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Modeling and optimization of a road–rail intermodal transport system under uncertain information

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ABSTRACT

A realistic road–rail intermodal transport system can be suitably modeled as a hub-and-spoke (H&S) network for which the parameters are subject to fuzzy uncertainty: demand, cost and time. For modeling uncertainty, we present a bi-objective optimization formulation for the hub-and-spoke based road–rail intermodal transportation (HS-RRIT) network design problem by taking into account the expected value criterion and the critical value criterion. Using the weighted sum method, we reformulate a single-objective mixed-integer linear programming (MILP) model to solve the equivalent HS-RRIT network design problem. Given the inherent complexity for solving this problem, we develop a memetic algorithm (MA) to obtain high quality solutions. This algorithm utilizes a genetic search method to explore the search space and two different local search strategies called shift and exchange to exploit information in the search region. Finally, we conduct computational analysis over the Turkish network data set to demonstrate the applicability of proposed model and the effectiveness of solution method.

1. Introduction

Road–rail intermodal transport is defined as a system that carries freight from origin to destination using two transportation modes: road and rail. Rail is cost-effective for transportation over a long distance and with large quantities while road is faster and has better accessibility for collection and distribution activities for medium to short distances. Road–rail intermodal transport has become a well-established sector of freight transport, with a market encompassing dozens of companies generating a joint turnover of several billion Euros per year. The strategic network designing for road–rail intermodal transport system needs to be considered carefully since it has direct and indirect impacts on the transport company as well as the economy and society. For this reason, the study presented in this paper aims at making a model to support the decision making process for optimizing a road–rail intermodal transport system.

It is natural that the hub-and-spoke (H&S) network has emerged as the most suitable network structure for road–rail intermodal transport system, which are combinations of their respective modal networks. As suggested by Crainic and Kim (2007), a road–rail intermodal transport system can be essentially formulated as a H&S network. The motivators for optimizing road–rail intermodal transport system embedded in a H&S framework are: (1) to improve customer service and increase intermodal transportation frequency, (2) to centralize operations at the intermodal hub leads to economies of scale, and (3) to dominate market share in a particular region. As a result, this paper models the road–rail intermodal transport system as a H&S network.

The performance of road–rail intermodal transport system can be gauged on the cost and time. In more specific terms, the cost (e.g. the transportation, construction and operational cost) is related to economic evaluation of the transport company and the time (e.g. the travel and operational time) refers to quality of the service offered. In fact, these two measures of performance are in fair amount of conflict and any gain in one is expected to be accompanied by a loss in the other. That is, a solution that yields the minimum total cost does not generally yield the minimum time. To this aim, the hub-and-spoke based road–rail intermodal transportation (HS-RRIT) network design needs to make a better trade-off between the economic objective and service objective.

In strategic planning, decisions may have a long lasting effect and the implementation may take considerable time. Moreover, input data is not precisely known in advance. Hence, decisions such as the location of intermodal hub facilities have to be made under high uncertainty on future conditions for relevant parameters that have a direct impact on the performance of HS-RRIT networks. In some cases, some probabilistic information is known for these parameters and can be used to characterize uncertain parameters by using stochastic programming techniques. However, in other cases, no information about

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their probability distributions is known except for the experiences and opinions of field experts, thus one must rely on fuzzy optimization techniques to handle the uncertain information. Motivated by this, we are particularly concerned with the problem of HS-RRIT network design, in which three sources of uncertainty are considered: demand, cost, and time.

By combining these aforementioned aspects, we intend to address the modeling and optimization road–rail intermodal transport system embedded in the H&S type network under uncertainty. For modeling uncertainty, we first formulate a fuzzy bi-objective optimization model for the HS-RRIT network design problem, where the economic objective and service objective are explicitly considered. Subsequently, we use the weighted sum method to reformulate the original one as a single-objective mixed-integer linear programming (MILP) formulation by making use of the mathematical properties. Specifically, this paper aims to make the following contributions to the study of HS-RRIT network design problems.

(i) We adopt the credibility distributions to capture the characteristics of uncertainty within a road–rail intermodal transport system. By doing so, the uncertain information (i.e., the demand, cost, and time) can be directly handled in the proposed modeling framework. Furthermore, the credibility distribution enable a feasible way to measure the uncertainty in strategic decision process, compared to probability distributions that typically rely on the sufficient historical data.
(ii) We employ the expected value criterion and the critical value criterion to formulate the economic objective and service objective, respectively. More specifically, the economic objective is to minimize the expected value of the total costs. The service objective is to minimize the maximum time requirement in terms of critical value. Compared with existing research, the proposed objective functions simultaneously consider the transport process and hub operation process.
(iii) We provide a highly efficient method to solve the proposed model. In order to balance the magnitude of each sub-objective function, we firstly suggest a weighted sum method by considering the difference in scale of cost and time. Then, we further design a memetic algorithm (MA) to obtain high quality solutions. This algorithm utilizes two different local search strategies called shift and exchange to exploit information in the search region.
(iv) We carry out numerical experiments based on the Turkish network data set to illustrate the practicability of the models as well as the effectiveness of the proposed approaches. The computational results demonstrate the superiority of the proposed approach. Further analysis shows that theoretically, the road–rail intermodal transportation mode can exert the cost advantage of rail transportation and speed advantage of road transportation to achieve a win–win situation between the economic and service goals.

The remainder of this paper is organized as follows. In Section 2, we briefly review related literature. In Section 3, we give the detailed problem statements and assumptions. In Section 4, we formulate a fuzzy bi-objective optimization model for HS-RRIT network design problem in detail. In Section 5, we provide theoretical analysis of the proposed model. Then, we develop the MA to solve the proposed model in Section 6. In Section 7, we conduct numerical experiments to verify the effectiveness of the model and approach. In Section 8, we draw some conclusions and outline directions for further research.

2. Literature review

This section presents a review of literature on the intermodal transportation and the H&S network design, highlighting the novelties of the proposed model and solution approach.

The first stream studies the intermodal transportation problem. Crainic and Kim (2007) defined intermodal transportation as the transportation of a person or a load from its origin to its destination by a sequence of at least two transportation modes, in which the transfer from one mode to the next is performed at an intermodal terminal. In general, the intermodal transportation problem includes three research lines: intermodal terminal location, transportation route selection and transportation mode choice. The first line of this stream studies the intermodal terminal location problem. For example, Duin and Ham (1998) presented a three-stage approach to decide the location of the intermodal terminal. Arnold et al. (2004) proposed a linear 0–1 programming model to optimize the terminal location problem. Lin et al. (2014) developed a modified mixed integer programming model for the intermodal terminal location problem in order to minimize the total transportation and operation costs through collaborations of unimodal road transport and intermodal transport chains. The second line of this stream focuses on the route selection in intermodal transportation networks. For example, Boussedjra et al. (2004) investigated the model for finding the origin–destination shortest path in the intermodal transportation networks by means of a multi-label graph. Zhang et al. (2006) applied the Dijkstra algorithm to solve the intermodal transportation optimal transportation path problem. Sawadogo et al. (2012) presented a multi-objective shortest path model for simultaneously reducing the environmental and social impact on intermodal transportation network. Zhang et al. (2015) formulated a bi-objective model for intermodal transportation route selection that explicitly considers two significant factors including the reliability and the cost. The third line of this stream considers intermodal transportation mode choice problem. For example, Zhang et al. (2011) introduced an approach to optimize the choice of transportation modes for intermodal transportation, of which the objective is to minimize the total cost including both logistics costs and costs related to carbon emissions. Saeed (2013) applied a two-stage game for analyzing three freight forwarders ('players') with two different modes of transportation. Reis (2014) developed a new agent-based model to simulate the transport operations and behavioral reactions of transport agents, and found the price is a key factor for the transportation mode choice in the process of short-distance transport. For a detailed review of intermodal transportation problem and its variations, interested readers can refer to Yaman (2009), Limbourg and Jourquin (2009) and Alumur et al. (2012). Our primary difference is that we present a model that has been developed to address the optimization of intermodal transportation problem through the use of H&S type networks.

The second stream of literature related to our work is on H&S network design problem, which is conventionally called p-hub location problem (pHLP). The pHLP mainly contains the p-hub median problem and the p-hub center problem. O'Kelly (1986, 1987) provided a quadratic integer programming formulation for p-hub median problem. Skorin-Kapov et al. (1996) developed tight linear relaxations of the formulation for p-hub median problem. Zarandi et al. (2015) investigated hierarchical single-allocation p-hub median problem, and designed two metaheuristics, namely simulated annealing (SA) and iterated local search (ILS). On the other hand, Campbell (1994) proposed the first formulation for p-hub center problem as a quadratic programming model. Kara and Tansel (2000) provided several linear formulations for p-hub center problem. Rabbani and Kazemi (2015) presented a complete definition of the uncapacitated multiple allocation p-hub center problem, and applied the genetic algorithm (GA) to solve the proposed problem. Another aspect of pHLP attempts to consider the fuzzy uncertainty. For instance, Yang et al. (2013) presented a new risk aversion pHLP with fuzzy travel times by adopting value-at-risk criterion in the formulation of the objection function. Mohammadi and Moghaddama (2016) addressed a fuzzy bi-objective pHLP to investigate the effect of delivery service requirement on the configuration of the H&S network. Zhalechian et al. (2017) presented a new multi-objective model for a pHLP under uncertainty, which simultaneously considers