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A self-adaptive evolutionary algorithm for a fuzzy multi-objective hub location problem: An integration of responsiveness and social responsibility

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ABSTRACT

In this paper, we present a new multi-objective model for a hub location problem under uncertainty. This model simultaneously considers economic, responsiveness and social aspects in designing a hub-and-spoke network. An $M/M/c$ queuing system is used to calculate waiting time at each hub node and maximize responsiveness. Employment and regional development are selected as social responsibility measures in the proposed model. Furthermore, a hybrid two-phase solution method is proposed based on possibilistic programming, fuzzy multi-objective programming and an efficient algorithm, called self-adaptive differential evolution algorithm. Finally, several numerical experiments and sensitivity analyses are carried out to assess the proposed model and the solution method.

1. Introduction

A hub location problem (HLP) is an extension of a classical facility location problem, which is extensively used in a wide range of areas such as transportation, telecommunications, and computer networks. Freight transportation is one of the major applications of HLPs as it has become a vital part of the global economy. Several companies (e.g. FedEx, UPS, DHL, and United States Postal Service) handle millions of packages every day. For instance, the United States Postal Service receives and delivers 2.3 million packages each day, and FedEx Memphis handles 2.2 million packages each night (Vidyarthi et al., 2013).

The HLP involves the movement of people, commodities or information between origin-destination (O-D) nodes. There are two types of nodes in a hub-and-spoke network, including hub and spoke nodes. In freight transportation, hub nodes usually serve as sorting (i.e., unloading and loading), transshipment and consolidation points, while the remaining nodes are called spoke nodes. In these networks, instead of sending flows directly between each pair of O-D nodes, flows with different origins but the same destinations are consolidated at hub nodes to take advantage of the economies of scale. Generally, there are two types of allocation strategies in hub-and-spoke networks, including single and multiple allocation. In a single allocation strategy, each spoke node must be allocated to just one hub node, while allocating a spoke node to more than one hub node is possible in the multiple allocation strategy (Zhalechian et al., 2017). Furthermore, there are two common assumptions in most HLPs based on which graph of hub nodes is considered as a complete one (i.e., hub nodes are completely linked together), and the flows have to be routed via at least one hub node.

In today's competitive business environment, cost reduction and customer service improvement are two main challenges in the logistic systems (Fattahi et al., 2015; Keyvanshokooh et al., 2013; Rezaei-Malek et al., 2016a). The classical HLP aims to find the location of hub nodes and the allocation of spoke nodes in order to minimize the total costs. However, the huge arrival rate of flows to hub nodes results in a queue and long waiting times for flows, and subsequently, reduces customer satisfaction. In this respect, the responsiveness of a logistic network should be considered as an important factor in designing a hub-and-spoke network. A queuing system is known as one of the main tools to manage congestion and improve responsiveness in the logistic systems. In the literature, several significant efforts have been done to show the validity of queuing systems to calculate waiting times and improve the responsiveness in the networks (see Van Woensel and Cruz (2009) and Van Woensel et al. (2006)). Hence, implementing queuing systems can be helpful to address the concern about extra waiting times and delay of deliveries.

Social responsibility (SR) is an important pillar of sustainability, which is rarely addressed in the literature. Based on the Global Reporting Initiative (GRI), SR is defined as a pillar of sustainability

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that "*concerns the impacts the organization has on the social systems within which it operates*" (Initiative, 2013). A general classification of SR is introduced by the GRI guidelines. This classification considers four major categories for social issues, including Labor Practices and Decent Work, Society, Human Rights, and Product Responsibility. To provide a comprehensive framework for social issues, International Standards Organization (ISO) developed a new standard (i.e. International Guidance Standard on Social Responsibility-ISO 26000), which classifies the social issues into seven major categories: (1) organizational governance, (2) human rights, (3) labor practices, (4) the environment, (5) fair operating practices, (6) consumer issues, and (7) community involvement and development (Pishvaee et al., 2012). It should be noted that the environmental category is usually considered as a dependent pillar of sustainability in the literature (see for example Savino and Apolloni, 2007; Zhalechian et al., 2016), and it is beyond the scope of this paper.

The multi-stakeholder nature of SR makes it hard to measure all aspects of SR. Furthermore, each type of enterprise has its own SR based on its features. HLPs are usually solved as part of a strategic decision-making process. In this regard, the aspects of SR related to strategic decisions can be considered in designing a hub-and-spoke network. Generally, organizations have a relationship with the social settlements located in a geographic area within an organization's areas of impact. In both ISO 26000 and GRI guidelines, the importance of respecting and enhancing the communities around the workplace is considerably highlighted. Indeed, there is a significant concern for employment opportunities and balanced economic development as strategic decisions in the mentioned guidelines (Mota et al., 2015; Pishvaee et al., 2014). In this regard, many countries have set national targets to increase job opportunities and provide balanced economic development in their communities. For example, these issues have been taken into account in the "Fifth development plan of Islamic Republic of Iran" (Pishvaee et al., 2014). Moreover, the main focus of the European Commission funding program for the period 2014–2020 is on fostering the economic growth through regional development and promoting job creation (Mota et al., 2015). However, there is no study that addresses SR in the context of a hub-and-spoke network.

In the real world, a lot of parameters (e.g., costs, demands, and transportation times) may change due to the uncertain circumstances. Due to the dynamic and chaotic nature of hub-and-spoke networks and the effects of uncertainty on designing a network, it is important to address uncertainty in the HLPs. In order to capture the uncertainty in the input data, three types of modeling techniques have been introduced in the literature, including stochastic programming, fuzzy programming and robust optimization (Zhalechian et al., 2016; Keyvanshokooh et al., 2016; Rezaei-Malek and Tavakkoli-Moghaddam, 2014; Rezaei-Malek et al., 2016b). Fuzzy programming approaches are the most applied methods to deal with uncertainty due to their capability in handling both epistemic and vague uncertainties. In this study, an efficient fuzzy programming approach is utilized to deal with uncertainty.

The first aim of this paper is to develop a new multi-objective mathematical programming model to design a hub-and-spoke network under uncertainty. The model aims to (1) minimize the total investment and transportation costs, (2) maximize the positive social impacts (SIs) (3) and maximize the responsiveness through minimizing the maximum transportation time between each pair of O-D nodes.

The considered hub-and-spoke network is very complicated in many different aspects: (1) the original HLP is known to be NP-hard, (2) implementing an M/M/c queuing system can substantially increase the complexity of the mathematical model, and (3) implementing a fuzzy programming method to handle epistemic uncertainty in input data adds a number of new constraints to the original mathematical model, and increases the required computation time. In this regard, the second aim of this paper is to propose an efficient and powerful evolutionary algorithm to solve the proposed mathematical model in a reasonable amount of time.

The remainder of the paper is organized into six sections. After the introduction, Section 2 presents the related literature. In Section 3, the problem description and mathematical formulation are described. The solution method is presented in Section 4. Section 5 presents the computational experiments and sensitivity analyses. Finally, conclusions are drawn in Section 6.

2. Literature review

In the area of HLPs, the first known quadratic integer formulation of an HLP was presented by O'kelly (1986). Campbell (1994) simplified this model by developing a linear version of the presented model. Ernst and Krishnamoorthy (1998) developed other linear formulations of an HLP with fewer variables and constraints. Skorin-Kapov et al. (1996) developed a tight linear relaxation of an HLP and obtained exact solutions for the *p*-hub median problem. In the literature, there are many other formulations for HLPs in different contexts. Among these studies, the *p*-hub median problem and capacitated/uncapacitated models are the most frequently studies in the literature (Alumur et al., 2012). The interested readers are referred to three comprehensive reviews in the literature to see more details about HLPs (Alumur and Kara, 2008; Campbell and O'Kelly, 2012; Farahani et al., 2013).

The first study addressed the importance of responsiveness in the hub-and-spoke networks was presented by Grove and O'Kelly (1986). Based on the results of a simulation, they concluded that the assignment of spoke nodes to hub nodes can affect the responsiveness of the network. Elhedhli and Hu (2005) modeled the effect of flow aggregation at hub nodes by adding a convex cost function to the objective functions. The application of a queueing theory in HLPs is a relatively new area. Due to the advantages of queuing systems to control the congestion and increase the responsiveness, a number of studies are integrated different queuing systems into HLPs. Marianov and Serra (2003) developed an HLP in an airline network and considered the congestion effects. They utilized an M/D/c queuing system to limit the length of the queue at each hub node to a predefined value. Rodriguez et al. (2007) presented an HLP in the context of cargo transportation. In this study, each hub node modeled as an M/M/1 queuing system and the respective costs due to the congestion in hub nodes were considered in the model. Ishfaq and Sox (2011) modeled hub operations as a G1/G/1 queuing system and investigated the effect of limited hub resources on the design of intermodal logistics. Rahimi et al. (2015) developed a bi-objective mathematical model for an HLP and utilized an M/M/c/k queuing system to control the congestion at hubs nodes. They also presented a meta-heuristic algorithm to solve large-sized problems.

There are several studies in the literature of supply chain network design (SCND) that addressed the SR aspect of sustainability. Among different SR metrics, there is a strong literature to support the practicality of considering two SR metrics, including employment and economic development. Dehghanian and Mansour (2009) presented a multi-objective mathematical programming model to design a recovery network. To maximize the social benefits of the designed network, several measures of SR, namely employment, damage to workers, product risk, and local development were considered in the developed mathematical model. Pishvaee et al. (2012) designed a socially responsible supply chain to minimize the total costs and maximize the SR of the supply chain. The created job opportunities alongside other social metrics (e.g., the number of potentially hazardous products, the number of lost days caused from work's damage, and the amount of produced waste) were considered in the designed supply chain network. Devika et al. (2014) developed a closed-loop supply chain which simultaneously considered three pillars of sustainability. In the presented model, two measures of SR, including created job opportunities and workers' safety were quantified as a separate objective function. Savino et al. (2014) addressed a workforce alloca-