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Optimisation of transportation service network using κ-node large neighbourhood search

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ABSTRACT

The Service Network Design Problem (SNDP) is generally considered as a fundamental problem in transportation logistics and involves the determination of an efficient transportation network and corresponding schedules. The problem is extremely challenging due to the complexity of the constraints and the scale of real-world applications. Therefore, efficient solution methods for this problem are one of the most important research issues in this field. However, current research has mainly focused on various sophisticated high-level search strategies in the form of different local search metaheuristics and their hybrids. Little attention has been paid to novel neighbourhood structures which also play a crucial role in the performance of the algorithm. In this research, we propose a new efficient neighbourhood structure that uses the SNDP constraints to its advantage and more importantly appears to have better reachability than the current ones. The effectiveness of this new neighbourhood is evaluated in a basic Tabu Search (TS) metaheuristic and a basic Guided Local Search (GLS) method. Experimental results based on a set of well-known benchmark instances show that the new neighbourhood performs better than the previous arc-flipping neighbourhood. The performance of the TS metaheuristic based on the proposed neighbourhood is further enhanced through fast neighbourhood search heuristics and hybridisation with other approaches.

1. Introduction

E-commerce and online shopping have rapidly transformed the formats of businesses in recent years. Online shopping companies like `Amazon.com` and China-based `Taobao.com` have seen significant growth in sales in recent years. While most companies are keen to leverage new business opportunities such as online shopping, many of them also encounter new issues, such as providing high quality delivery of billions of products. Hence the problem of logistics has received increasing attention from both industry and the research communities.

Freight transportation has great potential for further improvement in efficiency and service level in the era of big data and cloud computing. The Service Network Design Problem (SNDP) is widely considered as the core problem of freight transportation planning for less-than truck load transport and express deliveries where consolidation is necessary to improve the efficiency. It involves the determination of a cost-effective transportation network and the services which it will provide, while satisfying the constraints related to geographically and temporally diverse demands, network availability, assets capacity, etc. The SNDP is strongly NP-Hard (Ghamlouche et al., 2003) and hence it is impractical to optimally solve the problem of realistic sizes. In fact, the SNDP is generally of large-scale, due to the size of potential network. This is particularly the case when the formulation is based on a time-space network in which each node and each arc has a copy in each period of the scheduling horizon (see Fig. 1).

Various heuristic and metaheuristic approaches have been applied to this problem and substantial progress has been made (Andersen et al., 2011; Bai et al., 2012; Chouman and Crainic, 2014; Crainic et al., 2000; Ghamlouche et al., 2003; 2004; Hoff et al., 2010; Minh et al., 2013; Pedersen et al., 2009). However, almost all of these research studies have focused on various intelligent high-level strategies for better trade-offs between search explorations and exploitations. Here, we consider high-level strategies

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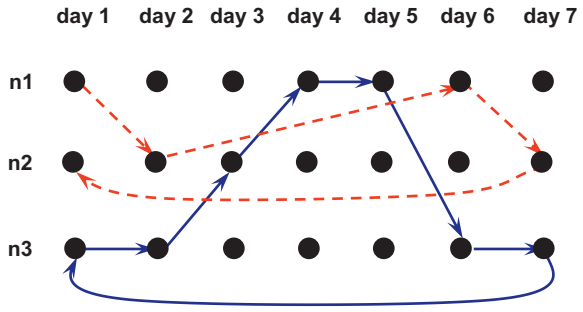

Fig. 1. An example of a time-space network with 3 nodes and 7 periods.

as domain-independent heuristic approaches that do not take specific advantage of a problem's underlying low-level solution structure. Examples of high-level strategies for more efficient search include the tabu-assisted guided local search by Bai et al. (2012) and the hybrid tabu search with path-relinking method by Minh et al. (2013). Analysis of the problem solution structure and its constraints is very limited. As indicated in Kendall et al. (2016), a lot of optimization research studies merely borrow different metaphors without much deep insights on algorithmic or problem properties. These approaches do not satisfy real-world requirements either in terms of solution quality delivered or in computational time required. This is because the SNDP contains some difficult constraints and a flow distribution sub-problem, generally referred to as the Capacitated Multicommodity Min-Cost Flow (CMMCF) problem, which can be very expensive to solve if it is called many times within an iterative metaheuristic approach. This motivates us to develop more efficient metaheuristics for this important and challenging sub-problem. Therefore, unlike the above papers which focus on high-level strategies, in this paper, we propose and study a new larger neighbourhood that exploits the special structure of the SNDP constraints and has much better reachability due to the implicit constraint handling. The experiments on two basic metaheuristic approaches and a hybrid algorithm show that the new neighbourhood is very effective and could be used to develop more efficient algorithms for the SNDP.

The remainder of the paper is structured as follows: Section 2 provides a brief introduction to the SNDP and an overview of the research in freight service network design. Section 3 presents the arc-node based mathematical formulation for SNDP. Section 4 discusses the neighbourhood structure used in the previous studies. Section 5 describes the proposed κ-node neighbourhood operator whose performance is evaluated in Section 6 through a basic Tabu Search (TS) method and a basic Guided Local Search (GLS) method. Section 7 describes a hybrid algorithm based on the κ-node neighbourhood. Section 8 concludes the paper.

2. Literature review

This section provides a brief overview of the previous research into SNDP which is closely related to classic network flow problems (Ahuja et al., 1993). Comprehensive reviews can be found in Crainic (2000), Crainic and Kim (2007) and Wieberneit (2008).

Early work in this field includes Crainic and Rousseau (1986), Powell (1986) and Crainic and Roy (1988). Crainic et al. (1993) applied a TS metaheuristic to the container allocation/positioning problem. Crainic et al. (2000) investigated a hybrid approach for capacitated multicommodity network design (CMND), combining a TS method with pivot-like neighbourhood functions and column generation. Ghamlouche et al. (2003) continued the work and proposed a more efficient cycle-based neighbourhood function for CMND. Experiments with a simple TS framework demonstrated the superiority of the method to the earlier pivot-like neighbourhood functions in Crainic et al. (2000). This approach was later enhanced by adopting a path-relinking mechanism (Ghamlouche et al., 2004).

Barnhart et al. (2002) addressed a real-life air cargo express delivery SNDP. The problem instances are characterised by their large sizes and the addition of further complex constraints to those in the general SNDP model. A tree formulation was introduced and the problem was solved heuristically using a method based on column generation. Armacost et al. (2002) introduced a new mathematical model based on an innovative concept called the *composite variable*, which has a better Linear Programming bound than other models. A column generation method using this new model was able to solve the problem successfully within a reasonable computational time, taking advantage of the specific problem details. However, it may be difficult to generalise their model to other freight transportation applications, especially when there are several classes of services being planned simultaneously. Pedersen et al. (2009) studied more generic SNDP in which a set of *asset balance constraints* was added to model the requirements that the number of incoming vehicles at each node must equal to the outgoing vehicles in order to maintain the continuity of freight services over time. A multi-start metaheuristic, based on TS, was developed and shown to outperform a commercially available MIP solver when computational time was limited to one hour per instance. Andersen et al. (2009) compared the node-arc based formulation, the path-based formulation and a cycle-based formulation for SNDPs. Computational results on a set of small randomly generated instances indicated that the cycle-based formulation gave significantly stronger bounds and hence may allow for much faster solution methods of problems. More recent work by Bai et al. (2012) attempted to further reduce the computational time and investigated a Guided Local Search (GLS) based hybrid approach. The computational study showed that GLS was able to obtain better solutions than Tabu Search (TS) but with less than two thirds of the computational time. However, GLS in that study was based on an arc-flipping neighbourhood which sometimes leads to poor solutions.

Other methods of approaching SNDP have included ant colony and a branch and price method. Barcos et al. (2010) investigated an ant colony optimization approach to address a simplified variant of freight SNDP. The algorithm was able to obtain solutions better than those adopted in the real-world within a reasonable computational time. Andersen et al. (2011) studied a branch and price method for the SNDP. Although the proposed algorithm was able to find solutions of higher quality than the previous methods, the 10-h computational time required by the algorithm poses a great challenge for practical applications.

Variants of SDNP have also been studied. Hoff et al. (2010) investigated a variable neighbourhood search based metaheuristic approach for the service network design with stochastic demand, a problem sharing similar structure to SNDP. However, the neighbourhood functions used in their approach are mainly based on path oriented operators which, like the arc-flipping operator, have limitations in dealing with asset balance constraints. Alumur et al. (2012) studied a heuristic approach for the simultaneous optimisation of hub locations and the service network. A multi-period supply chain network design problem was studied in Carle et al. (2012) and an agent-based metaheuristic was proposed based on the idea of asynchronous cooperation between agents. Nickel et al. (2012) studied a stochastic supply network design problem with financial decisions and risk management for which the authors only managed to solve small instances. Heuristic approaches appear to be the most promising methods for these types of problems. Yaghini et al. (2012) proposed a simulated annealing metaheuris-