European Journal of Operational Research 217 (2012) 287–299

Contents lists available at SciVerse ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Production, Manufacturing and Logistics

Optimally routing and scheduling tow trains for JIT-supply of mixed-model assembly lines

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ARTICLE INFO

Article history:
Received 28 June 2010
Accepted 6 September 2011
Available online 25 September 2011

Keywords:
Mixed-model assembly lines
Just-in-Time
Material supply
Tow trains

ABSTRACT

In recent years, more and more automobile producers adopted the supermarket-concept to enable a flexible and reliable Just-in-Time (JIT) part supply of their mixed-model assembly lines. Within this concept, a supermarket is a decentralized in-house logistics area where parts are intermediately stored and then loaded on small tow trains. These tow trains travel across the shop floor on specific routes to make frequent small-lot deliveries which are needed by the stations of the line. To enable a reliable part supply in line with the JIT-principle, the interdependent problems of routing, that is, partitioning stations to be supplied among tow trains, and scheduling, i.e., deciding on the start times of each tow train's tours through its assigned stations, need to be solved. This paper introduces an exact solution procedure which solves both problems simultaneously in polynomial runtime. Additionally, management implications regarding the trade-off between number and capacity of tow trains and in-process inventory near the line are investigated within a comprehensive computational study.

1. Introduction

With increasing product variety, which nowadays seems inevitable to satisfy highly diversified customer demands, thousands of different parts need to be delivered Just-in-Time (JIT) to a multitude of stations of today's mixed-model assembly lines, e.g., in automobile industry. On the one hand, a reliable and flexible part supply is indispensable, because otherwise material shortages leading to line-stoppages and hundreds of assembly workers being idle threaten. On the other hand, enlarged safety stocks near the line impede the assembly process within the scarce space of stations. Thus, to enable a reliable, small-lot part supply in line with the JIT-principle an increasing number of automobile producers implements the so-called "supermarket-concept". Here, supermarkets serve as decentralized logistics areas, where parts assembled in neighboring line segments are intermediately stored and sorted according to the needs of the assembly process. The remaining distance between supermarket and assembly line is bridged via small tow trains (or tuggers). A tugger consists of a towing vehicle (driven by an operator), which is connected with a few waggons. These waggons are loaded with parts in a supermarket and, then, a train circulates through assigned stations along its given tour. At each stop, bins filled with parts for the respective station are unloaded and empty bins are returned. Finally, an empty train returns to the supermarket to be reloaded for its next tour.

Clearly, the routing and scheduling of tow trains is an important optimization problem in this context. Each tow train is to be assigned to a subset of stations to be supplied with parts and the sequence of station visits is to be specified (routing). Moreover, for a given route the delivery schedule defining arrivals and departures at each stopover is to be determined (scheduling). Obviously, both problems are heavily interdependent, so that a very complex decision problem arises. However, some real-world conditions in automobile industry, i.e., limited maneuverability of tow trains when driven through the narrow aisles of a shop floor and loading tuggers according to the JIT-principle, allow for some simplifications, so that optimal solutions can be determined in one joint optimization approach. For this purpose, this paper introduces an exact nested dynamic programming procedure with polynomial runtime.

The remainder of the paper is organized as follows: Section 2 characterizes the organizational settings of a supermarket in detail and provides a literature review. Then, Section 3 introduces the routing and scheduling problem of tow trains and formalizes it. The optimization procedure is described in Section 4 and extensions of the base model (and required modifications of solutions procedures) are presented in Section 5. In a comprehensive computational study (Section 6) we investigate the benefits of optimal routes and schedules as well as the elementary trade-off between number and capacity of tuggers and in-process inventory near the line. Finally, Section 7 concludes the paper.

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doi:10.1016/j.ejor.2011.09.013

2. Organization principles of JIT-supermarkets and literature review

A supermarket as a decentralized storage area for parts used at nearby line segments substitutes frequent small-lot deliveries for centralized part supply from a remote receiving store, so that the intermediate node "supermarket" can be interpreted as being the in-house logistics counterpart of a cross dock (e.g., see Boysen and Fliedner, 2010). Supermarkets are replenished from receiving store with (comparatively) large industrial trucks, whereas line segments are served with small tow trains. This way, part supply can be adjusted more flexibly to unforeseen events as small-lot deliveries can be quickly replanned while large-lot deliveries, once made, are hard to revoke. This advantage of the supermarket-concept is very important in today's automobile production as the space at the stations of the line is notoriously scarce. Finally, small-lot deliveries entail smaller bins, which can be stored in comfortable racks near the line. Assembly workers can access parts in an ergonomic and efficient manner, which reduces the strain on the workforce and saves handling time when parts are fetched. The complete part supply process via supermarkets is described in the following:

When an industrial truck arrives at the supermarket, logistics workers sort incoming parts into the racks of the supermarket. There, parts are intermediately stored until a part demand from an assembly station is communicated to the supermarket. Then, a pick list is generated and a logistics worker assembles bins according the pick list, where some parts, e.g., windshields, additionally need to be sorted just-in-sequence as defined by the given assembly sequence of automobiles. Filled bins are loaded on empty waggons and moved to the stopping point of tow trains. Note that, typically, bins are assigned to waggons such that each waggon contains parts for a separate station.

As soon as a towing vehicle arrives at a supermarket's stopping point, the driver couples waggons for the stations assigned to his/her tour and starts visiting them as defined by the tow train schedule. Similar to a bus schedule, it precisely specifies the sequence of station visits and the point in time of each stopover. One automobile producer we visited was experimenting with display panels installed at each station similar to those of bus and railway stations. Here, a countdown until the tugger's next arrival was announced, so that anticipating material shortages in a credible and timely manner got much easier for assembly workers and team leaders.

When a tugger arrives at a station, the driver unloads bins and exchanges empty with filled bins in the material racks of the station without impeding the assembly process. Empty bins are reloaded into the tow train. Some automobile producers have already fully automated these stops by applying "shooter-racks" (see Emde et al., 2011). These special gravity flow racks allow tow train waggons to dock while driving by. As soon as a tugger stops, gates sideways of the waggon and at the back of the rack are opened automatically and bins are injected by elastic springs into the rack and vice versa. These racks reduce the length of a stopover to merely a few seconds, so that reliable tow train schedules can be derived. As soon as all stations on a tugger's tour have been supplied, the vehicle returns to the supermarket, decouples empty waggons and will repeat the above steps to set off on its next tour.

A typical supermarket we observed at multiple German OEMs shows the following properties: A supermarket serves between 20 and 30 stations and is located in direct vicinity of the assigned line segment, so that a complete tow train tour typically amounts to merely 200–500 meters. Three to five tow trains are assigned to each supermarket, so that five stations is a representative number of stopovers visited per tour and up to three visits per station and hour are planned.

In recent years, supermarkets and tow trains became increasingly popular for a JIT-supply of mixed-model assembly lines. However, a "kanban supermarket" is not a novel phenomenon but rather a core element of the famous Toyota Production System (see Vatalaro and Taylor, 2005; Holweg, 2007) with a long tradition in many industrial sectors (Rees et al., 1989; Hodgson and Wang, 1991; Spencer, 1995).

The planning and control of this in-house logistics concept amounts to a complex task where several interrelated decision problems have to be solved:

(i) Decide on the number and location of decentralized supermarkets and assign line segments.
(ii) Determine the number of tow trains per supermarket and decide on the route of each tugger.
(iii) Determine each tow train's delivery schedule for supplying parts on its given route.
(iv) Decide on the bins to be loaded per tour of a tow train.

In spite of their great practical relevance, literature on supermarkets and the coordination of tow trains is scarce. Emde et al. (2011) consider problem (iv) and present an exact solution procedure which determines the bins to be loaded for each tour (of a given schedule) with limited tugger capacity, so that inventory near the line is minimized. Battini et al. (2010) tackle the problem of locating supermarkets on the shop floor in a production setting with multiple parallel assembly lines where entire lines (as opposed to individual stations on a single line) have to be supplied. They assign lines to supermarkets according to their component commonality and then place the supermarkets such that they are as close to their respective lines as possible. Emde and Boysen (2011) consider a similar problem by presenting an optimal algorithm for optimally placing supermarkets to supply the stations along a single assembly line. Golz et al. (2010) present a case-study from a major German motor company where the supermarket concept has been implemented. They also develop a heuristic procedure to decide on the routes (ii), schedules (iii) and load (iv) of the tow trains, aiming to minimize the number of vehicles and operators while avoiding stock-outs at the line, where the routing is limited to picking a path from a predefined set.

Although there is little literature to date explicitly dealing with the routing and scheduling problem in the context of supermarkets, it should be noted that these in-house logistics decision problems show some similarities to problems of designing and operating traditional distribution networks. This paper jointly treats problems (ii) and (iii), which are related to traditional vehicle routing (for surveys see, e.g., Fisher, 1995; Campbell et al., 1998; Toth and Vigo, 2001; Laporte, 2009) and inventory routing problems (e.g., Dror et al., 1985; Baita et al., 1998; Cordeau et al., 2007).

However, the vehicle routing problem (VRP) demands that customers (or stations) are visited exactly once without restrictions on the order in which this is done, which does not reflect the reality of the assembly line parts supply. In addition, it only explicitly covers the routing aspect of the problem and does not concern itself with scheduling, which is an integral part of the tow train routing problem as we will discuss in the next section. Specifically, the classic VRP (Dantzig and Ramser, 1959) is single-period, precluding multiple deliveries over a longer time horizon as they are the norm in inhouse logistics, but even multi-period versions of the VRP (Christofides and Beasley, 1984; Cordeau et al., 1997; Angelelli and Speranza, 2002) reduce the scheduling facet to selecting a sequence of visits from a given set for each customer.