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Energy-efficient rail guided vehicle routing for two-sided loading/unloading automated freight handling system

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ABSTRACT

Rail-guided vehicles (RGVs) are widely employed in automated freight handling system (AFHS) to transport surging air cargo. Energy-efficient routing of such vehicles is of great interest for both financial and environmental sustainability. Given a multi-capacity RGV working on a linear track in AFHS, we consider its optimal routing under two-sided loading/unloading (TSLU) operations, in which energy consumption is minimized under conflict-avoidance and time window constraints. The energy consumption takes account of dynamics and routing-dependent gross weight of the RGV. And the conflict-avoidance constraints ensure conflict-free transport service under TSLU operations. The problem is formulated as a mixed-integer linear program, and solved by incorporating valid inequalities that exploit structural properties of the problem. The static problem model and solution approach are then integrated with a rolling-horizon approach to solve the dynamic routing problem where air cargo enters and departs from the system dynamically in time. Simulation results suggest that the proposed strategy is able to route a RGV to transport air cargo with an energy cost that is considerably lower than one of the most common heuristic methods implemented in current practice.

1. Introduction

Automated freight handling system (AFHS) is a type of automated material handling system (AMHS), which is widely adopted in facilities with massive material handling requests, such as freight terminals, distribution centers and production plants. AFHS is able to minimize operating cost and risk of human errors, and consequently enhances the efficiency and reliability of a material handling system. As operating cost of AMHS can represent up to 70% of the cost of a product (Giordano, Zhang, Naso, & Lewis, 2008; Liu, Jula, & Ioannou, 2002), it is critical to smartly design and operate AMHS to improve the overall economic and environmental performance. There has been a considerable growth of interest in studying such problems in both industrial and academic contexts.

This work considers improving AFHS installed in a freight terminal, which employs railed-guided vehicles (RGVs) to transport a tremendous amount of inbound and outbound cargo. The origins and destinations of the cargo are distributed along a linear track. The workload, which is especially high at its peak hour around midnight, leads to a conflict-prone environment that poses great challenges to terminal operations. The present AFHS has been developed to improve the terminal's throughput while eliminating potential human errors. However, the design is not optimal, especially in terms of energy efficiency. As energy consumption constitutes one of the major sources of operating cost and has gained increasing attention for enabling a greener and sustainable earth, improving energy efficiency of AFHS and in particular developing an energy-efficient RGV routing strategy is of great interest to the industry. So far only heuristic methods are employed to route RGVs in the current system. This motivates us to develop a rigorous mathematical programming method to improve the system performance. The method is able to meet various service requirements/constraints such as avoidance of unloading deadlocks, delivery time windows (TWs), limited capacity, *etc*. This is contrast to the applied heuristic methods, which meet the requirements by abruptly compromising the system's performance or by means of a posteriori sophisticated supervisory control (Giordano et al., 2008).

1.1. Problem description

A typical work area of the considered AFHS is depicted in Fig. 1. A RGV is operated on a linear track to transport containers

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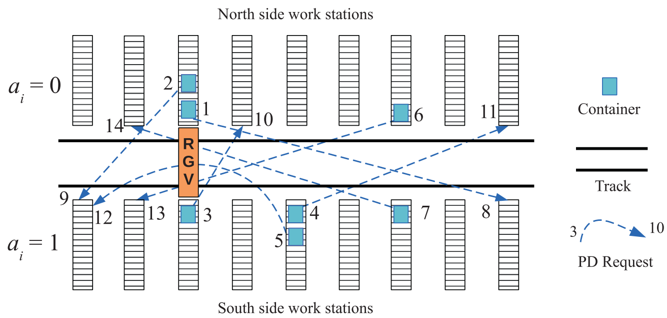

Fig. 1. Typical work area of a RGV in AFHS with exemplary PD requests.

between work stations which are located along both sides of the track. Containers are queued at work stations, and will be picked up and delivered to their destined stations on either sides of the track. This is achieved by the RGV via so-called *two-sided loading/unloading* (TSLU) operations. The RGV and work stations are equipped with roller decks to support the TSLU operations. When the RGV is docked to a station, the roller decks rotate accordingly forward or backward to load or unload containers sequentially. The RGV can carry multiple containers subject to a capacity limit.

Each transportation of a container is initiated with a pickup and delivery (PD) request to the central control system. Midway drop-off is not allowed in the application because of substantial overhead caused by frequent acceleration and deceleration of the RGV. Once a container is picked up, it remains on the RGV until being delivered to its destination. As containers enter and depart from AFHS dynamically, the control system accumulates unfinished PD requests and aims at routing the RGV to pick up and deliver the associated containers in an optimal sequence. The PD sequence needs to minimize energy consumption for completing all transportation subject to various service and operational constraints.

1.2. Related literature

Sequencing PD tasks to be handled by a single vehicle is often referred to as vehicle routing or job sequencing (Carlo, Vis, & Roodbergen, 2014; Roodbergen & Vis, 2009; Vis, 2006), and can be treated as a pickup and delivery problem (PDP) (Berbeglia, Cordeau, Gribkovskaia, & Laporte, 2007; Parragh, Doerner, & Hartl, 2008). The problem is NP-hard in general due to a complex combinatorial nature, and it includes the considered problem as a sophisticated case. Indeed our problem is further complicated by dynamic arrivals of PD requests. So far there have been a variety of research investigations on static/dynamic vehicle routing problems (VRPs) for different applications (Berbeglia, Cordeau, & Laporte, 2010; Pillac, Gendreau, Guéret, & Medaglia, 2013; Psaraftis, 1988; Ritzinger, Puchinger, & Hartl, 2016). The literature confined to a single vehicle is briefly reviewed as follows.

Static VRPs assume that all transport requests are known *a priori*. Atallah and Kosaraju (Atallah & Kosaraju, 1988) proved that the problem is polynomial-time solvable if the vehicle has unit capacity while confined to a linear track when no precedence and TW constraints are imposed on the transport requests. The same problem turns out to be NP-hard if the track topology changes to be a tree (or general graph) (Frederickson & Guan, 1993; Frederickson, Hecht, & Kim, 1976). If the vehicle has multiple capacity, the problem is NP-hard even if the track is a simple path (Guan, 1998). Another closely related problem, the PDP (for goods transportation) or the dial-a-ride problem (DARP, for passenger transportation) which includes TW constraints on PD requests has been well studied. Algorithms based on branch-and-cut or column generation are available for solving the problem for small to medium size instances (Cordeau, Laporte, & Ropke, 2008; Parragh et al., 2008). Readers are referred to Roodbergen and Vis (2009) for a review of other related literature which investigates request/job sequencing in automated storage and retrieval systems (AS/RS).

The aforementioned literature all considered PDPs without loading constraints. In many applications, however, constraints appear also on loading (Iori & Martello, 2010; Pollaris, Braekers, Caris, Janssens, & Limbourg, 2015). In the *traveling salesman problem with pickup and delivery and LIFO loading* (TSPPDL), a single vehicle serves paired PD requests while both pickup and delivery follow LIFO (last in first out) service order. Heuristic algorithms for solving this problem were introduced in Ladany and Mehrez (1984), Carrabs, Cordeau, and Laporte (2007b). While, exact formulations and solutions using tailored branch-and-cut algorithms were developed in Carrabs, Cerulli, and Cordeau (2007a), Cordeau, Iori, Laporte, and Salazar González (2010b). Another related problem is the *traveling salesman problem with pickup and delivery and FIFO loading* (TSPPDF), in which both pickup and delivery must be performed in FIFO (first in first out) order. To solve the problem, heuristic algorithms were introduced in Erdoğan, Cordeau, and Laporte (2009), while tailored branch-and-bound and branch-and-cut algorithms were explored in Carrabs et al. (2007a) and Cordeau, Dell'Amico, and Iori (2010a), respectively.

In practice, VRPs are dynamic because PD requests appear stochastically in time. Related research assumes that the requests arrive either in an unknown or in a known stochastic process (Berbeglia et al., 2010; Pillac et al., 2013; Ritzinger et al., 2016). With an unknown arrival process, deterministic algorithms have been proposed to solve various dynamic problems (*e.g.*, DARP and its variants) and their performances are evaluated by competitive analysis (which compares the worst-case cost achieved by the algorithm with the optimal cost obtained for its counterpart assuming all requests being known *a priori*) (Ascheuer, Krumke, & Rambau, 2000; Berbeglia et al., 2010; Feuerstein & Stougie, 2001). However, the algorithms and their analyses all rely on the assumption that the dynamic problem has no side constraints such as loading or precedence or TW constraints. On the other hand, if the PD arrival process is known, strategies based on sampling or Monte Carlo simulations are often used to handle dynamic VRPs (Berbeglia et al., 2010). Rolling-horizon based algorithms can alternatively be developed if deterministic estimates of future requests are available (Cordeau, Dell'Amico, Falavigna, & Iori, 2015; Psaraftis, 1988). Many heuristic algorithms to handle dynamic VRPs can also be found in a recent survey conducted in Berbeglia et al. (2010).

In addition, among existing literature (*e.g.*, Hu & Mao, 2012; Lau & Zhao, 2006; Ou, Hsu, & Li, 2010; Tang, Ng, & Lam, 2010) that investigates operational aspects of AFHS (other high-layer issues can be referred to Derigs and Friederichs, 2013 and the references therein), the reference (Hu & Mao, 2012) studied a most relevant but simpler problem; that is, the RGV is assumed to have unit capacity and the goal is to minimize its travel distance for completing all transport requests. The study can be viewed as a pilot study of the present work which considers a more complex problem with a capacitated RGV bearing TSLU operations.

This work differs from existing literature in several aspects. *First*, the problem under investigation is a capacitated PDP under new conflict-free service constraints which arise from the unique TSLU operations. The well-known LIFO and FIFO loading restrictions are special cases of the derived conflict-free service constraints. A novel representation by means of linear integer constraints is developed to completely characterize the conflict-free service. This is the first time that such kind of characterization has become available for TSLU operations, to the best of our knowledge. *Second*, the RGV routing problem aims to minimize total energy consumption of operating a RGV for completing all PD requests. The goal meets well with the interest of saving energy and