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Integrated scheduling of production and distribution to minimize total cost using an improved ant colony optimization method ☆

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ABSTRACT

In this paper, we consider an integrated scheduling problem of production and distribution for manufacturers. In the production part, the batch-processing machines have fixed capacity and the jobs have arbitrary sizes and processing times. Jobs in a batch can be processed together, provided that the total size of the jobs in the batch does not exceed the machine capacity. The processing time of a batch is the largest processing time of all the jobs in the batch. In the distribution part, the vehicles have identical transport capacity and all the deliveries are done by a third-party logistic (3PL) provider. The objective is to minimize the total cost of production and distribution for the manufacturer. Since the problem is NP-hard in the strong sense, we propose an improved ant colony optimization method to solve the production part, and a heuristic method for the distribution part. We derive a lower bound for the optimal total cost. We generate a large number of random data to test the performance of the proposed heuristic versus the lower bound. Our results show that the performance of the heuristic is excellent while the running time is no more than five seconds for 200 jobs.

1. Introduction and literature review

In recent years, integrated scheduling has generated a lot of interest among researchers. In contrast to classical scheduling, this type of scheduling problem is concerned with not only the production part, but also the inventory, distribution and other parts in the supply chain. The objective of integrated scheduling is to obtain an overall optimization for the supply chain. The obtained plan will become a detailed schedule that can provide an effective guidance for operations management.

In this paper, we consider a class of integrated scheduling problems involving production and distribution. In the production part, we consider manufacturers having batch-processing machines and jobs having arbitrary sizes and processing times. This production mode is widely used in many industries such as the porcelain manufacturing industry, semi-conductor manufacturing industry (Jula & Leachman, 2010), food processing industry (Melouk, Demodaran, & Chang, 2004), and so on. Take the porcelain manufacturing industry for example (Carter & Norton, 2013). The production of porcelain products consists of two steps, where the first step is to make a standard mode using clay and other specific materials and the second step is to process the mode into porcelain in a calcinatory. The calcinatory is heated to a very high temperature that exceeds 1800 degrees Fahrenheit most of the time. The calcinatory step often takes more than one day. To keep a high temperature, a large amount of energy is needed. After the calcination step, qualified products can be delivered to the customers. The porcelain products have different sizes and the calcinatory has a fixed capacity. Thus, it is possible to put several porcelain products into the calcinatory so that they are heated together, provided that the total size of the porcelain products does not exceed the capacity of the calcinatory. The processing time of a batch is the largest processing time of all the jobs in the batch. Clearly, minimizing the makespan will minimize the amount of energy used.

After the porcelain products have been made, they need to be shipped to the customers. There are a number of vehicles and each vehicle has a fixed capacity. To obtain a low distribution cost, it is desirable to minimize the number of deliveries. This is especially true when the manufacturer hires a third-party logistic (3PL) provider to deliver the products, since the 3PL provider will charge the manufacturer an amount proportional to the number of deliveries. Clearly, the distribution schedule is influenced by the production

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plan. Therefore, an integrated scheduling method is needed to achieve a total optimization of production and distribution.

Another example of batch-processing machines can be found in semi-conductor industry (Uzsoy, 1994). In the final testing stage, integrated circuits are subject to burn-in operation that applies thermal stress to the circuits. Those circuits that pass the burn-in test will be delivered to the customers, while those that are found to be defective will be discarded. The circuits are put on the boards which will then be put into an oven. The oven has a fixed capacity. Each circuit has a size, e.g., several boards. Therefore, several circuits can be put into the oven at the same time, provided that the total size of the circuits does not exceed the capacity of the oven. Since the processing time of the burn-in operation is much longer than other operations (e.g., 120 h versus 4–5 h), the burn-in operation is often the bottleneck in the manufacturing process. Minimizing the makespan will minimize the energy used and maximize the throughput of the system. Once the circuits pass the burn-in operation, they will be shipped to the customers. Again, minimizing the number of deliveries will save money for the manufacturer.

The purpose of this paper is to propose a method to tackle this problem. We will develop an improved ant colony optimization method to batch the jobs in the production part. We then employ the First-Fit-Decreasing (FFD) rule used in the bin-packing problem to group the jobs into delivery runs. Our objective is to minimize the sum of the production and delivery costs.

Integrated scheduling includes the system of supplier, manufacturer and customers. As such, it is a three-stage problem (Hall & Potts, 2003). Selvarajah and Steiner (2009) proposed a 3/2 approximation algorithm to minimize delivery and inventory holding costs. Sawik (2009) extended the problem to a long-term product case. Yeung, Choi, and Cheng (2011) and Osman and Demirli (2012) considered the three-stage problem with time windows and synchronized replenishment, respectively. Yimer and Demirli (2010) proposed a division technique for the problem. The problem was divided into two phases, i.e., the manufacturing and the delivery phase, and a genetic algorithm was used to solve it. Two-stage integrated scheduling problems consist of two types, where one type is concerned with the supplier and manufacturer and the other type is concerned with the manufacturer and customers. Chen and Vairaktarakis (2005) showed that most of the two-stage problems are also NP-hard. Chen and Hall (2007) investigated the conflict between the optimal schedules of the supplier and the manufacturer. They proposed a cooperation mechanism for the two sides. Agnetis, Hall, and Pacciarelli (2006) proposed an interchange cost that is incurred when the orders of jobs are different in the optimal schedules of the two sides. They also provided a cooperation scheme. Torabi, Ghomi, and Karimi (2006) considered the objective of minimizing the average of holding setup and delivery costs per unit time of the supply chain and they designed an intelligent algorithm. The other kind of two-stage problem is the scheduling between the manufacturer and its customers. Agnetis, Aloulou, and Fu (2014) considered the coordination of production and interstage batch delivery using a third-party logistic (3PL) provider. Algorithms for solving the problem include approximation algorithms (Averbakh & Xue, 2007) and intelligent algorithms (Naso, Surico, Turchaiano, & Kaymak, 2007; Zegordi, Abadi, & Nia, 2007). Other works stressing the two-stage problems between the manufacturer and customers include the joint scheduling of time-sensitive products (Chen & Pundoor, 2006) and capacity allocation (Hall & Liu, 2010). Chen (2010) gave an excellent survey of integrated production and outbound distribution scheduling.

Current research on joint scheduling focuses on the classical production model (Pinedo (2002)), in which a machine processes one job at a time. However, little research has been done on the production model with batch-processing machines and arbitrary-size jobs. In contrast to the classical production model, this type of production is more complex to solve. Uzsoy (1994) introduced several heuristics for the single-machine scheduling problem and approximation ratios were analyzed by Zhang, Cai, Lee, and Wong (2001). Indeed, the problems addressed in Uzsoy (1994), Zhang et al. (2001) are identical to the problem addressed in this paper, except that they did not consider the delivery part. Approximation algorithms with better performances were proposed to solve single-machine problems (see Kashan, Karimi, & Ghomi, 2009; Li, Li, Wang, & Liu, 2005) and multi-machine problems (Cheng, Yang, & Ma, 2012; Cheng, Yang, Hu, & Li, 2014). Jula and Leachman (2010) provided a greedy heuristic method and Parsa, Karimi, and Kashan (2010) provided a branch and price algorithm. Intelligent algorithms were also applied to solve the problem including genetic algorithms (Sevaux & Peres, 2003; Koh, Koo, Kim, & Hur, 2005; Demodaran, Manjeshwar, & Srihari, 2006; Kashan, Karimi, & Jenabi, 2008), simulated annealing (Melouk et al., 2004) and ant colony optimization (Cheng, Wang, Yang, & Hu, 2013).

The rest of the paper is organized as follows. In Section 2, we define the problem and provide a lower bound for the optimal solution. In Section 3, we design an improved ant colony optimization (IACO) method and show the detailed implementation. Then we report the experimental results in Section 4, where 36 levels of instances are tested to show the performance of the algorithm. In Section 5, we conclude this paper and give directions for future research.

2. Model and preliminaries

The integrated scheduling problem can be defined as follows. There are n jobs to be processed and delivered to the customer. The job set is $\mathcal{J} = \{1, 2, \ldots, n\}$. The size of job j is s_j and its processing time is t_j. Jobs are grouped into batches to be processed on a batch-processing machine. The capacity of the machine is B; i.e., jobs can be processed together provided that the total size is no more than B. The processing of a batch b_k cannot be interrupted until all the jobs in it are completed. The processing time of b_k, denoted by T_k, is the longest processing time among all the jobs in b_k. The completion time of b_k is denoted by C_k. We assume that $C_0 = 0$. Note that some batches may be empty; i.e., there is no job in the batch. If batch b_k is an empty batch, then its processing time T_k is zero. We assume that $T_0 = 0$. The number of non-empty batches is denoted by K. Given a set of batches, the production cost, PC, is a linear function of its processing time; i.e.,

$$\mathrm{PC} = \sum_{k=1}^{n} T_k.$$

Once jobs are completed, they can be delivered to the customers. For simplicity, we assume that the size of a job on the production side is the same as its size on the distribution part. The vehicles have a common capacity G; i.e., products can be delivered in one run provided that the total size of all the products in the delivery run does not exceed G. The delivery set is denoted by $D = \{d_1 d_2, \ldots, d_n\}$, where d_l is the l-th delivery run. Note that some delivery runs may be empty; i.e., there is no job in the delivery run. The number of non-empty delivery runs is denoted by L. The distribution cost, DC, is a linear function of L since each delivery has a similar cost in practice. That is,

$$\mathrm{DC} = \delta L,$$

where $\delta > 0$. The objective is to minimize the total cost of production and distribution; i.e.,

$$\mathrm{TC} = \mathrm{PC} + \mathrm{DC}.$$