further, multinomial logit (MNL) discrete choice model is widely used to investigate shippers' choice behavior (Xu et al., 2018; Zhang et al., 2018). MNL model assumes that the random term in utility function is independently and identically distributed according to a Gumbel distribution (Larranaga et al., 2017). One limitation of MNL model is its independence of irrelevant alternatives (IIA) property, which means the ratio of choice probabilities of any two alternatives is independent of the presence or absence of a third alternative in the choice set (Wang and Meng, 2017). The IIA property overestimates the probabilities of related alternatives and underestimates the probabilities of unrelated alternatives (Qin et al., 2017). The model structure of MNL restricts the substitution among alternatives and does not allow for correlations due to unobserved factors (Larranaga et al., 2017). However, because unobserved attributes of inland transport routes to a port may be correlated (Tapia et al., 2019), the IIA property of MNL model could not be satisfied. Besides, the influence of dry port service range and quality, custom clearance time, transport mode reliability, freight shipment size, ship call frequency on shippers' hinterland transport chain choice is neglected. As dry port can provide a range of services at different levels, dry port service quality and range is an important selection criterion for its users (Nguyen and Notteboom, 2016). Dry port can serve as an inland clearance depot (Roso et al., 2009), which may greatly improve customs clearance efficiency of multimodal transport. As shippers often worry about the simplicity and transparency of custom procedure (Chen et al., 2017), custom clearance time should be incorporated. Reliability is an important factor influencing transport mode choice for firms operating in a just-in-time context (Kim et al., 2017). The size of freight shipment determines transport mode (Piendl et al., 2017) . Greater frequency of ship call allows for greater flexibility and lower transit time at port (Kavirathna et al., 2018; Tongzon, 2009). In the meantime, the coefficients of attributes in the utility function of shippers' choice are exogenously given in most researches (Xu et al., 2018; Zhang et al., 2018). These gaps in literature may lead to biased results of freight flow and dry port location strategy.

This paper aims to explore the impact of sequential port competition in multimodal network design considering shippers' hinterland transport chain choice behavior (the joint choice behavior of port, transport mode and dry port), and the capacity constraint of dry port. Two competitive ports are serving a common hinterland and there are some demand cities with containers of shippers to be exported. The two ports sequentially make multimodal network design decisions by determining the location of new dry ports to maximize their captured multimodal flow by dry ports. Each shipper transports all his/her containers to one of the two ports using a road or multimodal transport route depending on the utility of port, transport mode and dry port. Considering the randomness of utility caused by unobserved factors (Zhang et al., 2018), a shipper chooses a hinterland transport chain from a set of available hinterland transport chains with a certain probability. Dry ports are responsible for integration, transshipment, temporary storage, consolidation and distribution, and custom clearance. Additional value-added logistics services can be provided at different levels or not provided at dry ports. Total flows that can be transported through a dry port cannot exceed its capacity. A two-level nested logit (NL) discrete choice model is established to describe the hinterland transport chain choice behavior of shippers. A Stackelberg game theoretical model of sequential port competition in multimodal network design is proposed combing the nested logit model. Two algorithms are adapted to obtain Stackelberg equilibrium solution. The models and algorithms are developed to answer the following questions: Whether nested logit model is more appropriate than multinomial logit model in describing shippers' hinterland transport chain choice behavior? Whether dry port service range and quality, custom clearance time, reliability, shipment size, ship call frequency have significant impacts on shippers' choice? How to estimate the coefficients of the attributes in utility function? What are the connections and distinctions between Stackelberg and Nash equilibrium solution? How port competition and dry port construction influence dry port location strategy and the market shares of ports and multimodal transport?

It seems unusual at first glance that port makes decision on dry port location without considering pricing strategy. However, according to our interview results with port managers, dry port construction in a competitive environment is a strategic investment. It means that occupying advantage places to capture more cargoes by dry ports is more important, even if that will lead to financial loss. Profit is not a primary goal for some ports in a competitive environment. It is common for decision makers to maximize their total captured flow in studies devoted to transport network design under competition (Ghaffarinasab et al., 2018; Mahmutogullari and Kara, 2016; Niknamfar et al., 2017). Thus, this paper focuses on port competition in a strategic level (dry port location decision) rather than operational level (port service price decision). Although port service charge is not optimized in the model, its impact will be analyzed in Section 6.2. Readers interested in both strategic and operational level of port competition in multimodal network design may refer to Zhang et al. (2018).

The remainder of this paper is organized as follows. Section 2 reviews previous relevant studies and identifies research gaps. Section 3 describes the sequential port competition in multimodal network design and the choice behavior of shippers. In Section 4, we set up a nested logit model and a Stackelberg game-theoretical model. The algorithms are presented in Section 5. Section 6 presents and analyzes the results. Section 7 summarizes key findings and discusses their implications.

## 2 Literature review

Table 1 classifies relevant studies into three categories: (1) dry port location problem, (2) multimodal transport network design problem (3) transport network design with competition and capacity constraints.

### *2.1 Dry port location problem*

Strategic planning issue for the development of multimodal network in hinterland is represented by dry port location problem (DPLP) (Crainic et al., 2015; Witte et al., 2019). In the first part of Table 1, only Xu et al. (2018) and Zhang et al. (2018) planned dry port-based network considering simultaneous port competition without capacity constraint of dry port. However, ports may not always design multimodal transport networks simultaneously. It is possible for ports to enter the multimodal transport market is a sequential way. Besides, considering dry port capacity in port competition in multimodal network design is more realistic. This paper explores the connection and distinction of simultaneous and sequential port competition in multimodal network design incorporating dry port capacity constraint.

Concerning attributes influencing shippers' choice, although Wei and Dong (2019) considered custom clearance cost, attributes such as custom clearance time, dry port service range and quality, transport mode reliability, freight shipment size, ship call frequency on shippers' hinterland transport chain choice are neglected. According to our survey with shippers, intermodal operators, and port managers, these attributes have important influence on their choice of dry port, transport mode and port. Since these factors are not included in the literature related to shippers' choice, it may lead to biased results of freight flow on each route. The impact of these factors is identified in this paper.

In modelling shippers' choice, some papers assumed deterministic utilities of all shippers and planned cargo flow by cost minimization (Chang et al., 2015; Tsao and Thanh, 2019; Tsao and Linh, 2018; C. Wang et al., 2018; Wei and Dong, 2019). However, this seems restrictive when we consider many shippers who have quite distinct perceptions on which hinterland transport chain is of the highest utility (Wang and Meng, 2017). Besides, not all attributes influencing choice behavior are known to the analyst or can be quantified and included in the model (Teye et al., 2017). To fix this drawback, multinomial logit (MNL) discrete choice model was widely used to investigate shippers' choice behavior (Xu et al., 2018; Zhang et al., 2018). In the framework of discrete choice modelling, utility is considered to be random over a lot of decision makers, which means that each decision maker chooses a hinterland transport chain from his/her available set with a probability (Wang and Meng, 2017). However, the MNL model restricts the substitution among alternatives and does not allow for correlations due to unobserved factors (Larranaga et al., 2017). The IIA property of MNL model overestimates the probabilities of related alternatives and underestimates the probabilities of unrelated alternatives. Besides, parameters in the utility functions of MNL model are exogenously given (Xu et al., 2018; Zhang et al., 2018), which may lead to simulation bias of shippers' choice. To fix the drawback of MNL model, we use nested logit model to depict shippers' choice behavior. Moreover, we use revealed preference (RP) and stated preference (SP) techniques for collecting data of shippers to calibrate the parameters in utility functions of both NL and MNL models.

### *2.2 Multimodal transport network design problem*

The multimodal transport network design problem (MTNDP) has attracted much attention in recent years (Crainic et al., 2018; Steadieseifi et al., 2014). The dry port location problem (DPLP) can be considered as a particular type of multimodal transport network design problem (MTNDP). But there are some differences between DPLP and MTNDP. Firstly in terms of network topology, a dry port must be connected with a port in DPLP (Roso et al., 2009; Woxenius et al., 2004). Shippers can transport containers to port(s) directly by truck, or first to/from a dry port by trucks and then to port(s) by train or barge (Teye et al., 2017). MTNDP involves two intermodal terminals (IMTs) in the movement between an origin-destination pair. Cargo is consolidated at an IMT and then transported by a high capacity means to another intermodal terminal before transported to destination by trucks. Compared with MTNDP, there is an extra shippers' choice problem between road only and multimodal transport route between an origin-destination pair in DPLP. Factors influencing transport mode choice should be considered, such as shipment size and reliability. Secondly in terms of terminal services, dry ports are much more consciously used than intermodal terminals as extended gates of ports and an interface with shipping lines (Monios, 2011; Roso et al., 2009). Apart from the transshipment and consolidation services that an intermodal terminal can provide, a dry port can also provide custom clearance service. Since more services can be provided at dry port, especially custom clearance, the impact of dry port service range and quality and custom clearance on shippers' choice should be investigated. Thirdly in terms of development motivation, dry ports are promoted by port actors to increase competitiveness, expand hinterland, reduce congestion, and deal with safety and environmental issues associated with the use of trucks (Notteboom and Rodrigue, 2005). While economies of scale between two intermodal terminals are key drivers for the use of terminals in MTNDP (Teye et al., 2017). Since dry port is paramount for port to increase competitiveness and relieve capacity limitations, the impact of port competition and dry port capacity on dry port location strategy should be investigated.

**Table 1**
Summary of the related studies

| Paper | Competition and decision | Objective | Capacity constraint | Factors influencing flow distribution | Flow assignment model | Parameter calibration technique | Solution method |
|---|---|---|---|---|---|---|---|
| 1. Dry port location | | | | | | | |
| Chang et al. (2015) | × | Cost minimization | Dry port | Transport cost, storage cost at dry port | × | × | Genetic algorithm |
| C. Wang et al. (2018) | × | Cost minimization | Dry port | Transport cost, congestion cost | × | × | CPLEX |
| Tsao and Linh (2018) | × | Cost minimization, profit maximization | × | Transport cost, storage cost at dry port, congestion cost, carbon emission cost | × | × | Heuristic |
| Zhang et al. (2018) | Nash competition of ports in dry port location, charge and port charge | Profit maximization | × | Transport cost, transport time, transport convenience, port berth number, ship routes number, port service quality | Multinomial logit model | × | Enumeration based Nash equilibrium solution algorithm |
| Xu et al. (2018) | Nash competition of ports in dry port location | Profit maximization | × | Transport cost, transit time, transport convenience, port berth number, ship routes number, port service quality, $CO_2$ emission | Multinomial logit model | × | Approximate Nash equilibrium solution algorithm |
| Tsao and Thanh (2019) | × | Minimization of economic cost, $CO_2$ emission, unemployment and immigration cost per laborer | Dry port | Transport cost, handling and storage cost at dry port, unit $CO_2$ emission per distance, congestion cost | × | × | ε-constraint solution method |
| Wei and Dong (2019) | × | Minimization of cost and time | Dry port | Transport cost and time, handling and storage cost and time at dry port, cross-border rail changing cost and time, custom clearance cost, inspection and quarantine cost | × | × | Adaptive weight Genetic Algorithm |
| This paper | Stackelberg competition of leader and follower ports in dry port location | Maximization of captured multimodal flow | Dry port | Inland transport cost, Inland transit time and custom clearance time, reliability, dry port service range and quality, shipment size, port charge, waiting time at port, ship call frequency | Nested logit model | Stated preference and revealed preference | Algorithms based on complete enumeration and smart enumeration method |
| 2. Strategic multimodal network design | | | | | | | |
| Teye et al. (2017) | × | Entropy maximization | Intermodal terminal | Transport cost, congestion cost | Nested logit model without port | × | Lagrangian relaxation |
| Wang and Meng (2017) | × | Cost minimization | Link | Transport fare, travel time, congestion cost and time | General discrete choice model | × | Branch and bound, heuristic |
| R. Wang et al. (2018) | × | Cost and maximum time minimization | × | Transport cost and time between an O-D pair | × | × | Memetic algorithm |
| Mokhtar et al. (2018) | × | Cost minimization | × | Transport cost between an O-D pair | × | × | CPLEX |
| 3. Transport network design with competition and capacity constraints | | | | | | | |
| Marianov et al. (1999) | Stackelberg competition of follower in hub location | Captured flow or revenue maximization | × | Transport cost between an O-D pair | × | × | Tabu heuristic |
| Lüer-Villagra and Marianov (2013) | Stackelberg competition of follower in hub location | Profit maximization | × | Service charge between an O-D pair | Multinomial logit model | × | Genetic algorithm |
| Sasaki et al. (2014) | Stackelberg competition of leader and follower in hub location | Revenue maximization | × | Transport cost or path distance ratios | × | × | Algorithm based on smart enumeration method |
| Mahmutogullari and Kara (2016) | Stackelberg competition of leader and follower in hub location | Captured flow maximization | × | Service level based on cost | × | × | CPLEX |
| Niknamfar et al. (2017) | Stackelberg competition of follower in hub location | Captured flow maximization and cost minimization | Hub | Transport cost | × | × | Opposition-based learning |
| Ghaffarinasab et al. (2018) | Stackelberg competition of leader and follower in hub location | Captured flow maximization | × | Transport cost between an O-D pair | × | × | Simulated annealing |

We found in Table 1 that the competition among network planners is neglected in researches concerning MTNDP. Most papers design network by minimizing cost (Mokhtar et al., 2018; R. Wang et al., 2018; Wang and Meng, 2017). However, in a competitive environment, a network planner should consider the decisions of his/her rivals and the preference of network users. This is one aspect we address in our problem.

Factors influencing the route choice of network users are mainly related to cost and time (Mokhtar et al., 2018; Teye et al., 2017; R. Wang et al., 2018; Wang and Meng, 2017), services of nodes along the routes and factors influencing transport mode choice are neglected in MTNDP. In DPLP, ports and dry ports are important nodes along hinterland transport chain. In a competitive environment, the differences in port and dry port service give one port competitive edge over its competitor. Besides, there is a transport mode choice problem in DPLP between multimodal and road transport route, which makes it necessary to consider factors influencing transport mode choice, like shipment size and reliability (Piendl et al., 2017). The influence of port and dry port services, shipment size and reliability on the choice of shippers is explored in our model.

In behavior modelling of multimodal network users, discrete choice models are used without parameter calibration. Teye et al. (2017) used a nested logit model to depict the choice of shippers between road and multimodal route without port, in which cost was the only factor influencing route choice. Wang and Meng (2017) modelled cargo flow under a general discrete choice model. Parameters are exogenously given in numerical test, which may lead to biased flow distribution results. Calibrated parameters based on revealed preference and stated preference data are used in the utility function of our model.

*2.3 Transport network design with competition and capacity constraints*

According to the third part in Table 1, the studies which considered the decisions of both leader and follower didn't consider hub capacity constraint. Some papers only addressed the problem of follower (Lüer-Villagra and Marianov, 2013; Marianov et al., 1999; Niknamfar et al., 2017), which means the decision of leader has been given. Only Niknamfar et al. (2017) considered hub capacity constraint in follower's location problem. Capacity constraints of leader and follower generate more unfeasible solutions, which makes it more complex to solve the two interdependent problems of leader and follower. In this paper, the problems of leader and follower are both considered with hub capacity constraint.

In the route choice of network users, hub services and attributes influencing transport mode choice are not considered. Transport cost and charge were mainly considered factors (Ghaffarinasab et al., 2018; Lüer-Villagra and Marianov, 2013; Mahmutogullari and Kara, 2016; Marianov et al., 1999; Niknamfar et al., 2017; Sasaki et al., 2014). Transport distance ratio was considered by Sasaki et al. (2014). Since shippers' choice is dependent on the whole hinterland transport chain, factors influencing port, transport mode, and dry port are considered in our model.

In behavior modelling of network users, Lüer-Villagra and Marianov (2013) used MNL model to reflect the distinct preferences of network users, but the IIA property of MNL model and the correlation of transport routes serviced by a firm due to unobserved attributes were neglected. Besides, parameters in utility function are not calibrated. This paper uses NL model to fix this drawback with calibrated parameters.

Besides, limited researches have integrated discrete choice model and hub capacity constraint with transport network design models of leader and follower. The nonlinear and concave objective function related to discrete choice model makes it hard to solve the two interrelated problems of leader and follower using exact algorithms. Probabilistic flow distribution based on discrete choice model considering hub capacity makes it hard to re-distribute flow under unfeasible strategy. This paper designs two exact solution algorithms to solve the multimodal transport network design problem of both leader and follower considering dry port capacity constraint and shippers' choice modelled by nested logit model.

In summary there are three major contributions of this paper. Firstly, a nested logit model is formulated to depict shippers' hinterland transport chain choice behavior with the consideration of custom clearance time, transport mode reliability, dry port service range and quality, shipment size and ship call frequency. Parameters in the utility function of both nested logit model (NL) and multinomial logit model (MNL) are calibrated using revealed preference (RP) and stated preference (SP) data. Secondly, we propose an integrated model combining Stackelberg game-theoretical model with nested logit model in which two ports sequentially make dry port location decisions considering shippers' hinterland transport chain choice behavior and dry port capacity constraint. Considering the nonlinear and concave objective functions, and the interdependent nature of the problems of leader port and follower port, two adapted exact algorithms applying game theory and computer technology are proposed to obtain the Stackelberg equilibrium solution. Thirdly, optimal strategies of dry port location under Stackelberg and Nash equilibriums are compared. Numerical examples are provided to give managerial insights into dry port location, port competition and multimodal transport development based on the analysis of shippers' choice and the impact of port competition and dry port construction.

## 3. Problem setting

*3.1 Port competition in multimodal network design*

Two competitive ports sequentially design multimodal transport networks in their common hinterland by determining the location of new dry ports with the goal of maximizing captured multimodal transport demand by dry ports. The port that makes the initial decision on multimodal transport network design is called leader. And the other port is called follower. If leader's dry port location decision is given, follower port makes decision with respect to its own objective, which is called follower's reaction function. Leader port observes the reaction function of follower, based on which the leader which makes its decision. Dry ports are responsible for integration, transshipment, temporary storage, consolidation and distribution, and customs clearance. Additional value-added logistics services can be provided at different levels or not provided at dry port facilities. Total flows that can be transported through a dry port cannot exceed its capacity.

We assume that the two ports can construct dry ports at the same cities, but they do not share dry port facilities. Only one new dry port facility can be opened by each port at each potential location. Port managers of the two ports are rational when making decisions and both ports are aware of this (Zhang et al.,2018). Both ports have complete knowledge of the competitors' decision and both are aware of this[1].

*3.2 Hinterland transport chain choice behavior of shippers*

There are some demand nodes as origins in the common hinterland with freight (e.g. containers) to be exported. From each demand node, the cargoes of each shipper must be directly transported to one of the two ports by truck or first to a dry port by truck followed by train to a port. Fig.1 shows a logistic system in hinterland composed of two ports, four dry ports and four demand nodes. The four nodes with freight export demands require transportation to one of the two ports. Shippers at the four demand nodes can transport freight to one of the two ports using road or multimodal transport route. The transport demand in each city is assumed to be fixed and known[2].

Each shipper is assumed to be rational and choose the hinterland transport chain (i.e. port, transport mode, and dry port) with the highest utility. The utility reflects a shipper's preference regarding port, transport mode and dry port. Considering distinct perceptions of shippers on which hinterland transport chain is of highest utility, the utility of a hinterland transport chain is considered to be random (Wang and Meng, 2017). And a shipper chooses a hinterland transport chain from a set of available hinterland transport chains with a certain probability.

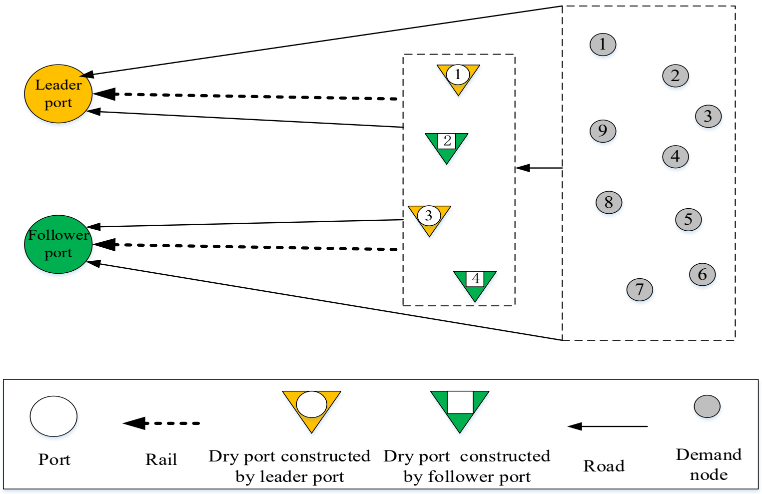


**Fig.1.** Transportation process illustration

## 4. Mathematical model

*4.1 Multimodal transport network formulation*

The multimodal network can be denoted as $G=(N,A)$, where $N$ is the set of nodes and $A$ is the set of links. Let $W \in N$ be the set of demand nodes. Transport demand at node $w \in W$ is denoted by $D_w$. Let $P=\{L,F\}$ be the set of port nodes, where $L$ and $F$ respectively denote leader port and follower port. Denote $H \subset N$ as the set of candidate dry port location for both ports. Denote $H_p \subset H$ as the set of selected dry port locations by port $p \in P$. Let $M=\{road, rail\}$ be the set of transport modes. A link exists between node $i \in N$ and $j \in N$ with mode $m \in M$. The set of links is denoted as $A \subset \{a_{ij}^m : i,j \in N, m \in M\}$. We use $A^{road} = \{a_{ij}^m : i,j \in N, m = road\}$ to denote the set of road

[1] The problem of port competition in multimodal transport network design with incomplete information of each port' payoff function and feasible set of dry port location decision is interesting and merits further study.

[2] The assumption about inelasticity of transport demand in common in facility location problems. The issue of uncertain transport demand in a competitive environment is interesting and we leave it for future research.

transport links and use $A^{rail}=\left\{a_{ij}^{m}:i\in H_{p},j\in P,m=rail\right\}$ to denote the set of rail transport links.

The set of available transport routes for demand node $w \in W$ is represented by $R_w$. Let $R_w^{\text{inter}}$ and $R_w^{road}$ denote the set of available multimodal and road transport routes for node $w \in W$ (Zhang et al.,2018; Xu et al., 2018). One reason to separate $R_w^{\text{inter}}$ and $R_w^{road}$ is that the available multimodal transport routes for each demand node can be different. The distance between a port and a demand node may be too short for multimodal transport to be economically viable (Limbourg and Jourquin, 2009). And we set that multimodal transport is not available if the distance between a demand node and a port is less than 300 km (Limbourg and Jourquin, 2009). Moreover, considering the available road and multimodal transport routes for each demand node is necessary when the model is extended to include disruptions at different transport links and nodes. Let $\delta_w^{a,r}=1$ if route $r \in R_w$ traverses link $a \in A$; otherwise, $\delta_w^{a,r}=0$. Let $\delta_w^{b,r}=1$ if route $r \in R_w$ traverses hub $b \in H \cup P$; otherwise, $\delta_w^{b,r}=0$ (Zhang et al.,2018; Xu et al., 2018). Let the links and nodes traversed by route $r \in R_w$ respectively be denoted as $A_w^r=\left\{a\in A \middle| \delta_w^{a,r}=1, r\in R_w, w\in W\right\}$ and $B_w^r=\left\{b\in H\cup P \middle| \delta_w^{b,r}=1, r\in R_w, w\in W\right\}$. For $w \in W$, the set of multimodal transport routes can be denoted as $R_w^{inter}=\left\{r \middle| \sum_{a\in A^{rail}}\delta_w^{a,r}=1, \sum_{a\in A^{road}}\delta_w^{a,r}=1, \sum_{p\in P}\delta_w^{p,r}=1, \delta_w^{a_{wh}^{road},r}=1, \delta_w^{a_{hp}^{rail},r}=1, \delta_w^{p,r}\cdot\delta_w^{h,r}=1, \sum_{h\in H}\delta_w^{h,r}=1, h\in H_p, p\in P\right\}$. $R_w^{road}=\left\{r \middle| \sum_{a\in A^{road}}\delta_w^{a,r}=1, \sum_{p\in\cup P}\delta_w^{p,r}=1, \delta_w^{a_{wp}^{road},r}\cdot\delta_w^{p,r}=1, p\in P\right\}$ denotes the set of road transport routes (Zhang et al.,2018; Xu et al., 2018).

If node $h$ is selected by port $p \in P$ to establish a dry port, $Y_h^p=1$; otherwise, zero. The set of decision variable about dry port location is defined as $Y^p=\left\{Y_h^p:\ h\in H\right\}$ for port $p \in P$. $y^p \in Y^p$ denotes a feasible decision of port $p \in P$ (Xu et al., 2018). To improve readability, all the relevant notations and their descriptions are presented in Table 2.

**Table 2**

Notations and descriptions

| Notations | Descriptions |
|---|---|
| $N$ | Set of nodes in the transport network |
| $A$ | Set of links in the transport network indexed by $a$, $A=A^{road}\cup A^{rail}$ |
| $W$ | Set of demand nodes indexed by $w$ |
| $D_w$ | Transport demand at $w \in W$, $D_w \in R_+ = [0,+\infty)$ |
| $P$ | Set of ports indexed by $p$ |
| $L$ and $F$ | Leader port, and follower port |
| $H$ | Set of candidate dry port locations indexed by $h$ |
| $H_p$ | Set of selected dry port locations by port $p \in P$, $H_p=\left\{h\in H \middle| Y_h^p=1\right\}$ |
| $M$ | Set of transport modes $M=\left\{road, rail\right\}$ |
| $a_{ij}^m$ | The transport link with transport mode $m \in M$ between node $i \in N$ and node $j \in N$ |
| $A^{road}$ and $A^{rail}$ | Set of road and rail transport links, $A^{road}=\left\{a_{ij}^{road}:i,j\in N,m=road\right\}$, $A^{rail}=\left\{a_{ij}^{m}:i\in H_p,j\in P,m=rail\right\}$ |
| $R_w$ | Set of available transport routes for demand node $w \in W$, $R_w=R_w^{road}\cup R_w^{inter}$ |
| $R_w^{road}$ and $R_w^{inter}$ | Set of available road and multimodal transport routes for demand node $w \in W$ |
| $\delta_w^{a,r}$ | If route $r \in R_w$ traverses link $a \in A$, $\delta_w^{a,r}=1$; otherwise, zero |
| $\delta_w^{b,r}$ | If route $r \in R_w$ traverses hub $b \in H \cup P$, $\delta_w^{b,r}=1$; otherwise, zero |
| $A_w^r$ and $B_w^r$ | Set of links contained in route $r \in R_w$, and set of dry ports and ports contained in route $r \in R_w$ |
| $Y_h^p$ | If $h \in H$ is selected by port $p \in P$ to establish a dry port, $Y_h^p=1$; otherwise, zero. |

| | |
|---|---|
| $Y^p$ | Dry port location decision of port $p \in P$, $Y^p = \{Y_h^p : h \in H\}$ |
| $y^p$ | A feasible set of dry port location decision of port $p \in P$, $y^p \in Y^p$ |
| $C_w^r$ | Inland transport cost per unit freight in transport route $r \in R_w$, $w \in W$ |
| $T_w^r$ | Inland transport time and custom clearance time in transport route $r \in R_w$, $w \in W$ |
| $c_a$ and $t_a$ | Transport cost, and transport time for link $a \in A$ |
| $c_h^p$ and $t_h^p$ | Service charge and time of dry port $h \in H_p$ operated by port $p \in P$ |
| $tcus^{road}$ and $tcus^{inter}$ | Custom clearance time for road and multimodal transport routes |
| $\eta^{road}$ and $\eta^{inter}$ | Parameter of inland transport cost per unit freight for road and multimodal transport in utility functions |
| $\mu^{road}$ and $\mu^{inter}$ | Parameter of inland transport and custom clearance time for road and multimodal transport in utility functions |
| $z^{road}$ and $z^{inter}$ | Reliability (on delivery percentage) of road transport routes and multimodal transport routes |
| $\theta^{road}$ and $\theta^{inter}$ | Parameter of reliability for road and multimodal transport in utility functions |
| $o_h^p$ | Service quality and range of dry port $h \in H_p$ operated by port $p \in P$ |
| $\sigma$ | Parameter of dry port service quality and range in utility function |
| $v_w$ | Shipment size for shippers at node $w \in W$ |
| $\chi^{road}$ and $\chi^{inter}$ | Parameter of shipment size for road and multimodal transport in utility functions |
| $c_p$ | Charge of port $p \in P$ |
| $\alpha$ | Parameter of port charge in utility function |
| $t_p$ | Waiting time at port $p \in P$ |
| $\beta$ | Parameter of waiting time at port in utility function |
| $f_p$ | Ship call frequency at port $p \in P$ |
| $\gamma$ | Parameter of ship call frequency in utility function |
| $U_w^{(r\|p)}$ | Random utility for shippers at $w \in W$ choosing transport route $r \in R_w^p$ when $p \in P$ is selected |
| $V_w^{(r\|p)}$ | Deterministic term of $U_w^{(r\|p)}$ |
| $\varepsilon_w^{(r\|p)}$ | Random term of $U_w^{(r\|p)}$ following distribution of Gumbel with a mean of zero and variance $\sigma_{00}$ |
| $ASC^{road}$ and $ASC^{inter}$ | Alternative specific constant for road and multimodal transport |
| $ASC_p$ | Alternative specific constant for port $p \in P$ |
| $U_w^p$ | Random utility for shippers at node $w \in W$ choosing port $p \in P$ |
| $V_w^p$ | Deterministic term of $U_w^p$ |
| $\varepsilon_w^p$ | Random term of $U_w^p$ following distribution of Gumbel with a mean of zero and variance $\sigma_0$ |
| $V_w^{p*}$ | Expected maximum utility of inland transport routes to port $p \in P$ for shippers at $w \in W$ |
| $\lambda_1$ and $\lambda_2$ | Parameter of variance $\sigma_{00}$ and $\sigma_0$, $\lambda_1 = \pi / \sqrt{6\sigma_{00}}$, $\lambda_2 = \pi / \sqrt{6\sigma_0}$ |
| $pr$ | A hinterland transport chain containing transport route $r \in R_w^p$ and port $p \in P$ |
| $\varphi_w^{pr}$ | Probability of choosing hinterland transport chain $pr$ for shippers at $w \in W$ |
| $\varphi_w^{(r\|p)}$ | Probability of shippers at $w \in W$ choosing route $r \in R_w^p$ under the condition of choosing port $p \in P$ |

| | |
|---|---|
| $\varphi_w^p$ | Probability of choosing port $p \in P$ by shippers at $w \in W$ |
| $\Omega_F^{inter}(y^F \mid y^L)$ | Amount of freight transported to follower port by multimodal transport with strategy $y^F$ under decision $y^L$ |
| $\Omega_h^p$ | Throughput of dry port $h \in H_p$ |
| $\delta_{wp}^{inter}$ | If multimodal transport is economically viable between $w \in W$ and $p \in P$, $\delta_{wp}^{inter}=1$; otherwise, zero |
| $n_p$ | Quantity of dry ports to be established by port $p \in P$ |
| $Q_h^p$ | Maximum capacity of dry port $h \in H_p$ |
| $\Omega_L^{inter}(y^L, y^F)$ | Amount of freight transported to leader port by multimodal transport with strategy $y^L$ and strategy $y^F$ |
| $\Omega_p$ | Throughput of port $p \in P$ |
| $\Omega^{inter}$ | Multimodal transport volume in hinterland |
| $y^{L*}$ | The optimal strategy of leader port, $y^{L*} \in y^L$ |
| $y^{F*} \mid y^L$ | The optimal strategy of follower port given $y^L$, $y^{F*} \in y^F$ |
| $(y^{L*}, y^{F*} \mid y^{L*})$ | Stackelberg equilibrium solution |
| $HL$ and $HF$ | The strategy sets of leader and follower, used in algorithms |
| $\bar{\Omega}_p^{inter}(y^L)$ | The upper bound of multimodal flow to port $p \in P$ under leader's strategy $y^L$, used in algorithms |
| $\Omega_L^{*inter}$ and $\Omega_F^{*inter}$ | The best-known objective values of leader port and follower port given ($y^{L*}$, $y^{L*} \mid y^{F*}$), used in algorithms |

### *4.2 Hinterland transport chain choice modeling based on nested logit model*

#### *4.2.1 Utility of hinterland transport chain*

We use nested logit (NL) model to describe shippers' hinterland transport chain choice behavior considering the possible correlation among unobserved attributes of inland transport routes to a port. NL model can be considered as a generalized case of MNL model. The NL model partially overcomes the limitation of the MNL model by considering the correlation among alternatives. NL model has been used to analyze the choice behavior of transport mode (Bai et al., 2017; Ravibabu, 2013), the joint choice of transport mode and shipment size (Stinson et al., 2017), the joint choice of port and transport mode (Nugroho et al., 2016; Tapia et al., 2019), and the combined choice of transport mode, transfer location and transport route (Lo et al., 2004). All these studies have proved the superiority and applicability of the NL model.

According to our survey with shippers, the decision process of a hinterland transport chain choice is as follow: a shipper first chooses a port to export cargo, then chooses a road or multimodal transport route to that port. According to this decision process, we develop a two-level NL model as shown in Fig.2. The first level focuses on port choice, and the second level focuses on transport route choice. In Fig.2, leader port and follower port are respectively denoted as 1 and 2. And the multimodal transport routes to leader port and follower port are $11, 12, \cdots, 1n$ and $21, 22, \cdots, 2n$.

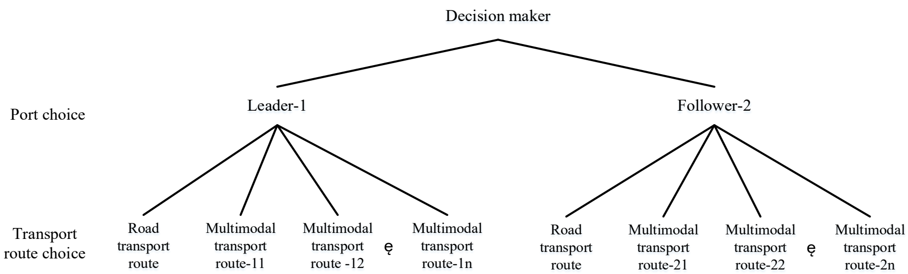


**Fig.2.** Nesting structure of hinterland transport chain choice

Inland transport cost is regarded as the one of most important considerations in transport mode choice (Kim et al., 2017; Larranaga et al., 2017; Meers et al., 2017). Inland transport cost consists of the fare charged by service providers for transporting a unit of cargo (e.g. one TEU) from a demand node through links and nodes to a port. The cost functions of road and multimodal transport route are shown as follow.

$$C_w^r = \sum_{a \in A_w^r \cap A^{road}} c_a \quad \forall w \in W, r \in R_w^{road} \tag{1}$$

$$C_w^r = \sum_{a \in A_w^r \cap A^{road}} c_a + \sum_{a \in A_w^r \cap A^{rail}} c_a + \sum_{h \in B_w^r \setminus P, p \in B_w^r \cap P} c_h^p \quad \forall w \in W, r \in R_w^{inter} \tag{2}$$

Eq. (1) represents the inland road transport cost which contains the transport cost through the links in the route by road. Eq. (2) represents the inland multimodal transport cost which contains road transport cost, rail transport cost and dry port charge. We use $\eta^{road}$ and $\eta^{inter}$ to convert inland transport cost into the utility of road and multimodal transport route.

Inland transit time is a factor of concern in transport mode choice (Kim et al., 2017; Larranaga et al., 2017; Meers et al., 2017). Besides, custom clearance time is consistently important as shippers often worry about the simplicity and transparency of custom procedure (Chen et al., 2017). To ensure better cargo flow, a shipper may declare custom at dry port in multimodal transport. Thus, the custom clearance time of road and multimodal transport may be different. The inland transit time and custom clearance time include the time spent on transporting one unit of cargo (e.g. one TEU) on the links, and on operating, waiting and custom clearance at the nodes[3]. The inland transit time and custom clearance time of road and multimodal transport routes can be calculated as follow.

$$T_w^r = \sum_{a \in A_w^r \cap A^{road}} t_a + tcus^{road} \quad \forall w \in W, r \in R_w^{road} \tag{3}$$

$$T_w^r = \sum_{a \in A_w^r \cap A^{road}} t_a + \sum_{a \in A_w^r \cap A^{rail}} t_a + \sum_{h \in B_w^r \setminus P, p \in B_w^r \cap P} t_h^p + tcus^{\text{inter}} \quad \forall w \in W, r \in R_w^{inter} \tag{4}$$

Eq. (3) shows that for road transport, the inland transit time and custom clearance time include the time of transporting freight by road and custom clearance time at a port. Eq. (4) shows that for multimodal transport, the inland transit time and custom clearance time include road transport time, rail transport time, transshipment service and custom clearance time at dry port. We use $\mu^{road}$ and $\mu^{inter}$ to convert inland transit and custom clearance time into the utility of road and multimodal transport route.

Reliability also plays an important role in transport mode choice (Kim et al., 2017; Larranaga et al., 2017; Meers et al., 2017). It refers to the percentage of on-time delivery of a transport mode. The reliability of road and multimodal transport are respectively measured by $z^{road}$ and $z^{inter}$ expressed as a percentage. We use $\theta^{road}$ and $\theta^{inter}$ to convert reliability percentage into the utility of road and multimodal transport route.

Dry port service quality and range is an important selection criterion for dry port users (Nguyen and Notteboom, 2016). Dry port service quality and range refer to the available services at a dry port and the level of those provided services. A variety of services can be provided or not at a dry port, such as cargo receipt and dispatch, containers packing and unpacking, storage and repair of containers, shunting service, relevant commercial activities (Nguyen and Notteboom, 2016). And shippers may evaluate dry port alternatives according to their service scope and quality (Nguyen and Notteboom, 2016).We use $o_h^p$ to reflect the quality and range of dry port $h \in H_p$ operated by port $p \in P$, which is scaled from 1 to 5 (Nguyen and Notteboom, 2016). $\sigma$ is used to transform the degree of dry port service quality and range to the utility of multimodal transport route.

Shipment size is an important variable for the choice between road and multimodal transport (Jiang et al., 1999; Piendl et al., 2017). Shipment size refers to the amount of transported goods per shipment (i.e. 20 feet TEU/shipment) for each shipper. We use $v_w$ to reflect shipment size for shippers at node $w \in W$ .To categorize continuous shipment size into different shipment size class (Piendl et al., 2017), we follow the classification of partial load and (multiple) full load railway wagons. Currently 20 feet and 40 feet containers are mainly used, and a railway wagon can load two 20 feet containers or one 40 feet container. As we set 20 feet container as the loading unit, we divide shipment size into two categories: if shipment size is no more than two 20 feet TEUs (partial load railway wagon), $v_w = 1$; otherwise (multiple full load railway wagons), zero (Piendl et al., 2017). $\chi^{road}$ and $\chi^{inter}$ are respectively used to transform $v_w$ to the utility of road and multimodal transport routes.

Port charge is an important determinant in port choice of shippers, as it is reflected in the freight rates that shippers have to pay (Tongzon, 2009; Wanke and Falcão, 2017). Port charge mainly include wharfage and demurrage (Tongzon, 2009). Let $c_p$ be the service charge of port $p \in P$. Parameter $\alpha$ is used to convert port charge into the utility of port.

As shippers may be affected by waiting time in queue because of demurrage cost, waiting time at port should be considered in port choice (Tongzon, 2009; Wanke and Falcão, 2017). Port waiting time represents the average waiting time in queue for each shipment from the moment is communicates its arrival to the port authority until berthing alongside the

[3] We assume that custom clearance time of one unit of cargo (e.g. one TEU) is not affected by the volume of cargo flows. Some researchers consider the congestion effect on transit time (e.g. Wang and Meng (2017)). The effect of cargo flows on custom clearance time is an interesting issue and we leave it for future research.

quay (Wanke and Falcão, 2017). Let $t_p$ be the waiting time at port $p \in P$. Parameter $\beta$ is used to convert port waiting time into the utility of port.

Ship call frequency is an important factor in port choice as greater frequency of ship call allows for greater flexibility and lower transit time (Kavirathna et al., 2018; Tongzon, 2009). Let $f_p$ be the frequency of ship call to port $p \in P$ and we use $\gamma$ to transform ship call frequency into the utility of port.

From the above, the deterministic utility of road transport route considers four attributes including inland transport cost, inland transit time and custom clearance time, reliability, and shipment size. The deterministic utility of multimodal transport is represented by five attributes including inland transport cost, inland transport time and custom clearance time, reliability, shipment size, and dry port service quality and range. Define $U_w^{(r|p)}$ as the random utility of route $r \in R_w^p$ given selected port $p \in P$, it represents the preference of shipper on route $r \in R_w^p$. Let $V_w^{(r|p)}$ and $\varepsilon_w^{(r|p)}$ respectively denote the deterministic and random term of $U_w^{(r|p)}$. The random utility functions of road and multimodal transport are shown as follow.

$$U_w^{(r|p)} = V_w^{(r|p)} + \varepsilon_w^{(r|p)} = \eta^{road} \cdot C_w^r + \mu^{road} \cdot T_w^r + \theta^{road} \cdot z^{road} + \chi^{road} \cdot v_w + ASC^{road} + \varepsilon_w^{(r|p)} \quad \forall w \in W, r \in R_w^{road}, p \in P \cap B_w^r \tag{5}$$

$$U_w^{(r|p)} = V_w^{(r|p)} + \varepsilon_w^{(r|p)} = \eta^{inter} \cdot C_w^r + \mu^{inter} \cdot T_w^r + \theta^{inter} \cdot z^{inter} + \chi^{inter} \cdot v_w + \sigma \cdot o_h^p + ASC^{inter} + \varepsilon_w^{(r|p)} \quad \forall w \in W, r \in R_w^{inter}, p \in P \cap B_w^r \tag{6}$$

$ASC^{road}$ and $ASC^{inter}$ are respectively the constant terms in the deterministic utility of road and multimodal transport (Lu et al., 2015; Nugroho et al., 2016). According to the theory of nested logit model, deterministic utility can be expressed as a linear regression equation.

The deterministic utility of port considers three attributes including port service charge, waiting time at port, and ship call frequency. Alternative specific constant $ASC_p$ is the constant term in the deterministic utility of port $p \in P$ (Lu et al., 2015; Nugroho et al., 2016). The random utility of port includes its deterministic utility and random term (Lu et al., 2015), and can be calculated by

$$U_w^p = V_w^p + \varepsilon_w^p = \alpha \cdot c_p + \beta \cdot t_p + \gamma \cdot f_p + ASC_p + \varepsilon_w^p \qquad \forall w \in W, p \in P \cap B_w^r \tag{7}$$

The expected maximum utility of inland transport routes to port $p$ for shippers at $w \in W$ is $V_w^{p*}$. According to Lu et al. (2015) and Qin et al. (2017), $V_w^{p*}$ is given by

$$V_w^{p*} = \frac{1}{\lambda_1} \ln \sum_{r \in R_w^p} \exp(\lambda_1 \cdot V_w^{(r|p)}) \quad \forall w \in W, r \in R_w^p, p \in P \tag{8}$$

$\lambda_1$ is a scale parameter relevant to the variance of $\varepsilon_w^{(r|p)}$ and is usually set to 1 (Lu et al., 2015; Qin et al., 2017). The values of $\eta^{road}$, $\eta^{inter}$, $\mu^{road}$, $\mu^{inter}$, $\theta^{road}$, $\theta^{inter}$, $\chi^{road}$, $\chi^{inter}$, $\sigma$, $ASC^{road}$, $ASC^{inter}$, $ASC_p$, $\alpha$, $\beta$, $\gamma$ are calibrated in Section 6.1.2.

*4.2.2 Hinterland transport chain choice model*

To obtain the flow on each hinterland transport chain, it is necessary to calculate the probability of choosing a hinterland transport chain $pr$ ($p \in P$, $r \in R_w^p$) by shippers at $w \in W$. As the unobserved attributes of road and multimodal transport route to a port are likely to be correlated, we formulate a nested logit model to calculate the probability of shippers at $w \in W$ choosing hinterland transport chain $pr$ ($p \in P$, $r \in R_w^p$). The probability of shippers at $w \in W$ choosing hinterland transport chain $pr$ ($p \in P$, $r \in R_w^p$) is defined as

$$\varphi_w^{pr} = \varphi_w^{(r|p)} \cdot \varphi_w^p, \quad \forall w \in W, r \in R_w^p, p \in P \tag{9}$$

$\varphi_w^{(r|p)}$ represents the probability of shippers at $w \in W$ choosing transport route $r \in R_w^p$ under the condition of choosing port $p \in P$. $\varphi_w^p$ represents the probability of shippers at $w \in W$ choosing port $p \in P$. In the two-level nested logit model, the lower level determines $\varphi_w^{(r|p)}$ and the higher level determines $\varphi_w^p$. According to Jones and Hensher (2007) and Zhang et al. (2012), $\varphi_w^{(r|p)}$ and $\varphi_w^p$ can be derived by the following equations.

$$\varphi_w^{(r|p)} = \frac{\exp(\lambda_1 \cdot V_w^{(r|p)})}{\sum_{r' \in R_w^p} \exp(\lambda_1 \cdot V_w^{(r'|p)})}, \quad \forall w \in W, r \in R_w^p, p \in P \tag{10}$$

$$\varphi_w^p = \frac{\exp[\lambda_2 (V_w^p + V_w^{p*})]}{\sum_{p' \in P \cap B_w^r} \exp[\lambda_2 (V_w^{p'} + V_w^{p'^*})]}, \forall w \in W, p \in P \cap B_w^r \tag{11}$$

$\lambda_2$ is a scale parameter relevant to the variance of $\varepsilon_w^p$ (Qin et al., 2017). When $\lambda_1 = 1$ and $0 < \lambda_2 < 1$, it indicates that NL model holds in accordance with discrete choice theory (McFadden and Manski, 1981). If $\lambda_1 = \lambda_2$, it will be reduced to an MNL model.

*4.3 Stackelberg game-theoretical model formulation*

To derive the best strategies of leader port and follower port, we adopt the following two models.

*4.3.1 Model of the follower port*

First, assume that the leader port's dry port location decision is given, the follower port will respond to locate several capacitated dry ports that maximize its captured multimodal flow. The dry port location model of follower port can be formulated as follow.

*Follower Model:*

$$max\ \Omega_F^{\text{inter}}(y^F | y^L) = \sum_{h \in H} \Omega_h^F \tag{12}$$

$$\Omega_h^p = \sum_{w \in W} \sum_{r \in R_w^{\text{inter}}} D_w \cdot \frac{\delta_{wp}^{\text{inter}} \cdot \delta_w^{h,r} \cdot y_h^p \cdot \exp(\lambda_1 \cdot V_w^{(r|p)})}{\sum_{r' \in R_w^p \cap R_w^{inter}} \delta_{wp}^{\text{inter}} \cdot \delta_w^{h,r'} \cdot y_h^p \cdot \exp(\lambda_1 \cdot V_w^{(r'|p)}) + \sum_{r' \in R_w^p \cap R_w^{road}} \exp(\lambda_1 \cdot V_w^{(r'|p)})} \cdot \frac{\delta_w^{p,r} \exp[\lambda_2 (V_w^p + V_w^{p*})]}{\sum_{p' \in P \cap B_w^r} \delta_w^{p',r} \exp[\lambda_2 (V_w^{p'} + V_w^{p'^*})]}, \ \forall h \in H, p \in P \tag{13}$$

$$\sum_{h \in H} y_h^p = n_p, \forall p \in P \tag{14}$$

$$\Omega_h^p \le Q_h^p, \ \forall h \in H, p \in P \tag{15}$$

$$y_h^p \in \{0,1\}, \forall h \in H, p \in P \tag{16}$$

Objective function (12) maximizes the multimodal flow captured by dry ports established by follower port given leader's decision $y^L$. Equations (13) calculate the throughput of each dry port based on the nested logit model. If multimodal transport is economically feasible between demand node $w \in W$ and port $p \in P$, $\delta_{wp}^{\text{inter}} = 1$; otherwise, zero. Constraints (14) specify the number of dry ports to be located. The maximum flow that each dry port can handle is expressed in constraints (15). Constraints (16) state the domains of decision variables.

*4.3.2 Model of the leader port*

The leader port makes dry port location decision knowing that the follower port is going to choose its optimal strategy after observing leader's decision. Therefore, the follower's problem is embedded in leader's problem, and leader's problem has a bilevel structure. The model for leader port can be formulated as follow:

*Leader Model:*

$$max\ \Omega_L^{\text{inter}}(y^L, y^F) = \sum_{h \in H} \Omega_h^L \tag{17}$$

Subject to constraints (13) - (16) and the following constraint

$$y^F \in argmax\{\Omega_F^{\text{inter}}(y^F | y^L)\} \tag{18}$$

Objective function (17) maximizes the expected multimodal flow captured by dry ports invested by leader port. Constraint (18) means that leader port solves its problem subject to the condition that follower port finds its optimal solution in *Follower Model*.

After solving the two problems shown above, we calculate the freight volume of both ports and multimodal transport in hinterland based on the following equations:

$$\Omega_p = \sum_{w \in W} \sum_{r \in R_w} \delta_w^{p,r} \cdot \varphi_w^{pr} \cdot D_w, \forall p \in P \tag{19}$$

$$\Omega^{inter} = \sum_{p \in P} \sum_{w \in W} \sum_{r \in R_w^{inter}} \varphi_w^{pr} \cdot D_w \tag{20}$$

## 5. Solution algorithms

Let $y^{L*}$ be leader's optimal strategy, and $y^{F*} \big| y^{L}$ be follower's optimal strategy under leader's strategy $y^{L}$. If $\Omega_L^{inter}(y^{L*}, y^{F*} \big| y^{L*}) \geq \Omega_L^{inter}(y^{L}, y^{F*} \big| y^{L})$ and $\Omega_F^{inter}(y^{F*} \big| y^{L*}) \geq \Omega_F^{inter}(y^{F} \big| y^{L*})$, ( $y^{L*}, y^{F*} \big| y^{L*}$ ) is called Stackelberg equilibrium solution. There exists a unique equilibrium solution in this Stackelberg competition. According to the Brouwer fixed point theorem, Nash proves that there exists at least one Nash equilibrium solution (pure or mixed Nash equilibrium solution) in the competition with finite pure strategies of finite players (Nash, 1950). As Stackelberg equilibrium solution is a refined Nash equilibrium solution in each subgame, Stackelberg equilibrium solution exists. The uniqueness of Stackelberg equilibrium solution can be proved by iterated elimination of strictly dominated strategies. In the above-mentioned port competition problem, ports are rational, and both ports are aware of this. The two ports know the payoff function and feasible strategy set of the other port. Follower port has a dominant strategy given a decision of leader port. And leader port can calculate its payoff function by anticipating the reaction of follower port. Thus leader port can eliminate its poor strategies to get its dominant strategy (Sasaki et al. ,2014; Mahmutogullari and Kara, 2016). As each port has a dominant strategy in Steenberg competition, there exists a unique Stackelberg equilibrium solution.

Since the objective functions of *Leader Model* and *Follower Model* are nonlinear and concave, and the decision variables are binary, the two models are mixed integer nonlinear programs (MINLP). Considering the interdependence of the problems of leader and follower ports, we do not solve the bilevel programming formulations separately. To find the Stackelberg equilibrium solution, previous studies employed complete enumeration method (Sasaki, 2005), greedy heuristic (Sasaki, 2005), and simulated annealing based algorithm (Ghaffarinasab et al., 2018). If the optimality of dry port location strategy can't be guaranteed, it can be costly to relocate those facilities. Therefore, it is more appropriate to find Stackelberg equilibrium solution by exact methods. However, our computational results indicate that multilevel optimization techniques that can solve MINLP like YALMIP fail to solve bilevel programs with nonlinear and concave inner problems.

To obtain Stackelberg equilibrium solution using exact methods, Mahmutogullari and Kara (2016) enumerate all the hub sets of leader and the corresponding responses of follower. Nevertheless, the running time of this complete enumeration method for our model is proportional to $|N|^2 |n_L(H)| |n_F(H)|$ (Mahmutogullari and Kara, 2016), where $|N|$ is the number of demand nodes, $|n_L(H)|$ and $|n_F(H)|$ are respectively the number of subsets of $H$ with cardinality $n_L$ and $n_F$ . Thus, enumerating all the strategies of leader and follower can be time consuming.

In recent years, smart enumeration algorithm has been used to improve the solution time of complete enumeration algorithm for finding Stackelberg equilibrium solution. Compared with complete enumeration algorithm, smart enumeration algorithm skips the search of follower's reaction to sub optimal leader's strategy. Sasaki et al. (2014) avoid enumerating all sets of follower's hub arc combination within an enumeration scheme. Mahmutogullari and Kara (2016) skip follower's hub location strategies to sub optimal leader's strategy.

In this section, we first propose an adapted complete enumeration algorithm based on Sasaki (2005) to obtain Stackelberg equilibrium solution for instances with reasonable size. Then, we propose an adapted smart enumeration algorithm based on the algorithm proposed by Mahmutogullari and Kara (2016) to improve the solution time.

### *5.1 Algorithm based on complete enumeration method*

Complete enumeration method applying computer technology and game theory is effective and convenience to obtain Stackelberg equilibrium solution. It is also used as a benchmark to test the computational performance of other algorithms. In the Stackelberg hub network design problem proposed by Sasaki (2005), the leader firm locates hubs and decides the services on OD pairs to maximize its profit, and a follower firm decides its location and service strategy in a similar way after that. The captured demand is determined by a multinomial logit function of service disutility related to the ratio of actual travel distance to direct distance between each OD pair. Their complete enumeration algorithm examines all strategy combinations of leader and follower satisfying flow threshold constraints.

As the objective function and flow assignment model in this paper are different from those in Sasaki (2005), and considering capacity constraint in our model, we have to adapt the complete enumeration method to solve our problem. Specify $HL$ and $HF$ as the strategy sets of leader and follower port. Let $\overline{\Omega}_p^{inter}(y^L)$ denotes the upper bound of objective value of port $p \in P$ given $y^L \in Y^L$. Let $\Omega_p^{*\,inter}$ denotes the best-known objective value of port $p \in P$ given ( $y^{L*}, y^{L*} \middle| y^{F*}$ ). The solution process is described below.

**Algorithm 1**

**Step 0.** Initialization. Construct $HL$ and $HF$, set $\bar{\Omega}_p^{inter}(y^L) \leftarrow \sum_{w \in W} D_w$, $\bar{\Omega}_F^{inter}(y^L) \leftarrow 0$.

**Step 1**. Iteration procedure of leader port.

**Step** 1.1 If $HL = \varnothing$, go to Step 4; else, go to Step 1.2.

**Step** 1.2 Select a $Y^L$ from $HL$ and set $HL \leftarrow HL \setminus \{Y^L\}$.

**Step 2**. Find the best feasible follower' strategy under leader's strategy $Y^L$.

**Step** 2.1 If $HF = \varnothing$, go to Step 3; else, go to Step 2.2.

**Step** 2.2 Select a $Y^F$ from $HF$ and set $HF \leftarrow HF \setminus \{Y^F\}$.

**Step** 2.3 According to $Y^L$ and $Y^F$, all the available routes for each demand node are generated. Calculate the flow on each hinterland transport chain based on the nested logit model.

**Step** 2.4 Calculate $\Omega_h^p$ according to $Y^L$ and $Y^F$. If $Y^L$ and $Y^F$ are both feasible, set $y^L \leftarrow Y^L$, $y^F \leftarrow Y^F$, and go to Step 2.5; otherwise, go to Step 2.1.

**Step** 2.5 Calculate $\Omega_L^{inter}(y^L, y^F)$ and $\Omega_F^{inter}(y^F \middle| y^L)$. If $\Omega_F^{inter}(y^F \middle| y^L) > \bar{\Omega}_F^{inter}(y^L)$, set $\bar{\Omega}_F^{inter}(y^L) \leftarrow \Omega_F^{inter}(y^F \middle| y^L)$. If $\Omega_L^{inter}(y^L, y^{F*} \middle| y^L) < \bar{\Omega}_L^{inter}(y^L)$, set $\bar{\Omega}_L^{inter}(y^L) \leftarrow \Omega_L^{inter}(y^L, y^{F*} \middle| y^L)$.

**Step 3**: If $\bar{\Omega}_L^{inter}(y^L) > \Omega_L^{*\,inter}$, set $\Omega_L^{*\,inter} \leftarrow \bar{\Omega}_L^{inter}(y^L)$, $y^{L*} \leftarrow y^L$. Set the $Y^F$ with objective value $\bar{\Omega}_F^{inter}(y^{L*})$ as $y^{F*} \middle| y^{L*}$. Go to Step 1.

**Step 4**: Obtain Stackelberg equilibrium solution ( $y^{L*}$, $y^{F*} \middle| y^{L*}$ ), and corresponding objective values $\Omega_L^{*\,inter}$ and $\Omega_F^{*\,inter}$.

In Step 1, we select a leader's strategy and remove it from $HL$. In Step 2.1 to 2.2, we select a follower's strategy and remove it from $HF$. In Step 2.3, for a strategy combination of leader and follower, all the available routes for each demand node are generated. The flow on each hinterland transport chain is calculated. In Step 2.4, according to the flow on each hinterland transport chain, we calculate the flow captured by each established dry port. If a leader's strategy does not satisfy dry port capacity constraint under all follower's strategies, this leader's strategy is unfeasible. If a follower's strategy does not satisfy dry port capacity constraint under a leader's strategy, this follower's strategy is unfeasible under this leader's strategy. In Step 2.5, if follower finds a feasible strategy that improves $\bar{\Omega}_F^{inter}(y^L)$ or lowers $\bar{\Omega}_L^{inter}(y^L)$, update the upper bound of objective values of the two ports under leader's strategy $y^L$. Step 3 updates the best-known leader's strategy and returns to Step 1 to consider its next strategy. The strategy with maximum upper bound of leader's objective value is leader's optimal strategy $y^{L*}$. And the strategy with upper bound objective value $\bar{\Omega}_F^{inter}(y^{L*})$ is follower's optimal strategy under $y^{L*}$.

*5.2 Algorithm based on smart enumeration method*

When the number of strategies is too large, Algorithm 1 may be not efficient because it checks every strategy combination. To improve calculation efficiency, we adapt the smart enumeration algorithm proposed by Mahmutogullari and Kara (2016) with reduced strategies. In the hub-centroid problem proposed by Mahmutogullari and Kara (2016), the leader makes his/her hub location decision knowing that the follower is going to choose the optimal solution of hub-medianoid problem after observing leader's decision. Each decision-maker aims to maximize his/her market share. Customers choose one firm with respect to provided service level, which is defined as the cost of routing the flow from a node to its destination via hubs. A theorem is proposed to decrease the running time of complete enumeration algorithm by skipping the search of follower's reaction to sub optimal leader's strategies. We use this theorem proved by Mahmutogullari and Kara (2016) to obtain Stackelberg equilibrium solution in a more efficient way. The adapted algorithm based on smart enumeration method is presented below.

**Algorithm 2**

**Step 0-Step 1** the same as those in Algorithm 1

**Step 2**. Skipping the search of follower's strategy to sub optimal leader's strategy.

**Step** 2.1-**Step 2.5** the same as those in Algorithm 1

**Step** 2.6 If the $y^F$ with objective value $\Omega_F^{\_inter}(y^L)$ makes $\Omega_L^{\_inter}(y^L) < \Omega_L^{*inter}$, go to Step 1; otherwise, go to Step 2.1.

**Step 3**: Update the best-known leader's strategy and return to consider its next strategy. If $\Omega_L^{\_inter}(y^L) > \Omega_L^{*inter}$, set $\Omega_L^{*inter} \leftarrow \Omega_L^{\_inter}(y^L), y^{L*} \leftarrow y^L$. Go to Step 1.

**Step 4**: Obtain Stackelberg equilibrium solution. The leader's optimal strategy is $y^{L*}$. Set the $Y^F$ with objective value $\Omega_F^{\_inter}(y^{L*})$ as $y^{F*}\big|y^{L*}$.The optimal objective values of leader and follower are $\Omega_L^{*inter}$ and $\Omega_F^{*inter}$.

In Step 2.6, as soon as the best-known feasible strategy of follower under a leader's strategy limits $\Omega_L^{\_inter}(y^L)$ worse than $\Omega_L^{*inter}$, no further analysis for this leader's strategy $y^L$ is needed. Step 2.6 also guarantees the enumeration of all follower's strategies under the best-known leader's strategy. Because when follower cannot find a strategy $y^F$ under $y^L$ making $\Omega_L^{\_inter}(y^L)$ lower than $\Omega_L^{*inter}$, it will keep searching until all of its strategies have been searched. Step 3 is reached when Step 2.6 is not able to end the enumeration of follower's strategies early. In Step 4, since all of follower's strategies under $y^{L*}$ have been searched in Step 2.6, we obtain the Stackelberg equilibrium solution.

## 6. Computational study

### *6.1 Numerical example*

#### *6.1.1 Case data*

In this section, we offer a case study about the multimodal transport network design of Dalian port (assumed as leader) and Yingkou port (assumed as follower) in Liaoning (one of the coastal regions in China with fierce port competition) to test the proposed models and algorithms. The export demands of hinterland cities are estimated based on their export values in 2017 (Chang et al., 2015). In Table 3, column ID represents the identification number of each city. Comprehensively considering transport demand, traffic location, and accessibility to railway and highway, 15 cities are selected as candidate dry port locations, as shown in Fig. 3.

**Table 3**
Cities in the hinterland

| ID | City | Export demand (TEU) | Candidate dry port | ID | City | Export demand (TEU) | Candidate dry port | ID | City | Export demand (TEU) | Candidate dry port |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Hulunbuir | 27336 | | 13 | Tieling | 3891 | √ | 25 | Jixi | 6916 | |
| 2 | Hinggan | 254 | | 14 | Changchun | 74320 | √ | 26 | Hegang | 653 | |
| 3 | Tongliao | 11102 | √ | 15 | Jilin | 25651 | √ | 27 | Shuangyashan | 2019 | |
| 4 | Chifeng | 8882 | | 16 | Siping | 1237 | | 28 | Daqing | 6928 | √ |
| 5 | XilinGol | 8772 | | 17 | Liaoyuan | 7466 | | 29 | Yichun | 1977 | |
| 6 | Shenyang | 173779 | √ | 18 | Tonghua | 9134 | | 30 | Jiamusi | 15014 | |
| 7 | Anshan | 78213 | √ | 19 | Baishan | 7380 | | 31 | Qitaihe | 203 | |
| 8 | Fushun | 16261 | √ | 20 | Songyuan | 6352 | | 32 | Mudanjiang | 58517 | √ |
| 9 | Benxi | 101918 | √ | 21 | Baicheng | 632 | | 33 | Heihe | 6375 | |
| 10 | Fuxin | 8589 | √ | 22 | Yanbian | 37429 | | 34 | Suihua | 5360 | |
| 11 | Chaoyang | 18609 | √ | 23 | Haerbin | 56341 | √ | | | | |
| 12 | Liaoyang | 16016 | √ | 24 | Qiqihaer | 6082 | √ | | | | |

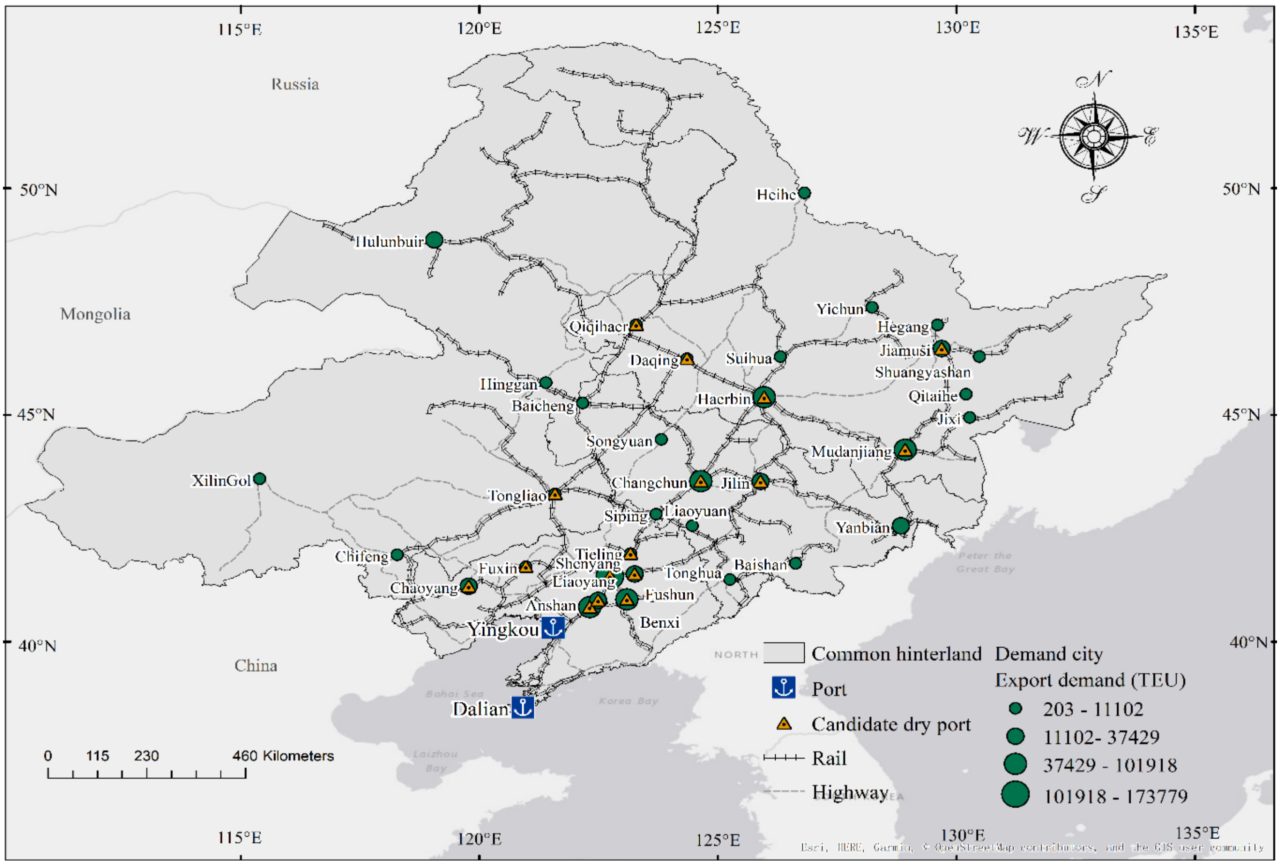


Fig.3 Location map of data area

The parameters about ports, transport modes and dry ports are shown in Table 4. Port service charge and waiting time, reliability of road and multimodal routes, custom clearance time, service charge, time and quality at dry ports are set based on surveys with port managers, shippers and freight forwarders. Ship call frequency is set according to China port year book 2017. Road and rail transport cost per unit freight are set respectively according to charging rules for truck and railway in China. Transport time is calculated according to the distance divided by the velocity. Velocity of road and rail transport are respectively set according to highway speed limit and the average speed of rail freight shuttles.

**Table 4**
Parameters used in the case study

| Parameter | Unit | Value |
|---|---|---|
| Charge of Dalian port ( $c_L$ ) | CNY/TEU | 300 |
| Charge of Yingkou port ( $c_F$ ) | CNY/TEU | 200,400 |
| Waiting time at Dalian port ( $t_L$ ) | Day | 0.5 |
| Waiting time at Yingkou port ( $t_F$ ) | Day | 0.3,1 |
| Ship call frequency at Dalian port ( $f_L$ ) | Calls/month | 4 |
| Ship call frequency at Yingkou port ( $f_F$ ) | Calls/month | 2,8 |
| Shipment size for shippers at node $w \in W$ ( $v_w$ ) | / | 1 (partial load railway wagon), 0 (multiple full load railway wagons) |
| Road and rail transport cost per unit freight | CNY/TEU | 6, 2.025 |
| Velocity of road and rail transport | km/h | 80, 120 |
| Custom clearance time of road and multimodal transport ( $tcus^{road}$ , $tcus^{inter}$ ) | Hour | 8, 5 |
| Reliability of road and multimodal transport ( $z^{road}$ , $z^{inter}$ ) | / | 0.7, 0.9 |
| Maximum capacity of dry port ( $Q_h^p$ ) | Thousand TEU | 500,200 |

| | | |
|---|---|---|
| Quantity of dry ports to be established by Dalian port ( $n_L$ ) | / | 3 |
| Quantity of dry ports to be established by Yingkou port ( $n_F$ ) | / | 3,4,5 |
| Service charge of dry port operated by Dalian port ( $c_h^L$ ) | CNY/TEU | 100 |
| Service charge of dry port operated by Yingkou port ( $c_h^F$ ) | CNY/TEU | 80,150 |
| Service time of dry port operated by Dalian port ( $t_h^L$ ) | Hour | 4 |
| Service time of dry port operated by Yingkou port ( $t_h^F$ ) | Hour | 2,6 |
| Service quality and range of dry port operated by Dalian port ( $o_h^L$ ) | / | 3 |
| Service quality and range of dry port operated by Yingkou port ( $o_h^F$ ) | / | 2,4 |

/ No unit

Various instances are generated to explore the connection and distinction between Nash and Stackelberg equilibrium solutions and the effect of port competition and dry port construction. We set the number of dry ports to be located by Dalian port is 3 and that by Yingkou port could be 3,4,5, so there are 3 combinations of dry port quantities. For service charge and waiting time at port, we set Dalian port as the benchmark and use the following 2 combinations for Yingkou port: if waiting time is 0.3 day, service charge is 400 CNY/TEU; if waiting time is 1 day, service charge is 200 CNY/TEU. Ship call frequency at Yingkou port can be 2 or 8 calls/month. For service charge, time, quality and range of dry port, we set the dry port of Dalian port as the benchmark and use the following 2 combinations for dry ports of Yingkou port: if dry port service time is 6 hours, and dry port service range and quality is 2, then dry port service charge is 80 CNY/TEU; if dry port service time is 2 hours, and dry port service range and quality is 4, then dry port service charge is 150 CNY/TEU. We set that for both ports the maximum capacity of each dry port can be 200 and 500 thousand TEUs per year. We set the transport volume of each shipment from demand nodes can be partial load railway wagon or multiple full load railway wagons. To avoid the impacts of strategy combination order in Algorithm 2, each instance has been run 10 times with random order of strategy combinations.

*6.1.2 Parameter calibration and comparison between NL model and MNL model*

To calibrate parameters in the utility functions of NL and MNL model, we use revealed preference (RP for short) and stated preference (SP for short) techniques for collecting relevant data of exporters and freight forwarders. RP data can't describe alternatives at different attribute levels. Some RP data on shippers' preferences are also unavailable. SP data can design alternatives under different conditions. But SP data may have biases in contradiction with RP data. Thus, we combine RP and SP data to study shippers' choice behavior.

The experiment design began by identifying 4 alternatives of hinterland transport chain, as shown in Table 5. The definitions and dimension of attributes of hinterland transport chain are as listed in Table 6. The data of shipment size are obtained using RP investigation techniques. The levels of other attributes are set in experiment design to be shown to respondents (SP investigation techniques). Orthogonal design method is used to obtain the most suitable attributes combination (Louviere et al., 2000).

**Table 5**

Alternatives of hinterland transport chain

| Alternative | Port | Alternative | Hinterland transport chain |
|---|---|---|---|
| 1 | Yingkou port | 1-1 | Yingkou port — Road |
| | | 1-2 | Yingkou port — Multimodal rail-road — Shenyang dry port operated by Yingkou port |
| 2 | Dalian port | 2-1 | Dalian port — Road |
| | | 2-2 | Dalian port — Multimodal rail-road — Shenyang dry port operated by Dalian port |

**Table 6**

The attributes of hinterland transport chain

| Attributes | Definition | Unit | Alternative | Level |
|---|---|---|---|---|
| Port charge | The handling cost of 1 TEU FCL[a] using port crane | CNY/TEU | 1,2 | 150,200,300 |
| Port waiting time | Average waiting time in queue for each shipment from the moment it communicates its arrival to port authority until berthing alongside the quay | day | 1,2 | 0.5,1,2 |
| Ship call frequency | Frequency of ship call at a port | Call/month | 1,2 | 2,4,8 |

| | | | | |
|---|---|---|---|---|
| Shipment size | Average freight transport volume per shipment | TEU | 1-1,1-2,2-1,2-2 | 1 (partial load railway wagon), and 0 (multiple full load railway wagons) |
| Inland transport cost | For road transport, it includes the transport cost by truck from a demand node to a port. For multimodal transport, it includes the transport cost by truck from a demand node to a dry port, transshipment cost at dry port, and transport cost from dry port to a port by train. | CNY/TEU | 1-1 | 600,700,800 |
| | | | 1-2 | 700,800,900 |
| | | | 2-1 | 500,600,700 |
| | | | 2-2 | 600,700,800 |
| Inland transit time and custom clearance time | For road transport, it includes the transport time from a demand node to a port by truck and custom clearance time at port. For multimodal transport, it includes the transport time from a demand node to a dry port by truck, transshipment and custom clearance time at dry port, and transport time from dry port to port by train. | day | 1-1,2-1 | 2,3,4 |
| | | | 1-2,2-2 | 0.5,1,1.5 |
| Inland mode reliability | Percentage of on-time delivery | % | 1-1,1-2,2-1,2-2 | 75,85,95 |
| Dry port Service quality and range | The available services at a dry port and the level of services | / | 1-2,2-2 | 1,3,5 |

Note: [a] FCL is full container load, / No unit

A survey was conducted in March 2018. 212 respondents including exporters and freight forwarders in China completed the survey online, with 9 choice scenarios per respondent. However, 47 respondents were excluded from parameter estimation because their completion time was less than 1 minute or giving same answers for all choice scenarios. Hence, data from 165 respondents were used. Parameter estimation in the utility functions of MNL model and NL model were carried out using BIOGEME (Bierlaire's Optimization Toolbox for General Extreme Value Model Estimation) (Bierlaire, 2003). The estimation results of the two models are presented in Table 7. The reference alternative is hinterland transport chain 1-1 in MNL model. In NL model, the reference alternatives are road transport in the lower level and Yingkou port in the upper level.

**Table 7**
Estimation results of NL model and MNL model

| Utility parameters | MNL model | | | NL model | | |
|---|---|---|---|---|---|---|
| | Coefficient | Std. err | *t*-statistics | Coefficient | Std. err | *t*-statistics |
| Alternative specific constant for alternative 1-1 | - | - | - | - | - | - |
| Alternative specific constant for alternative 2-1 | -0.174 | 0.0795 | -2.18** | - | - | - |
| Alternative specific constant for alternative 1-2 | 2.51 | 0.758 | 3.31*** | - | - | - |
| Alternative specific constant for alternative 2-2 | 2.46 | 0.775 | 3.18*** | - | - | - |
| Alternative specific constant for Yingkou port $ASC_p$ | - | - | - | - | - | - |
| Alternative specific constant for Dalian port $ASC_p$ | - | - | - | 0.139 | 0.0646 | 2.15** |
| Alternative specific constant for road transport $ASC^{road}$ | - | - | - | - | - | - |
| Alternative specific constant for multimodal transport $ASC^{inter}$ | - | - | - | 1.24 | 0.695 | 1.78* |
| Port service charge parameter $\alpha$ | -0.00291 | 0.000451 | -6.46*** | -0.0613 | 0.0646 | -2.15** |
| Port waiting time parameter $\beta$ | -0.110 | 0.0440 | -2.5** | -0.463 | 0.00063 | -9.73*** |
| Ship call frequency parameter $\gamma$ | 0.0274 | 0.0113 | 2.42** | 0.433 | 0.0412 | 10.51*** |
| Shipment size parameter for road transport $\chi^{road}$ | 1.85 | 0.0950 | 19.48*** | 1.81 | 0.101 | 17.85*** |
| Shipment size parameter for multimodal transport $\chi^{inter}$ | / | / | / | / | / | / |
| Inland transport cost parameter for road transport $\eta^{road}$ | -0.000845 | 0.000451 | -1.83* | -0.00174 | 0.000373 | -4.65*** |
| Inland transport cost parameter for multimodal transport $\eta^{inter}$ | -0.00192 | 0.000452 | -4.25*** | -0.00187 | 0.00384 | -4.86*** |
| Inland transit and custom clearance time parameter for road transport $\mu^{road}$ | -0.153 | 0.0494 | -3.11*** | -0.0917 | 0.0462 | -1.98** |

| | | | | | | |
|---|---|---|---|---|---|---|
| Inland transit and custom clearance time parameter for multimodal transport $\mu^{inter}$ | -0.392 | 0.0887 | -4.42*** | -0.263 | 0.0896 | -2.93*** |
| Reliability parameter for road transport $\theta^{road}$ | 1.41 | 0.460 | 3.0*** | 0.0200 | 0.00479 | 4.18*** |
| Reliability parameter for multimodal transport $\theta^{inter}$ | / | / | / | 0.0133 | 0.00551 | 2.41*** |
| Dry port service and range parameter $\sigma$ | 0.0450 | 0.0216 | 2.08** | 0.0519 | 0.024 | 2.17** |
| Scale parameter $\lambda_2$ | | - | | 0.92 | 0.123 | 8.76*** |
| Final log-likelihood | | -2637.009 | | Upper level: -1135.13 Lower level: -1693.396 | | |
| Rho-square | | 0.208 | | Upper level: 0.304 Lower level: 0.229 | | |

* Significant at 10% level; ** Significant at 5% level; *** Significant at 1% level; / Not significant above 10% level

According to the values of final log-likelihood, Rho-square, and the signs of estimated parameters, we find NL model is more appropriate than MNL model for describing shippers' choices. In addition, scale parameter $\lambda_2$ is between 0 and 1, which confirms that NL model should be used. The *t*-statistics in NL model indicate that all attributes have statistically significant impacts on shippers' choice. Port charge, port waiting time, inland transport cost, inland transit and custom clearance time have negative signs. Ship call frequency, reliability, dry port service quality and range have positive signs.

We are interested the difference of parameter values in road and multimodal transport. We find that inland transport cost, inland transit and custom clearance time are given more weight in multimodal transport than in road transport. These happen for two reasons. Firstly, the inland transport cost per TEU of multimodal transport is lower than that of road transport due to economies of scale. Shippers pay close attention to cost difference between multimodal transport and road transport. Secondly, meeting time requirement is a prerequisite for the use of multimodal transport. Inland transit time of multimodal transport might be longer than that of road transport due to transshipment at dry port. However, custom clearance time of multimodal transport at dry port may be shorter than that of road transport at port. Therefore, the difference of inland transport cost, inland transit time and custom clearance time between road and multimodal transport have important influence on the choice of multimodal transport.

We also find that reliability is given more weight in road transport than in multimodal transport. Reliability of train shuttles is an attractive factor for shippers choosing multimodal transport, especially those shippers with high value goods, having just-in-time production and zero inventory. In contrast, highway transport is vulnerable to harsh weather, congestion, driver state and safety factors. As the reliability of road transport may be lower than that of multimodal transport, shippers pay more attention to the reliability of road transport.

Some attributes have strong correlations with multimodal transport. We find that for large-scale freight shipment, multimodal transport tends to be favored. Besides, service quality and range of dry port have positive effects on multimodal transport.

### *6.2 Computational results*

96 instances are generated according to different values of parameters in Table 4. To compare results of Stackelberg and Nash games, we apply Nash game model and its solution algorithm to these instances (Xu et al., 2018; Zhang et al., 2018). The algorithms are coded in MATLAB R2017a software processed by a PC with a 2.8GHz Intel (R) Xeon E5-1603 v4 CPU supported by 8GB RAM running Windows 10 (64 bit).

#### *6.2.1 Comparison between Nash and Stackelberg equilibrium*

Table 8 compares dry port location strategy of both ports in Stackelberg equilibrium and Nash equilibrium. Pure Nash equilibrium solution is identified in column "Nash equilibrium". To compare Stackelberg equilibrium solution with pure and mixed Nash equilibrium solution, dominated strategies in Nash game are also reported. Besides, whether a port's strategy in Stackelberg equilibrium is its dominant strategy in Nash game and the number of its dominant strategies are listed in column "Dominated strategies in Nash game".

First, we analyze the connection and distinction among dry port location strategy in Stackelberg equilibrium, pure Nash equilibrium and the dominant strategies in Nash game. We find that dry port location strategy of each port in Stackelberg equilibrium is the same with its strategy in pure Nash equilibrium. And the dry port location strategy of each port in Stackelberg equilibrium is a subset of dominant strategies of that port in the Nash game with a pure Nash equilibrium. Comparing column "Stackelberg equilibrium" with column "Dominated strategies in Nash game", we can observe two results based on the analysis of instances with a pure Nash equilibrium. First, if leader's strategy in Stackelberg equilibrium is its only dominant strategy in Nash game, follower's strategy in Stackelberg equilibrium would be the same with its strategy in pure Nash equilibrium. This is because follower's best strategy is dependent on leader's decision in both Stackelberg game and Nash game. Second, if follower's strategy in Stackelberg equilibrium is its only dominant strategy in Nash game, leader's strategy in Stackelberg equilibrium would be the same with its only dominant strategy in Nash game. This is because in Nash game leader port (in Stackelberg game) can obtain its best strategy by eliminating dominated strategies according to follower's (in Stackelberg game) only dominant strategy. In Stackelberg game leader port chooses its best strategy considering follower's reaction function. If follower's strategy in Stackelberg equilibrium is its only dominant strategy in Nash game, the best strategy of leader considering follower's strategy in Stackelberg equilibrium would be leader's strategy in Nash equilibrium. Thus, when the only dominant strategy of one port in Nash game is its strategy in Stackelberg equilibrium, pure Nash equilibrium solution would be the same as Stackelberg equilibrium solution.

We are also interested in the connection and distinction between dry port location strategies in Stackelberg equilibrium with dominant strategies in mixed Nash equilibrium. We find that the dry port location strategy of leader port in Stackelberg equilibrium can be different from its dominant strategies in Nash games with mixed Nash equilibriums. This can be observed by comparing the strategy of Dalian port in Stackelberg equilibrium with its dominant strategies in Nash game in instances 61, 93 and 94 (bold formatting in Table 8). This is occurred because the dominant strategies of Dalian port in Nash game are made without considering the impact of its decision on the decision of its competitor. Thus, the dominant strategies of Dalian port in Nash game don't necessarily have to include its strategy in Stackelberg equilibrium. In contrast, the dry port location strategies of follower port in Stackelberg equilibrium are included in its dominant strategies in Nash game under the setting. This is occurred because the best strategy of follower under different leader's strategies can be the same. Thus, leader's strategy in Stackelberg equilibrium can be different from its dominant strategies in Nash game.

Table 8 also compares the two adapted algorithms based on the case study. Results show that Stackelberg equilibrium solutions achieved by these two algorithms are the same for all instances. The column "gap" reports the computation time in terms of relative gap in percent between algorithm 1 and 2. $Gap = (time1 - time2)/time1$, where $time1$ and $time2$ are respectively the computation time of Algorithm 1 and Algorithm 2. On average, the gap between the two algorithms is 57%. Moreover, when the value of maximum capacity of dry port decreases, the computation time by Algorithm 2 may increase. This is because Algorithm 2 skips only the search of feasible follower's strategies to feasible sub optimal leader's strategies. When the value of maximum capacity of dry ports decreases, the number of unfeasible solutions of both leader and follower increases. In comparison, the computation time by Algorithm 1 is rather robust when $n_F$ is fixed. These findings suggest that both algorithms are efficient for solving the proposed model. And Algorithm 2 is more efficient than algorithm 1, but the efficiency of algorithm 2 may be affected the maximum capacity value of dry port.

Table 9 reports the market shares of multimodal transport to each port, the total share of each port and the share of multimodal transport in hinterland. As the dry port location strategy of each port in Stackelberg equilibrium is the same with its strategy in pure Nash equilibrium under the settings, the related market shares in pure Nash equilibriums are the same with those in Stackelberg equilibrium. In Section 6.2.2 and 6.2.3, we will analyze the impact of port competition and dry port construction on dry port location strategies in Stackelberg equilibrium and pure Nash equilibrium and on the market shares of port and multimodal transport.

**Table 8**

Dry port location strategies in Stackelberg equilibrium and Nash equilibrium.

| Instance | $n_F$ | $v_w$ | $f_F$ | $Q_h^p$ | $c_F$ | $t_F$ | $c_h^F$ | $t_h^F$ | $o_h^F$ | Stackelberg Equilibrium | | Nash Equilibrium | | Dominated strategies in Nash game | | Computation time | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | D (ID) | Y (ID) | D (ID) | Y (ID) | D (ID) | Y (ID) | *time1* (CPU/s) | *time2* (CPU/s) | Gap (%) |
| 1 | 3 | 0 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,11,15 | 23,24,32 | - | - | 6,11,15; 9,11,14 | 23,24,32 (23) | 40.05 | 18.18 | 55 |
| 2 | 3 | 0 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,11,15 | 23,24,32 | - | - | 6,11,15; 9,11,14 | 23,24,32 (23) | 36.54 | 17.85 | 51 |
| 3 | 3 | 0 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 10,14,15 | 6,9,12 | 10,14,15 | 6,9,12 (4) | 10,14,15 | 36.77 | 17.07 | 54 |
| 4 | 3 | 0 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 10,14,15 | 6,9,12 | 10,14,15 | 6,9,12 (4) | 10,14,15 | 36.72 | 17.12 | 53 |
| 5 | 3 | 0 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 23,28,32 | 3,14,15 | 23,28,32 | 3,14,15 | 23,28,32 | 3,6,7;3,14,15;13,14,15 | 40.89 | 36.28 | 11 |
| 6 | 3 | 0 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 23,28,32 | 3,14,15 | 23,28,32 | 3,14,15 | 23,28,32 | 3,6,7;3,14,15;13,14,15 | 37.83 | 33.94 | 10 |
| 7 | 3 | 0 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 10,14,15 | 6,9,12 | 10,14,15 | 6,9,12 (9) | 10,14,15 | 39.87 | 18.13 | 55 |
| 8 | 3 | 0 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 10,14,15 | 6,9,12 | 10,14,15 | 6,9,12 (8) | 10,14,15 | 42.07 | 19.70 | 53 |
| 9 | 3 | 0 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,10,15 | 23,24,32 | - | - | 6,10,15 (9) | 23,24,32 (19) | 39.12 | 20.08 | 49 |
| 10 | 3 | 0 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,10,15 | 23,24,32 | - | - | 6,10,15 (9) | 23,24,32 (19) | 46.11 | 23.34 | 49 |
| 11 | 3 | 0 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 10,14,15 | 6,9,12 | 10,14,15 | 6,9,12 (4) | 10,14,15 | 40.64 | 19.49 | 52 |
| 12 | 3 | 0 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 10,14,15 | 6,9,12 | 10,14,15 | 6,9,12 (4) | 10,14,15 | 40.20 | 17.26 | 57 |
| 13 | 3 | 0 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 3,11,23 | 14,15,32 | - | - | 3,11,23;15,23,32;23,28,32 | 14,15,32 (6) | 47.95 | 36.21 | 24 |
| 14 | 3 | 0 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 3,11,23 | 14,15,32 | - | - | 3,11,23;15,23,32;23,28,32 | 14,15,32 (6) | 40.58 | 31.17 | 23 |
| 15 | 3 | 0 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 10,14,15 | 6,9,12 | 10,14,15 | 6,9,12 (5) | 10,14,15 | 38.46 | 18.02 | 53 |
| 16 | 3 | 0 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 10,14,15 | 6,9,12 | 10,14,15 | 6,9,12 (5) | 10,14,15 | 40.04 | 18.50 | 54 |
| 17 | 3 | 1 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,9,14 | 23,24,32 | - | - | 6,9,14;6,9,15 | 23,24,32 (16) | 42.57 | 18.44 | 57 |
| 18 | 3 | 1 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,9,14 | 23,24,32 | - | - | 6,9,14;6,9,15 | 23,24,32 (16) | 39.78 | 18.33 | 54 |
| 19 | 3 | 1 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,14,15 | 6,9,32 | 3,14,15 | 6,9,32 (11) | 3,14,15 | 41.83 | 20.05 | 52 |
| 20 | 3 | 1 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,14,15 | 6,9,32 | 3,14,15 | 6,9,32 (11) | 3,14,15 | 41.29 | 21.15 | 49 |
| 21 | 3 | 1 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 10,14,15 | 23,24,32 | 10,14,15 | 23,24,32 | 10,14,15 | 23,24,32 (15) | 39.85 | 31.55 | 21 |
| 22 | 3 | 1 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 10,14,15 | 23,24,32 | 10,14,15 | 23,24,32 | 10,14,15 | 23,24,32 (15) | 38.96 | 32.15 | 17 |
| 23 | 3 | 1 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,14,15 | 6,9,32 | 3,14,15 | 6,9,32 (13) | 3,14,15 | 38.33 | 17.88 | 53 |
| 24 | 3 | 1 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,14,15 | 6,9,32 | 3,14,15 | 6,9,32 (14) | 3,14,15 | 37.81 | 21.05 | 44 |
| 25 | 3 | 1 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,9,15 | 23,24,32 | - | - | 6,9,14;6,9,15;6,9,23 | 23,24,32 (13) | 43.30 | 19.37 | 55 |
| 26 | 3 | 1 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,9,15 | 23,24,32 | - | - | 6,9,14;6,9,15;6,9,23 | 23,24,32 (13) | 38.57 | 19.49 | 49 |
| 27 | 3 | 1 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,14,15 | 6,9,32 | 3,14,15 | 6,9,32 (12) | 3,14,15 | 38.07 | 19.38 | 49 |
| 28 | 3 | 1 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,14,15 | 6,9,32 | 3,14,15 | 6,9,32 (12) | 3,14,15 | 38.70 | 19.36 | 50 |
| 29 | 3 | 1 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 8,13,14 | 23,24,32 | - | - | 6,8,9;8,13,14;10,14,15 | 23,24,32 (13) | 38.30 | 35.22 | 8 |
| 30 | 3 | 1 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 8,13,14 | 23,24,32 | - | - | 8,13,14 (4) | 23,24,32 (13) | 38.22 | 33.68 | 12 |
| 31 | 3 | 1 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,14,15 | 6,9,32 | 3,14,15 | 6,9,32 (13) | 3,14,15 | 38.04 | 19.58 | 49 |
| 32 | 3 | 1 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,14,15 | 6,9,32 | 3,14,15 | 6,9,32 (13) | 3,14,15 | 38.07 | 19.38 | 49 |
| 33 | 4 | 0 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,11,15 | 14,23,24,32 | - | - | 6,11,15;9,11,14 | 14,23,24,32 (27) | 78.24 | 24.38 | 69 |
| 34 | 4 | 0 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,11,15 | 14,23,24,32 | - | - | 6,11,15;9,11,14 | 14,23,24,32 (27) | 84.93 | 24.30 | 71 |
| 35 | 4 | 0 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 3,11,14,15 | - | - | 6,9,12;6,9,32 | 3,11,14,15;11,13,14,32 | 87.40 | 21.81 | 75 |
| 36 | 4 | 0 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 3,11,14,15 | - | - | 6,9,12;6,9,32 | 3,11,14,15 (3) | 83.81 | 21.06 | 75 |
| 37 | 4 | 0 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 23,28,32 | 3,13,14,15 | 23,28,32 | 3,13,14,15 | 23,28,32 | 3,6,7,8;3,13,14,15 | 89.54 | 56.66 | 37 |
| 38 | 4 | 0 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 23,28,32 | 3,13,14,15 | 23,28,32 | 3,13,14,15 | 23,28,32 | 3,6,7,8;3,13,14,15 | 82.99 | 58.04 | 30 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 39 | 4 | 0 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 3,11,14,15 | - | - | 6,9,12 (7) | 3,11,14,15;11,13,14,32 | 83.58 | 21.92 | 74 |
| 40 | 4 | 0 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 3,11,14,15 | - | - | 6,9,12 (5) | 3,11,14,15 (3) | 84.56 | 21.50 | 75 |
| 41 | 4 | 0 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,10,15 | 14,23,24,32 | - | - | 6,10,15 (9) | 14,23,24,32 (21) | 84.27 | 27.77 | 67 |
| 42 | 4 | 0 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,10,15 | 14,23,24,32 | - | - | 6,10,15 (9) | 14,23,24,32 (21) | 81.38 | 26.56 | 67 |
| 43 | 4 | 0 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 3,11,14,15 | 6,9,12 | 3,11,14,15 | 6,9,12;6,9,32 | 3,11,14,15 | 83.44 | 21.65 | 74 |
| 44 | 4 | 0 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 3,11,14,15 | 6,9,12 | 3,11,14,15 | 6,9,12;6,9,32 | 3,11,14,15 | 85.39 | 22.70 | 73 |
| 45 | 4 | 0 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 3,11,23 | 8,14,15,32 | - | - | 3,11,23;3,14,15;15,23,32 | 8,14,15,32 (7) | 82.18 | 56.55 | 31 |
| 46 | 4 | 0 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 3,11,23 | 8,14,15,32 | - | - | 3,11,23;3,14,15;15,23,32 | 8,14,15,32 (7) | 80.74 | 51.68 | 36 |
| 47 | 4 | 0 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 3,11,14,15 | 6,9,12 | 3,11,14,15 | 3,6,7;6,9,12;6,9,32 | 3,11,14,15 | 79.10 | 20.77 | 74 |
| 48 | 4 | 0 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 3,11,14,15 | 6,9,12 | 3,11,14,15 | 3,6,7;6,9,12;6,9,32 | 3,11,14,15 | 78.69 | 20.64 | 74 |
| 49 | 4 | 1 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,9,14 | 15,23,24,32 | 6,9,14 | 15,23,24,32 | 6,9,14 | 15,23,24,32 (20) | 77.95 | 20.72 | 73 |
| 50 | 4 | 1 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,9,14 | 15,23,24,32 | 6,9,14 | 15,23,24,32 | 6,9,14 | 15,23,24,32 (20) | 78.66 | 21.38 | 73 |
| 51 | 4 | 1 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,8,14,15 | 6,9,32 | 3,8,14,15 | 6,9,32 (10) | 3,8,14,15 | 77.65 | 21.25 | 73 |
| 52 | 4 | 1 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,8,14,15 | 6,9,32 | 3,8,14,15 | 6,9,32 (10) | 3,8,14,15 | 78.17 | 21.21 | 73 |
| 53 | 4 | 1 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 10,14,15 | 23,24,28,32 | 10,14,15 | 23,24,28,32 | 10,14,15 | 23,24,28,32 (18) | 82.61 | 56.68 | 31 |
| 54 | 4 | 1 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 10,14,15 | 23,24,28,32 | 10,14,15 | 23,24,28,32 | 10,14,15 | 23,24,28,32 (18) | 78.66 | 55.74 | 29 |
| 55 | 4 | 1 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,8,14,15 | 6,9,32 | 3,8,14,15 | 6,9,32 (11) | 3,8,14,15 | 78.47 | 21.70 | 72 |
| 56 | 4 | 1 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,8,14,15 | 6,9,32 | 3,8,14,15 | 6,9,32 (12) | 3,8,14,15 | 78.82 | 21.31 | 73 |
| 57 | 4 | 1 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,9,15 | 14,23,24,32 | - | - | 6,9,14;6,9,15;6,9,23 | 14,23,24,32 (16) | 78.64 | 22.36 | 72 |
| 58 | 4 | 1 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,9,15 | 14,23,24,32 | - | - | 6,9,14;6,9,15;6,9,23 | 14,23,24,32 (16) | 78.16 | 22.42 | 71 |
| 59 | 4 | 1 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,8,14,15 | 6,9,32 | 3,8,14,15 | 6,9,32 (10) | 3,8,14,15 | 78.19 | 21.38 | 73 |
| 60 | 4 | 1 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,8,14,15 | 6,9,32 | 3,8,14,15 | 6,9,32 (10) | 3,8,14,15 | 77.60 | 21.41 | 72 |
| 61 | 4 | 1 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | **12,13,15** | 14,23,24,32 | - | - | **6,8,9;8,12,13;8,13,14;10,14,15;10,14,32** | 14,23,24,32 (17) | 78.66 | 52.92 | 33 |
| 62 | 4 | 1 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 12,13,15 | 14,23,24,32 | - | - | 12,13,15 (6) | 14,23,24,32 (17) | 79.47 | 53.35 | 33 |
| 63 | 4 | 1 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,8,14,15 | 6,9,32 | 3,8,14,15 | 6,9,32 (12) | 3,8,14,15 | 77.83 | 21.30 | 73 |
| 64 | 4 | 1 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,8,14,15 | 6,9,32 | 3,8,14,15 | 6,9,32 (11) | 3,8,14,15 | 78.62 | 22.01 | 72 |
| 65 | 5 | 0 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,11,15 | 14,23,24,28,32 | - | - | 6,11,15;9,11,14 | 14,23,24,28,32 (32) | 151.76 | 28.12 | 81 |
| 66 | 5 | 0 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,11,15 | 14,23,24,28,32 | - | - | 6,11,15;9,11,14 | 14,23,24,28,32 (32) | 153.02 | 28.86 | 81 |
| 67 | 5 | 0 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 3,8,11,14,15 | - | - | 6,9,12;6,9,32 | 3,8,11,14,15 (5) | 150.40 | 23.66 | 84 |
| 68 | 5 | 0 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 3,8,11,14,15 | - | - | 6,9,12;6,9,32 | 3,8,11,14,15 (5) | 151.24 | 23.68 | 84 |
| 69 | 5 | 0 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 23,28,32 | 3,8,13,14,15 | 23,28,32 | 3,8,13,14,15 | 23,28,32 | 3,6,7,8,9;3,8,13,14,15 | 155.09 | 132.61 | 14 |
| 70 | 5 | 0 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 23,28,32 | 3,8,13,14,15 | 23,28,32 | 3,8,13,14,15 | 23,28,32 | 3,6,7,8,9;3,8,13,14,15 | 152.63 | 132.67 | 13 |
| 71 | 5 | 0 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 3,8,11,14,15 | - | - | 6,9,12 (6) | 3,8,11,14,15 (5) | 150.99 | 23.85 | 84 |
| 72 | 5 | 0 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 3,8,11,14,15 | - | - | 6,9,12 (5) | 3,8,11,14,15 (5) | 151.33 | 23.83 | 84 |
| 73 | 5 | 0 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,10,15 | 14,15,23,24,32 | - | - | 6,10,15 (7) | 14,15,23,24,32 (28) | 151.78 | 35.36 | 77 |
| 74 | 5 | 0 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,10,15 | 14,15,23,24,32 | - | - | 6,10,15 (7) | 14,15,23,24,32 (28) | 151.65 | 35.69 | 76 |
| 75 | 5 | 0 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 3,8,11,14,15 | 6,9,12 | 3,8,11,14,15 | 6,9,12;6,9,32 | 3,8,11,14,15 | 151.40 | 23.71 | 84 |
| 76 | 5 | 0 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 3,8,11,14,15 | 6,9,12 | 3,8,11,14,15 | 6,9,12;6,9,32 | 3,8,11,14,15 | 151.60 | 23.81 | 84 |
| 77 | 5 | 0 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 3,11,23 | 8,13,14,15,32 | - | - | 3,11,23;15,23,32 | 8,13,14,15,32 (7) | 152.37 | 139.43 | 8 |
| 78 | 5 | 0 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 3,11,23 | 8,13,14,15,32 | - | - | 3,11,23;15,23,32 | 8,13,14,15,32 (7) | 152.55 | 139.68 | 8 |
| 79 | 5 | 0 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,12 | 3,8,11,14,15 | 6,9,12 | 3,8,11,14,15 | 6,9,12 (4) | 3,8,11,14,15 | 154.41 | 23.89 | 85 |
| 80 | 5 | 0 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,12 | 3,8,11,14,15 | 6,9,12 | 3,8,11,14,15 | 6,9,12 (4) | 3,8,11,14,15 | 151.13 | 23.91 | 84 |
| 81 | 5 | 1 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,9,14 | 15,23,24,28,32 | 6,9,14 | 15,23,24,28,32 | 6,9,14 | 15,23,24,28,32 (21) | 151.31 | 25.19 | 83 |

| | | | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 82 | 5 | 1 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,9,14 | 15,23,24,28,32 | 6,9,14 | 15,23,24,28,32 | 6,9,14 | 15,23,24,28,32 (21) | 150.63 | 25.32 | 83 |
| 83 | 5 | 1 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,8,11,14,15 | - | - | 6,9,32 (7) | 3,8,11,14,15 (3) | 150.78 | 24.31 | 84 |
| 84 | 5 | 1 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,8,11,14,15 | - | - | 6,9,32 (7) | 3,8,11,14,15 (3) | 150.96 | 24.27 | 84 |
| 85 | 5 | 1 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 10,14,15 | 14,23,24,28,32 | 10,14,15 | 14,23,24,28,32 | 10,14,15 | 14,23,24,28,32 (16) | 152.80 | 135.34 | 11 |
| 86 | 5 | 1 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 10,14,15 | 14,23,24,28,32 | 10,14,15 | 14,23,24,28,32 | 10,14,15 | 14,23,24,28,32 (16) | 152.98 | 136.83 | 11 |
| 87 | 5 | 1 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,8,11,14,15 | - | - | 6,9,32 (8) | 3,8,11,14,15 (3) | 152.41 | 24.20 | 84 |
| 88 | 5 | 1 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,8,11,14,15 | - | - | 6,9,32 (8) | 3,8,11,14,15 (3) | 151.92 | 24.20 | 84 |
| 89 | 5 | 1 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 6,9,15 | 14,23,24,28,32 | - | - | 6,9,14;6,9,15 | 14,23,24,28,32 (17) | 152.27 | 28.44 | 81 |
| 90 | 5 | 1 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 6,9,15 | 14,23,24,28,32 | - | - | 6,9,14;6,9,15 | 14,23,24,28,32 (17) | 150.75 | 28.26 | 81 |
| 91 | 5 | 1 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,8,11,14,15 | 6,9,32 | 3,8,11,14,15 | 6,9,32 (8) | 3,8,11,14,15 | 150.26 | 24.72 | 84 |
| 92 | 5 | 1 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,8,11,14,15 | 6,9,32 | 3,8,11,14,15 | 6,9,32 (7) | 3,8,11,14,15 | 150.34 | 24.88 | 83 |
| 93 | 5 | 1 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | **6,9,15** | 14,23,24,28,32 | - | - | **6,8,9; 8,12,13; 8,13,14; 10,14,15; 10,14,32; 12,13,15** | 14,23,24,28,32 (18) | 151.83 | 136.19 | 10 |
| 94 | 5 | 1 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | **6,9,15** | 14,23,24,28,32 | - | - | **6,8,9; 8,12,13; 8,13,14; 10,14,15; 10,14,32; 12,13,15** | 14,23,24,28,32 (18) | 154.05 | 137.98 | 10 |
| 95 | 5 | 1 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 6,9,32 | 3,8,11,14,15 | 6,9,32 | 3,8,11,14,15 | 6,9,32 (9) | 3,8,11,14,15 | 151.29 | 24.65 | 84 |
| 96 | 5 | 1 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 6,9,32 | 3,8,11,14,15 | 6,9,32 | 3,8,11,14,15 | 6,9,32 (8) | 3,8,11,14,15 | 151.44 | 24.55 | 84 |

Note:”-” means no pure Nash equilibrium solution. “()” implies the number of dominant strategies in Nash game; “D” and “Y” respectively denote Dalian port and Yingkou port.

**Table 9**
Market shares of ports and multimodal transport in Stackelberg equilibrium and pure Nash equilibrium.

| Instance | $n_F$ | $v_w$ | $f_F$ | $Q_h^p$ | $c_F$ | $t_F$ | $c_h^F$ | $t_h^F$ | $o_h^F$ | Multimodal (%) | | Port (%) | | Multimodal (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Dalian port | Yingkou port | Dalian port | Yingkou port | |
| 1 | 3 | 0 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 86.11 | 77.60 | 99.40 | 0.60 | 86.06 |
| 2 | 3 | 0 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 86.11 | 77.86 | 99.39 | 0.61 | 86.06 |
| 3 | 3 | 0 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 97.70 | 47.84 | 3.27 | 96.73 | 49.47 |
| 4 | 3 | 0 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 97.70 | 47.87 | 3.27 | 96.73 | 49.50 |
| 5 | 3 | 0 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 42.88 | 66.10 | 98.49 | 1.51 | 43.23 |
| 6 | 3 | 0 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 42.88 | 66.42 | 98.47 | 1.53 | 43.24 |
| 7 | 3 | 0 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 97.70 | 47.84 | 3.27 | 96.73 | 49.47 |
| 8 | 3 | 0 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 97.70 | 47.87 | 3.27 | 96.73 | 49.50 |
| 9 | 3 | 0 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 86.39 | 74.80 | 94.62 | 5.38 | 85.77 |
| 10 | 3 | 0 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 86.38 | 75.05 | 94.56 | 5.44 | 85.77 |
| 11 | 3 | 0 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 97.76 | 46.53 | 0.32 | 99.68 | 46.70 |
| 12 | 3 | 0 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 97.76 | 46.56 | 0.32 | 99.68 | 46.73 |
| 13 | 3 | 0 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 75.90 | 75.31 | 90.54 | 9.46 | 75.84 |
| 14 | 3 | 0 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 75.88 | 75.52 | 90.45 | 9.55 | 75.84 |
| 15 | 3 | 0 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 97.76 | 46.53 | 0.32 | 99.68 | 46.70 |
| 16 | 3 | 0 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 97.76 | 46.56 | 0.32 | 99.68 | 46.73 |
| 17 | 3 | 1 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 77.57 | 71.96 | 99.28 | 0.72 | 77.53 |
| 18 | 3 | 1 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 77.57 | 72.27 | 99.27 | 0.73 | 77.53 |
| 19 | 3 | 1 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 88.27 | 40.79 | 0.86 | 99.14 | 41.20 |
| 20 | 3 | 1 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 88.23 | 40.87 | 0.86 | 99.14 | 41.28 |
| 21 | 3 | 1 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 64.71 | 47.79 | 99.36 | 0.64 | 64.60 |
| 22 | 3 | 1 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 64.70 | 48.17 | 99.36 | 0.64 | 64.60 |
| 23 | 3 | 1 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 88.27 | 40.79 | 0.86 | 99.14 | 41.20 |
| 24 | 3 | 1 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 88.23 | 40.87 | 0.86 | 99.14 | 41.28 |
| 25 | 3 | 1 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 77.76 | 65.05 | 94.00 | 6.00 | 76.99 |
| 26 | 3 | 1 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 77.75 | 65.34 | 93.95 | 6.05 | 77.00 |
| 27 | 3 | 1 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 88.34 | 40.73 | 0.08 | 99.92 | 40.77 |
| 28 | 3 | 1 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 88.29 | 40.81 | 0.08 | 99.92 | 40.85 |
| 29 | 3 | 1 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 75.07 | 64.93 | 93.35 | 6.65 | 74.39 |
| 30 | 3 | 1 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 75.06 | 65.22 | 93.29 | 6.71 | 74.40 |
| 31 | 3 | 1 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 88.34 | 40.73 | 0.08 | 99.92 | 40.77 |
| 32 | 3 | 1 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 88.29 | 40.81 | 0.08 | 99.92 | 40.85 |
| 33 | 4 | 0 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 86.09 | 81.10 | 99.29 | 0.71 | 86.06 |
| 34 | 4 | 0 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 86.09 | 81.33 | 99.28 | 0.72 | 86.06 |
| 35 | 4 | 0 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 97.73 | 48.43 | 3.26 | 96.74 | 50.04 |
| 36 | 4 | 0 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 97.73 | 48.46 | 3.25 | 96.75 | 50.06 |
| 37 | 4 | 0 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 42.85 | 69.81 | 98.31 | 1.69 | 43.31 |
| 38 | 4 | 0 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 42.84 | 70.11 | 98.29 | 1.71 | 43.31 |
| 39 | 4 | 0 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 97.73 | 48.43 | 3.26 | 96.74 | 50.04 |
| 40 | 4 | 0 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 97.73 | 48.46 | 3.25 | 96.75 | 50.06 |
| 41 | 4 | 0 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 86.26 | 78.75 | 93.65 | 6.35 | 85.78 |
| 42 | 4 | 0 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 86.25 | 78.97 | 93.58 | 6.42 | 85.78 |
| 43 | 4 | 0 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 97.79 | 47.10 | 0.32 | 99.68 | 47.26 |
| 44 | 4 | 0 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 97.79 | 47.12 | 0.32 | 99.68 | 47.28 |
| 45 | 4 | 0 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 75.84 | 77.01 | 89.89 | 10.11 | 75.95 |
| 46 | 4 | 0 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 75.82 | 77.21 | 89.80 | 10.20 | 75.96 |
| 47 | 4 | 0 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 97.79 | 47.10 | 0.32 | 99.68 | 47.26 |
| 48 | 4 | 0 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 97.79 | 47.12 | 0.32 | 99.68 | 47.28 |
| 49 | 4 | 1 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 77.56 | 74.96 | 99.19 | 0.81 | 77.53 |
| 50 | 4 | 1 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 77.55 | 75.24 | 99.18 | 0.82 | 77.53 |
| 51 | 4 | 1 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 88.15 | 41.96 | 0.84 | 99.16 | 42.34 |
| 52 | 4 | 1 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 88.11 | 42.03 | 0.83 | 99.17 | 42.42 |
| 53 | 4 | 1 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 64.69 | 52.14 | 99.30 | 0.70 | 64.60 |
| 54 | 4 | 1 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 64.69 | 52.52 | 99.30 | 0.70 | 64.60 |
| 55 | 4 | 1 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 88.15 | 41.96 | 0.84 | 99.16 | 42.34 |
| 56 | 4 | 1 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 88.11 | 42.03 | 0.83 | 99.17 | 42.42 |
| 57 | 4 | 1 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 77.61 | 69.63 | 93.16 | 6.84 | 77.06 |
| 58 | 4 | 1 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 77.60 | 69.91 | 93.10 | 6.90 | 77.07 |
| 59 | 4 | 1 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 88.21 | 41.88 | 0.08 | 99.92 | 41.91 |
| 60 | 4 | 1 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 88.17 | 41.95 | 0.08 | 99.92 | 41.99 |
| 61 | 4 | 1 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 75.89 | 67.29 | 93.09 | 6.91 | 75.30 |
| 62 | 4 | 1 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 75.88 | 67.58 | 93.03 | 6.97 | 75.30 |
| 63 | 4 | 1 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 88.21 | 41.88 | 0.08 | 99.92 | 41.91 |
| 64 | 4 | 1 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 88.17 | 41.95 | 0.08 | 99.92 | 41.99 |
| 65 | 5 | 0 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 86.08 | 83.35 | 99.19 | 0.81 | 86.06 |
| 66 | 5 | 0 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 86.08 | 83.56 | 99.18 | 0.82 | 86.06 |
| 67 | 5 | 0 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 97.73 | 48.85 | 3.23 | 96.77 | 50.42 |
| 68 | 5 | 0 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 97.73 | 48.86 | 3.22 | 96.78 | 50.44 |
| 69 | 5 | 0 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 42.83 | 72.50 | 98.15 | 1.85 | 43.38 |
| 70 | 5 | 0 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 42.82 | 72.78 | 98.13 | 1.87 | 43.38 |
| 71 | 5 | 0 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 97.73 | 48.85 | 3.23 | 96.77 | 50.42 |
| 72 | 5 | 0 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 97.73 | 48.86 | 3.22 | 96.78 | 50.44 |
| 73 | 5 | 0 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 86.18 | 80.67 | 93.02 | 6.98 | 85.79 |
| 74 | 5 | 0 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 86.17 | 80.87 | 92.95 | 7.05 | 85.79 |
| 75 | 5 | 0 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 97.80 | 47.49 | 0.32 | 99.68 | 47.65 |
| 76 | 5 | 0 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 97.80 | 47.51 | 0.32 | 99.68 | 47.67 |
| 77 | 5 | 0 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 75.76 | 78.28 | 89.32 | 10.68 | 76.03 |
| 78 | 5 | 0 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 75.74 | 78.48 | 89.23 | 10.77 | 76.03 |

| | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 79 | 5 | 0 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 97.80 | 47.49 | 0.32 | 99.68 | 47.65 |
| 80 | 5 | 0 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 97.80 | 47.51 | 0.32 | 99.68 | 47.67 |
| 81 | 5 | 1 | 2 | 500 | 400 | 0.3 | 80 | 6 | 2 | 77.54 | 77.23 | 99.11 | 0.89 | 77.54 |
| 82 | 5 | 1 | 2 | 500 | 400 | 0.3 | 150 | 2 | 4 | 77.54 | 77.50 | 99.10 | 0.90 | 77.54 |
| 83 | 5 | 1 | 2 | 500 | 200 | 1 | 80 | 6 | 2 | 88.47 | 42.93 | 0.83 | 99.17 | 43.30 |
| 84 | 5 | 1 | 2 | 500 | 200 | 1 | 150 | 2 | 4 | 88.44 | 43.01 | 0.83 | 99.17 | 43.38 |
| 85 | 5 | 1 | 2 | 200 | 400 | 0.3 | 80 | 6 | 2 | 64.67 | 55.54 | 99.25 | 0.75 | 64.60 |
| 86 | 5 | 1 | 2 | 200 | 400 | 0.3 | 150 | 2 | 4 | 64.67 | 55.91 | 99.24 | 0.76 | 64.60 |
| 87 | 5 | 1 | 2 | 200 | 200 | 1 | 80 | 6 | 2 | 88.47 | 42.93 | 0.83 | 99.17 | 43.30 |
| 88 | 5 | 1 | 2 | 200 | 200 | 1 | 150 | 2 | 4 | 88.44 | 43.01 | 0.83 | 99.17 | 43.38 |
| 89 | 5 | 1 | 8 | 500 | 400 | 0.3 | 80 | 6 | 2 | 77.53 | 72.10 | 92.58 | 7.42 | 77.13 |
| 90 | 5 | 1 | 8 | 500 | 400 | 0.3 | 150 | 2 | 4 | 77.52 | 72.36 | 92.51 | 7.49 | 77.13 |
| 91 | 5 | 1 | 8 | 500 | 200 | 1 | 80 | 6 | 2 | 88.53 | 42.84 | 0.08 | 99.92 | 42.88 |
| 92 | 5 | 1 | 8 | 500 | 200 | 1 | 150 | 2 | 4 | 88.49 | 42.92 | 0.08 | 99.92 | 42.96 |
| 93 | 5 | 1 | 8 | 200 | 400 | 0.3 | 80 | 6 | 2 | 77.53 | 72.10 | 92.58 | 7.42 | 77.13 |
| 94 | 5 | 1 | 8 | 200 | 400 | 0.3 | 150 | 2 | 4 | 77.52 | 72.36 | 92.51 | 7.49 | 77.13 |
| 95 | 5 | 1 | 8 | 200 | 200 | 1 | 80 | 6 | 2 | 88.53 | 42.84 | 0.08 | 99.92 | 42.88 |
| 96 | 5 | 1 | 8 | 200 | 200 | 1 | 150 | 2 | 4 | 88.49 | 42.92 | 0.08 | 99.92 | 42.96 |

*6.2.2 The effect of port competition*

First, we are interested how port charge and port waiting time influence dry port location strategies and market shares of ports. According to Table 9, we find in all instances that the decrease of $c_F$ from 400 to 200 and the increase of $t_F$ from 0.3 to 1 would not only impact the dry port location decisions of both ports, but also impact the shares of ports and transport modes. This is occurred because port service charge and waiting time account for a large proportion in the cost and time of hinterland transport chain. For instance, comparing instance 1 with 3, when $c_F$ decreases from 400 to 200 and $t_F$ increases from 0.3 to 1, the share of $c_F$ in hinterland transport cost decreases from 12.23% to 6.7% and the share of $t_F$ in hinterland transport time increases from 27% to 56% on average. And the change of port service charge and waiting time would impact the utility of all hinterland transport chains and the probability of shippers choosing each route. Thus, port service charge and waiting time have strong association with dry port location strategy, market shares of ports and transport modes.

Then we focus on the impact of ship call frequency. As shown in Table 9, we find in all instances that the increase of $f_F$ from 2 to 8 would increase the total share of Yingkou port and decrease the total share of Dalian port. But the impact of ship call frequency on dry port location strategy and the share of multimodal transport is rather limited. This implies that port competition is related to ship call frequency.

*6.2.3 The effect of dry port construction*

First, we are interested in the impact of dry port location number. As shown in Table 9, we find in all instances that the increase of $n_F$ from 3 to 4 and 5 would increase the share of multimodal transport to Yingkou port, the total share of Yingkou port and the share of multimodal transport in hinterland. Besides, the share of multimodal transport to Dalian port is also affected by $n_F$. In contrast, the impact of $n_F$ on the dry port location strategy of the leader is rather limited. This is because the increase of $n_F$ changes the location strategy of follower port, and that leads to changes in the shares of multimodal routes and ports. Thus, the number of dry ports to be located can influence the share of both ports and transport modes.

Then we focus on the impact of dry port service charge, time, quality and range. Based on the analysis of Table 9, we find in all instances that when $c_h^F$ increases from 80 to 150, $t_h^F$ decreases from 6 to 2, and $o_h^F$ increases from 2 to 4, the total share and multimodal share of Yingkou port would increase, the multimodal transport share in hinterland would increase, but the total share of Dalian port would decrease. Besides, the share of multimodal transport to Dalian port is also affected by $c_h^F$, $t_h^F$ and $o_h^F$. In contrast, the dry port location strategy of each port doesn't change with variations in $c_h^F$, $t_h^F$ and $o_h^F$. This implies that dry port service charge, time, quality and range will affect the share of multimodal transport and port.

We are also interested in the impact of maximum capacity of dry port. According to Table 9, we find in all instances that when the decreased value of dry port capacity changes the location strategy of either port, the shares of ports and transport modes would change. Therefore, dry port location strategy has a strong connection with its maximum capacity.

## 7. Conclusions and discussions

The choice behavior of shippers and dry port capacity constraint are important considerations for ports to develop multimodal transport network in a competitive environment. Previously limited researches have explored the effect of sequential port competition in which noncooperative ports develop multimodal network in a sequence order considering dry port capacity constraint. Besides, the correlations of inland transport routes to a port due to unobserved factors are not incorporated in the multinomial logit model of shippers' choice. Parameters in the utility functions are exogenously given without calibration. The influence of dry port service and range, custom clearance time, transport mode reliability, freight shipment size, and ship call frequency on shippers' choice is overlooked. These research gaps can lead to biased analysis of shippers' choice behavior and freight distribution. They can also prevent the explanation of different strategies adopted by two competitive ports when they develop multimodal network in the meantime or in a sequence way. To fill these gaps, this paper formulates a nested logit discrete choice model to describe shippers' choice behavior considering the influence of dry port service and range, custom clearance time, transport mode reliability, freight shipment size, and ship call frequency with parameter calibration based on data collected using revealed preference and stated preference techniques. A model that integrates Stackelberg-game theoretical model with nested logit model is established, in which two ports sequentially design multimodal network considering shippers' choice and dry port capacity. Two algorithms are adapted to obtain the Stackelberg equilibrium solution.

Our empirical result confirms that nested logit model is more appropriate than multinomial logit model in describing shippers' hinterland transport chain choice behavior. Dry port service range and quality, custom clearance time, transport mode reliability, freight shipment size, ship call frequency have significant impacts on shippers' hinterland transport chain choice behavior. Inland transport cost, transit time and custom clearance time are more valued in multimodal transport than in road transport. Reliability and large-scale freight shipment are key factors for shippers to choose multimodal transport. This suggests that lower freight rates of multimodal transport than that of road transport, especially for freight with large-scale shipment could help to attract more multimodal cargo flow. Boosting the speed of train shuttles, maintaining and improving the reliability of multimodal transport, especially the punctuality rate of rail transport, could help shift cargo from road to multimodal transport routes. Improving working efficiency and service level at dry port, especially the efficiency of custom clearance could motivate shippers to choose multimodal transport.

We also find that when the only dominant strategy of one port in Nash game is its strategy in Stackelberg equilibrium, pure Nash equilibrium solution would be the same as Stackelberg equilibrium solution. However, the strategy of leader port in Stackelberg equilibrium may not be included in its dominant strategies in Nash game. This implies that dry port location strategy in mixed Nash equilibrium can be different from that in Stackelberg equilibrium. And it is important for port operators to consider the order of action in developing multimodal network in overlapping hinterland, especially when there are several dominant strategies for both ports.

Dry port location strategy could be influenced by port service charge and waiting time. Market share of ports are influenced by ship call frequency, dry port number, service charge, time, quality and range. Multimodal transport share is influenced by port service charge and waiting time, dry port number, service charge, time, quality and range. These results provide evidence that the competitiveness of a hinterland transport chain is jointly determined by ports, transport modes, dry ports, and the services that are provided by shipping lines at port and dry port.

It should be mentioned that the numerical results are based on simplified assumptions and not all cases perfectly fit in our model. For example, ports may not only compete in a strategic level, it is also possible for them to compete simultaneously in strategic, tactic and operational level. Therefore, optimizing the charge of port and dry port in the models can be more realistic. The objective function for ports might be profit maximization when optimizing service charge in the model. The situation of no-choice alternative for shippers can be considered. It is worthwhile to investigate the problem when more than two ports compete with different payoff functions, incomplete information and uncertain transport demands. The effect of cargo flow on custom clearance time, transit time and transport cost can be included in the model.

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