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Multi-objective design of an organ transplant network under uncertainty

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ABSTRACT

We propose a novel multi-period location–allocation model for the design of an organ transplant transportation network under uncertainty. The model consists of a bi-objective mathematical programming model that minimizes total cost and time, including waiting time in the queue for the transplant operation, while considering organs' priorities. A fuzzy multi-objective programming based approach is presented to solve the small and medium size problems to optimality. For larger problems, we propose two meta-heuristics based algorithms. Lower bounds, and several numerical examples with managerial insights are discussed. A real case-study is provided, and the existing and the proposed optimal solutions are compared.

1. Introduction

Supply chain management (SCM) is the process of planning, implementing and controlling the operations of the supply chain efficiently (Melo et al., 2009). The supply chain network design (SCND), as one of the most important subsets of strategic decision making of SCM, plays an important role in the overall economic performance of the chain. SCDN addresses the number of facilities, their location, and the allocation of flows among these facilities (Pishvaee and Razmi, 2012). Location–allocation models play critical roles in health service planning. They provide frameworks for investigating accessibility problems, comparing the quality (i.e., in terms of cost efficiency and public welfare), and suggesting alternative solutions to improve existing systems (Shariff et al., 2012; Rahman and Smith, 2000).

Organ transplantation, which is one of the most vital subset of healthcare systems, has become a successful treatment for many diseases that otherwise would have been fatal (Beliën et al., 2012). Despite all the advances and sophisticated technologies in operations and transportation methods in healthcare facilities, management on location–allocation of organ transplant centers in some districts has remained far from being cost and time efficient on a consistent basis.

The transplant surgical process involves a donor (i.e., a volunteer or brain-death patient) and a recipient (i.e., the patient who receives the organ). The concerned network system consists of donors, recipients' region/zone, shipping agents, hospitals and transplant centers (TCs). Donors are kept in hospitals, where some necessary analyses are carried out and organ is removed (harvested). Recipient zones are populated areas, in which majority of applicants for receiving organs locate. Transplant centers are facilities where the registration and surgical operations for transplanting the recipients are done. And finally, shipping agents are in charge of transporting the organs and the required materials from hospitals to TCs. Therefore,

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there are several decisions that should be simultaneously made, including: (1) establishing hospitals among a potential set of locations, (2) establishing TCs among a given set of candidate locations, (3) determining which hospitals or TCs are capable of treating specific organs. Furthermore, the following decisions are dynamically made in each time period: (4) assigning different shipping agents to transfer donors' organs and necessary materials between hospitals and TCs, (5) selecting transportation modes with different cost and time while the transplant operation is performed within specified perishable time for each organ, and (6) allocating different regions of patients to TCs.

The complexity of the organ transplant network and the intense interaction between facilities require efficient management to maximize the benefits of the stakeholders involved. In such networks, donors are usually transferred to hospitals, or may refer directly to TCs for donation. As the demand zones and the TCs may be located in disperse geographical areas with often long distances, servicing all demands via a single transportation mode may not be practical. On the other hand, organ perishability is a critical issue in transplant supply chains. According to Uehlinger et al. (2010), each organ is constrained by the cold ischemia time, defined as the maximum time that the organ can be kept outside the body.

Due to dynamic nature of this industry, the respective costs, supplies, demands, distances, travel times and other relevant parameters may change due to uncertain circumstances. This will greatly affect the design of the network. Therefore, it is important to address uncertainties in the problem.

This paper introduces a new bi-objective mixed-integer programming (BOMIP) model for the multi-period location–allocation problem of the organ transplant supply chain that minimizes the total cost and travel time. The main contributions of this paper, which differentiate our efforts from related studies, are as follows:

- Designing a novel multi-period transplant network that addresses fluctuations in demands and supplies, while considering different transportation modes, and possible integrated facilities (i.e., facilities which can simultaneously function as a hospital and a TC).
- Developing a multi-priority queuing system to model the congestion of organs at each TC.
- Applying an efficient hybrid fuzzy multi-objective programming approach to cope with uncertainties.
- Developing two meta-heuristic based algorithms to efficiently solve large size instances of the problem.
- Proposing lower bounds for evaluating the performance of the proposed meta-heuristic algorithms in cases that the optimal solutions are not available.
- Applying the proposed methods in a real-case study.

The rest of the paper is organized as follows: Section 2 represents a literature review. Problem definition and mathematical formulation are presented in Section 3. In Section 4, the proposed possibilistic programming is explained. Meta-heuristic algorithms and the lower bound approach are presented in Section 5. Section 6 handles the computational experiments and an industrial case-study. Finally, conclusion and future research are provided in Section 7.

2. Literature review

Focus on the current research can be classified into two main categories: first, designing location–allocation of healthcare facilities (or healthcare supply chain network design), and second, optimizing organ transplant supply chains.

2.1. Location–allocation design of healthcare networks

In the area of healthcare facilities network design, Papageorgiou (1978) and Rais and Viana (2010) proposed a comprehensive survey on applying operations research on such systems. In this field, several researchers have presented different models for location–allocation of healthcare facilities. Shariff et al. (2012) formulated a capacitated maximal covering healthcare location–allocation problem and applied it to one of the districts of Malaysia. For determining the percentage of coverage of the existing facilities, they proposed a new genetic algorithm (GA). Benneyan et al. (2012) presented a model for multi-period location–allocation of Veterans Health Administration. They presented a multi-period mathematical integer programming model considering the trade-offs between costs, coverage, service location and capacity. Syam and Côté (2012) proposed a model for location–allocation of a treatment department related to traumatic brain injuries. They considered the minimization of the total cost as an objective function. The data obtained from department of veterans affairs have been used for testing the applicability of their model. They also examined the effects of five critical factors, such as the degree of service centralization, service level mandates by acuity, lost admission cost by acuity, facility overload penalty cost by acuity and target utilization level by acuity and treatment unit. Furthermore, Syam and Côté (2010) for location–allocation of specialized healthcare systems proposed a model based on three main factors; i.e., geographic density of the patient population, degree of centralization of services, and the role of patient retention as a function of distance to a treatment unit. Zhang and Jiang (2013) presented a bi-objective robust programming approach for an emergency medical services system under uncertainty that minimizes the total costs and determines the assignment of demand points to EMS, location of EMS facilities, and the number of EMS vehicles at each station. Shariff et al. (2012) focused on multi-period location–allocation of healthcare systems (i.e., emergency blood facilities) for a case study in Beijing. They proposed a heuristic algorithm based on the Lagrangian relaxation method.