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Innovative Applications of O.R.

Integrated machine scheduling and vehicle routing with time windows

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ABSTRACT

This paper integrates production and outbound distribution scheduling in order to minimize total tardiness. The overall problem consists of two subproblems. The first addresses scheduling a set of jobs on parallel machines with machine-dependent ready times. The second focusses on the delivery of completed jobs with a fleet of vehicles which may differ in their loading capacities and ready times. Job-dependent processing times, delivery time windows, service times, and destinations are taken into account. A genetic algorithm approach is introduced to solve the integrated problem as a whole. Two main questions are examined. Are the results of integrating machine scheduling and vehicle routing significantly better than those of classic decomposition approaches which break down the overall problem, solve the two subproblems successively, and merge the subsolutions to form a solution to the overall problem? And if so, is it possible to capitalize on these potentials despite the complexity of the integrated problem? Both questions are tackled by means of a numerical study. The genetic algorithm outperforms the classic decomposition approaches in case of small-size instances and is able to generate relatively good solutions for instances with up to 50 jobs, 5 machines, and 10 vehicles.

1. Introduction

Increasing pressure on global markets forces companies as well as entire supply chains to capitalize rigorously on saving potentials. For example, just-in-time concepts are widely used to reduce logistics expenditures which often represent over 30% of the total costs of a product (Thomas and Griffin, 1996). Such approaches, however, involve a need to comply with due dates since tardy deliveries may cause the recipients to struggle with meeting their own due dates. Manufacturers of special purpose machines, for example, are not able to assemble a machine until their suppliers release the required components such as motors, cases, and control modules. A similar problem arises in modular construction. Warehouses or parking decks cannot be built until special industry doors, concrete modules, and steel components have been supplied. Tardiness of a single component can cause problems for the entire supply chain. Rearrangement or interruption of production schedules, idle time, tardiness penalties, and unnecessarily high inventories often drive up costs considerably. However, just-in-time approaches are pointless if they incur high transportation costs in an attempt to prevent such situations. In order to reduce total logistics cost, production and delivery operations need to be well coordinated, first within single companies and then within whole supply chains (Manoj et al., 2008). Efficient suppliers that rarely exceed due dates are essential for just-in-time supply chain environments and hence hold an enormous competitive advantage.

This paper deals with the coordination of a company's production and distribution operations. A given set of jobs has to be processed on parallel machines and delivered to job-dependent destinations by a fleet of vehicles, taking account of distinct delivery time windows. Such problems often occur in the automotive industry. Suppliers of injection molded plastic components, for example, usually run many parallel machines and deliver to several manufacturers like BMW, Daimler, and VW. If they deliver late, suppliers may cause the above mentioned problems, damage their reputation, and often incur contractual penalties. Hence, minimizing tardiness-based performance measures such as the number of tardy jobs, maximum tardiness, and total (weighted) tardiness is frequently encountered in practice. Because of its widespread use (Koulamas, 1994), the objective criterion here is minimizing total tardiness.

In order to reduce overall complexity, classic decomposition approaches break down the overall problem, solve the production and delivery subproblems successively, and merge the subsolutions to form a solution to the overall problem. Such approaches are especially reasonable if interdependencies between the two planning subproblems can be prevented by high buffer stocks. However, low or even zero buffer inventories are frequently encountered in practice. The popularity of the just-in-time philosophy, which serves to cut down on holding costs, is only one of several reasons for that. Make-to-order, perishable, and time-sensitive goods such as ready-mixed concrete (Garcia et al., 2002, 2004) simply cannot

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be kept in stock. Especially for companies selling such products, the coordination of production and distribution is seen as one of the most important success factors (Dawande et al., 2006; Geismar et al., 2008; Akkerman et al., 2010; Huo et al., 2010; Geismar et al., 2011; Cakici et al., 2012). In order to be up to date, newspaper printing cannot be started before midnight (Hurter and Van Buer, 1996; Van Buer et al., 1999). Drop-off points, however, have to be supplied with area-dependent editions until, say, 4:00 am so home delivery carriers can pick up the newspapers early enough to prevent tardy delivery and thus dissatisfied customers. The same applies to the customized computer and food catering industries where fierce competition causes the need to produce and deliver high quality goods within very narrow time windows (Chen and Vairaktarakis, 2005; Farahani et al., 2012). Wal-Mart and Amazon venture on same-day delivery for online orders placed before noon (Bhattarai, 2012; Clifford, 2012). Customers can select a 4-h time window during which they want to receive the ordered items. The coordination of picking and delivery is a very demanding logistical task but also the key success factor for same-day delivery strategies. Effective and efficient integrated planning approaches are indispensable for managers who work with such business models.

Classic decomposition approaches that successively deal with the associated subproblems are often considered to cause poorly coordinated overall plans and therefore to result in high tardiness. Hence, there are two questions that motivate this paper. Are the results of integrating machine scheduling and vehicle routing significantly better than those of classic decomposition approaches? And if so, is it possible to capitalize on these potentials despite the complexity of the integrated problem? Both questions are addressed by means of a numerical study. A genetic algorithm that tackles the integrated problem as a whole is compared to two classic decomposition approaches.

The remainder is structured as follows. Section 2 surveys the related literature. In Section 3, the machine scheduling and vehicle routing subproblems as well as the integrated overall problem are described by mixed integer linear programs. The generation of instances, needed for the numerical study, is explained in Section 4. Section 5 introduces the decomposition approaches and the genetic algorithm. The results of the numerical study are provided in Section 6. Section 7 concludes.

2. Literature

Chen (2004) and Chen (2010) extensively review papers that deal with integrated scheduling of machines and outbound job delivery. The literature can be divided into two main areas. Some studies focus on rather 'simple' delivery considerations, like direct or shuttle shipments, while others allow for vehicle routing. Tables 1 and 2 provide an overview of the literature on these two problem types, subdividing the publications in question according to whether they consider due dates or not. Furthermore, the articles are categorized by the number of job destinations. Some papers consider a single job destination, like a distribution center or a warehouse, while others deal with multiple job destinations such as several customer locations. Since vehicle routing does not make sense in case of a single job destination, Table 2 contains only papers with multiple job destinations.

As they concern machine scheduling and vehicle routing, the publications listed in Table 2 are most closely related to this paper. Chang and Lee (2004) examine a single machine scheduling and vehicle routing problem. Only one vehicle with a limited loading capacity is available for delivery. Each job requires a job-dependent amount of loading capacity and is preassigned to one of only two possible destinations. A tailor-made heuristic is proposed to minimize the arrival time of the last job at its destination. Chen and Vairaktarakis (2005) extend the problem to more destinations and an infinite number of vehicles with a loading capacity limited to a maximum number of jobs. Single as well as parallel machine scheduling problems are addressed. The authors propose tailor-made algorithms to minimize convex combinations of the maximum arrival time (average arrival time) and the transportation costs which depend on the number of employed vehicles and the routes assigned to them. Their integrated production and delivery approaches are compared to classical decomposition approaches. Numerical experiments reveal that integration induces average relative improvements of between 12% and 40%. Li and Vairaktarakis (2007) focus on a similar problem with jobs that consist of two tasks. There is a special machine for each task. Both tasks can be done at the same time. Tailor-made heuristics are developed to minimize the sum of the weighted total arrival time and transportation costs. Garcia et al. (2004) deal with several plants, each equipped with parallel machines, and a fleet of vehicles that can deliver no more than one job at a time. The jobs can be processed only in job-dependent subsets of the plants and must be delivered immediately after completion. Furthermore, the jobs are characterized by job-dependent due dates, destinations, and service times at the destinations. The author's tailor-made heuristic aims to maximize the total weighted number of just-in-time delivered jobs minus the transportation costs. Garcia et al. (2002) apply a genetic algorithm to a similar problem which is described below.

Inspired by Thomas and Griffin (1996), who call for deterministic approaches to operational supply chain problems, Hall and Potts (2003) address integrated machine scheduling and batch

Table 1
Integrated scheduling of machines and 'simple' delivery operations.

Problems	Without due dates	With due dates
With a single job destination	Cheng and Kahlbacher (1993), Cheng and Gordon (1994), Cheng et al. (1996), Cheng et al. (1997), Wang and Cheng (2000), Lee and Chen (2001), Chang and Lee (2004), Li and Ou (2005), Soukhal et al. (2005), Chen and Pundoor (2006), Chen et al. (2007), Ji et al. (2007), Yuan et al. (2007), Wang and Cheng (2007), Zhong et al. (2007), Pan et al. (2009), Wang and Cheng (2009a), Wang and Cheng (2009b), Lee and Yoon (2010), Mazdeh et al. (2011), and Ng and Lingfa (2012)	Matsuo (1988), Herrmann and Lee (1993), Chen (1996), Yuan (1996), Yang (2000), Hall et al. (2001), Hall and Potts (2005), Qi (2008), Chen and Pundoor (2009), Fu et al. (2012), and Hamidinia et al. (2012)
with multiple job destinations	Potts (1980), Woeginger (1994), Zdrzalka (1995), Woeginger (1998), Gharbi and Haouari (2002), Liu and Cheng (2002), Hall and Potts (2003), Averbakh and Xue (2007), Li and Vairaktarakis (2007), Mazdeh et al. (2007), Chen and Lee (2008), Mazdeh et al. (2008), Li and Yuan (2009), Selvarajah and Steiner (2009), Averbakh (2010), Li et al. (2011), and Averbakh and Baysan (2012)	Hall and Potts (2003), Pundoor and Chen (2005), Wang and Lee (2005), Qi (2006), Stecke and Zhao (2007), Steiner and Zhang (2009), Huo et al. (2010), Cakici et al. (2012), and Farahani et al. (2012)