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Modelling port competition for intermodal network design with environmental concerns

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A B S T R A C T

In the fast-moving and competitive market conditions, port operators need to improve their competitiveness to attract more customers. With the rise of stakeholders' (e.g., shippers and port operators) environmental concerns, intermodal transport offers an opportunity to reduce environmental impacts and improves port competitiveness, due to the benefit on environmental protection. However, it is a challenge to understand how port operators make their plans for intermodal network design with consideration for port competition, shippers' route choice behaviors and environmental concerns of stakeholders. In this paper, we develop a game-theoretical model of port competition with environmental concerns. A logit model is used to formulate shippers' discrete choice behaviors. With respect to the probability of nonexistence of pure Nash equilibrium, we propose an approximate equilibrium and a corresponding solution algorithm. A case study on the competition between Dalian port and Yingkou port in the northeast of China is used to verify the effectiveness of the proposed model and algorithm. Results show that, in competitive settings, the rise of stakeholders' environmental concerns will make the market less competitive and always be beneficial to the port closer to the market (here Yingkou port). Moreover, when shippers pay more attention to the environment, the total CO_2e emissions will decrease. As the number of dry ports increases, the CO_2e emissions will decrease. There are also some interesting findings of effects of environmental concerns on the intermodal network, profits, and CO_2e emissions.

1. Introduction

Human expansion of greenhouse effect is commonly believed to be the major cause of dramatic climate changes. The greenhouse gases (GHGs), which contribute to the greenhouse effect, include carbon dioxide (CO_2), methane and Nitrous oxide. In 2013, around 23% of all CO_2 was emitted by transport sectors globally. Take the United States as an example, transport sectors contribute more than 30% of CO_2 emissions and about 85% of these emissions are attributable to road transport. A study commissioned by U.S. Energy Information Administration (EIA), reports that transport sectors will surpass energy sectors and become the biggest contributor before 2020 (EIA, 2017). As the world's second largest economy, China, whose CO_2 emissions has ranked the first globally, is confronted with the enormous pressure to reduce emissions. From the perspective of freight transport, besides alternative fuels and the innovations in vehicles, one of the efficient methods of reducing CO_2 is to promote the use of intermodal transport.

As the average carbon intensity of intermodal transport is 46% lower than truckload, according to the estimation conducted by Craig et al. (2013), intermodal transport makes it possible that freights shift from road transport to rail transport. For this purpose, the rise of environmental concerns will encourage port operators to develop intermodal transport in the hinterland. When designing intermodal network, port operators must consider the port competition. Each port must consider the competitors' strategies under competition. Nowadays port competition is growing severe as the global economy has stepped into a new era characterized by the slower economic growth and weak global trade. In order to keep the competitiveness in the overlapping hinterland, more ports shift their focus to hinterland freight intermodal transport in terms of port regionalization (Notteboom and Rodrigue, 2005; Roso and Lumsden, 2010). A considerable number of dry ports, which play a vital role in the intermodal transport network, are planned and constructed by port operators. From the perspective of shippers, the rising awareness of the need for environmental-friendly

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transport modes may directly influence the freight transport modal choice.

It is a challenge to solve the problem how port operators make plans about intermodal network considering port competition, shippers' route choice behavior, and stakeholders' environmental concerns. Therefore, some research questions will be naturally proposed: How to develop a model to design intermodal transport with the environmental concerns of port operators and shippers under the context of competition? How to find the equilibrium strategies of port operators? What is the effect of the stakeholders' environmental concerns on strategies and profits of port operators and CO_2 emissions?

The intermodal network design problem (INDP), as a special case of hub location problem, has attracted more attention in recent years. The interested readers could refer to Farahani et al. (2013) and Alumur and Kara (2008) for a complete review of hub location problems. Limbourg and Jourquin (2009) focused on their research on the intermodal hub locations on the European network based on p-hub median model. Ishfaq and Sox (2010) proposed a model which extends the p-hub median model for interacting hub location-allocation problems to the domain of intermodal logistic. An increasing number of works have paid attention to the topic of intermodal transport network design. Ambrosino and Sciomachen (2016) proposed the formulation of INDP with capacity bounds which are given both for the candidate hub nodes and arcs. Resat and Turkay (2015) formulated a multi-objective optimization model for the INDP. The work aimed to minimize the transportation cost and time and used an augmented ε-constraint method to solve the problem. Lin et al. (2014) developed a modified model and a heuristic method simplified the models proposed by Sörensen et al. (2012). Ishfaq and Sox (2011) established a model on the basis of the model proposed by themselves in 2010, and encompassed the constraint service time. Then in 2012 they Meng and Wang (2011) considered multiple stakeholders and multiple types of containers and incorporated user equilibrium behavior of intermodal operators in route choice. Wang and Meng (2017) extended their own work (Wang and Meng (2011)) and investigated the intermodal network problem with a random route utility of intermodal operators. The readers interested in INDP could refer the literature review in SteadieSeifi et al. (2014). However, aforementioned studies did not involve the environmental concerns of stakeholders or competition between the network planners. Furthermore, it is still a neglected research question required to be investigated that how to design the intermodal network when the planner is the hub operator.

There exists an emerging trend of studies on intermodal network design with environmental concerns recently. Lam and Gu (2016) developed a bi-objective optimization model to simultaneously minimize cost and transit time with constrained carbon emissions. Demir et al. (2016) proposed a stochastic model to decide robust transportation plans with different objectives, including cost, time and greenhouse gas emissions. In addition, the usage effect of intermodal transport and dry ports on the environment has been investigated by various methods. Discrete-event simulation method was used by Lättilä et al. (2013) to estimate the cost and CO_2e emission development in different scenarios in a Finnish context. Zhang et al. (2013) introduced a bi-level programming model for the optimization of the intermodal network with the cost of CO_2e emissions. The upper-level model searches for the optimal terminal and the lower-level model performs multi-commodity flow assignment. Qu et al. (2016) considered the GHG emissions in the objective function to minimize the total cost and linearized the formulation to find the solution. However, the relevant studies are still scarce, and the works only study the intermodal network design with the environmental concern of planners, the consideration of route choice makers (e.g. shippers) on environment has not thus far appeared in the studies on the classical intermodal network design.

Moreover, a few number of literature focused on the study on the transport network design with competition. Marianov et al. (1999) was the first to study the transport network design with competition. This work assumed that the current player (i.e. the follower) optimized the locations of hubs based on the context where the transport network of the competitor (i.e. the leader) is given. The same assumption was also used by Wagner (2008), Eiselt and Marianov (2009) and Lüer-Villagra and Marianov (2013). Another stream of literature on transport network design with competition was to use a Stackelberg model to investigate the decisions of two planners. In these models, the planners sequentially made a decision on the locations of their hubs. Mahmutogullari and Kara (2016) developed a game model in which both planers aimed to maximize the market share of himself/herself and the customers chose one of the planners to provide transport service after the networks was determined. Sasaki et al. (2014) adopted a generic hub arc model in which the planners located arcs with discounted transport costs connecting pairs of hubs. Sasaki (2005) addressed a game model incorporating flow threshold constraints to void unprofitable services. Lin and Lee (2010) adopted Nash game model to find the equilibrium strategies of both planners. However, those studies did not consider the features of intermodal transport and incorporate the environmental concerns of the stakeholders.

To fill the gap of studies on the intermodal transport network design with environmental concerns and port competition, we develop a game-theoretical model of port competition on the problem proposed in this paper. In the model, each port operator aims to maximize the payoff considering profits and environment. The inland route choice behavior of shippers is formulated by a logit discrete choice model. The environmental concerns of port operators and shippers are considered respectively in the port operator's payoff function and shipper' utility functions. It is also a challenge to find equilibrium strategies of port operators. An equilibrium state means that none of the players would unilaterally alternate their respective strategies to increase profits, which is called a Nash equilibrium. With respect to the possibility of inexistence of pure Nash equilibrium due to the non-differential objective function of the game model, an approximate equilibrium and the corresponding algorithm are proposed based on the works of Grauberger (2015) and Wang et al. (2014). Furthermore, a case study of port competition between Dalian port and Yingkou port is used to verify the proposed model and algorithm. We analyze the effect of environmental concerns on intermodal network design and CO_2e emissions. The result of our analysis has important implications for port management and policymakers.

The paper is structured as follows. Section 2 presents the formulation of intermodal network and introduces CO_2e estimation models. In Section 3, we formulate the problem of intermodal transport network design with environmental concerns and port competition as a Nash game model. An approximate equilibrium and the corresponding algorithm are proposed in Section 4. Section 5 is structured to test the algorithm and analyze the effect of environmental concerns on port competition with a case study. Conclusions and future research directions are stated in Section 6.

2. Intermodal network

2.1. Network formulation

In this subsection, we introduce the presentation of the inland intermodal network. The network is denoted as $G = (N,A)$, where N