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Integrated production and delivery with single machine and multiple vehicles

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ABSTRACT

This paper considers a class of multi-objective production–distribution scheduling problem with a single machine and multiple vehicles. The objective is to minimize the vehicle delivery cost and the total customer waiting time. It is assumed that the manufacturer's production department has a single machine to process orders. The distribution department has multiple vehicles to deliver multiple orders to multiple customers after the orders have been processed. Since each delivery involves multiple customers, it involves a vehicle routing problem. Most previous research work attempts at tackling this problem focus on single-objective optimization system. This paper builds a multi-objective mathematical model for the problem. Through deep analysis, this paper proposes that for each non-dominated solution in the Pareto solution set, the orders in the same delivery batch are processed contiguously and their processing order is immaterial. Thus we can view the orders in the same delivery batch as a block. The blocks should be processed in ascending order of the values of their average workload. All the analysis results are embedded into a non-dominated genetic algorithm with the elite strategy (PD-NSGA-II). The performance of the algorithm is tested through random data. It is shown that the proposed algorithm can offer high-quality solutions in reasonable time.

1. Introduction

This paper is concerned with a production–distribution scheduling problem. There are n orders to be processed by a single machine. These n orders belong to n different customers. Each order has a processing time and a size. After the orders are processed, they are batched together so that each batch will be delivered by a vehicle. The total size of the orders in a batch cannot exceed the capacity of the vehicle. Starting from the manufacturing plant, the vehicle travels to the customers to deliver the products, and returns to the manufacturing plant at the end. There are two objectives we want to minimize. First, we want to minimize the delivery cost which is a linear combination of the number of deliveries and the total distance traveled. Second, we want to minimize the total waiting time of the customers. We are in fact looking at the Pareto solutions of these two objective functions. That is, a solution is an ordered pair (f_1, f_2), where f_1 is the delivery cost and f_2 is the total waiting time of the customers.

In traditional scheduling, the production and distribution processes are treated as two separate phases. In the production phase, the jobs are processed based on the job's processing time and the objective we want to optimize. It never considers the distribution phase. After the jobs are processed, the distribution phase will come up with a delivery plan based on the order the jobs are completed. In other words, the output of the production phase becomes the input of the delivery phase. Clearly, an integrated production–delivery scheduling will be more effective than two stand-alone processes.

Let us consider a simple example to illustrate this point. There are five orders belonging to five different customers. The processing times of the orders are $(p_1, p_2, p_3, p_4, p_5) = (8, 7, 8, 9, 6)$, and the sizes are $(v_1, v_2, v_3, v_4, v_5) = (48, 36, 35, 47, 57)$. The capacity of the vehicle is $Q = 100$. The shipping time between customers i and j is denoted by t_{ij}. We assume that $t_{ij} = t_{ji}$; i.e., the distances are symmetric. We use t_{0i} to denote the distance between the manufacturing plant and customer i. For our problem, the shipping times are given by $(t_{01}, t_{02}, t_{03}, t_{04}, t_{05}, t_{12}, t_{13}, t_{14}, t_{15}, t_{23}, t_{24},$

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t_{25}, t_{34}, t_{35}, t_{45}) = (88, 71, 45, 31, 21, 41, 75, 93, 50, 38, 90, 73, 29, 15, 88).

If we use the traditional scheduling method, the production sequence will be (5, 2, 1, 3, 4); i.e., order 5 will be processed first and order 4 will be processed last. This sequence is an SPT (Shortest Processing Time first) sequence, which is known to be able to minimize the total waiting time of the orders. Then the completed orders would be grouped in batches, taking into consideration of the capacity of the vehicles. There will be three batches formed: the first batch consists of orders 5 and 2, the second batch consists of orders 1 and 3, and the last batch consists of order 4. The first vehicle's route is "$0 \to 5 \to 2 \to 0$", the second one is "$0 \to 1 \to 3 \to 0$", and the last one is "$0 \to 4 \to 0$". The first batch of jobs is completed at time $p_5 + p_2 = 13$. Therefore, order 5 will be received by its customer at time $13 + t_{05} = 34$, and order 2 will be received by its customer at time $34 + t_{52} = 107$. Computing in the same fashion, we obtain that the total waiting time of all the orders is 519. The shipping time on the first vehicle is 165 (21 plus 73 plus 71), the second one is 208 (88 plus 75 plus 45) and the last one is 62 (31 plus 31). Therefore, the total distance traveled by the vehicles is 435 and the number of deliveries is 3.

However, if we use the integrated scheduling method, the production sequence would be (5, 3, 1, 2, 4). Then the first vehicle's route is "$0 \to 5 \to 3 \to 0$", the second one is "$0 \to 1 \to 2 \to 0$", and the last one is "$0 \to 4 \to 0$". In this case, the total waiting time of the orders is 429. The total distance traveled by the vehicles is 343 and the number of deliveries is 3. In this example, the second approach has better total waiting time as well as total distance traveled by the vehicles than the first approach.

Compared with the independent production scheduling system or vehicle routing scheduling system, the integrated production and delivery scheduling system is more complex. For the multi-objective and complex problem, we will construct a mathematical model, and systematically analyze the properties of the optimal solutions from the perspective of scheduling experts. And then, we combine the properties with intelligent methods to construct intelligent algorithm. In particular, we will be proposing a non-dominated genetic algorithm with the elite strategy (PD-NSGA-II) for this NP-hard problem.

The organization of the paper is as follow. In the next section, we will review the literature on integrated scheduling model and the application of non-dominated genetic algorithm with the elite strategy. In Section 3, we will formally define the problem. In Section 4, we derive some properties of optimal solutions. These properties will enable us to speed up the optimization process. In Section 5, we will present the heuristic. In Section 6, we describe the computational experiments and the results obtained. Finally, we draw some concluding remarks in the last section.

2. Literature review

Integrated scheduling of production–distribution has received a great deal of attention by many researchers in recent years. Chen (2010) suggested that integrated scheduling can make less inventory in the supply chain or in a time-sensitive product production environment. There is closer relationship between the production and distribution to make the coordination significant in both theory and practice. Hall and Potts (2003) considered the coordination scheduling of production–distribution with batch distribution as Supply Chain Scheduling, which is the first paper about coordination scheduling of production–distribution with direct distribution or vehicle routing distribution. Li, Yang, and Ma (2011) considered the direct distribution model and assumed that the delivery time is a fixed constant. Therefore, it is a simple model that is hard to describe more complex situations. Fan, Lu, and Liu (2015) studied the problem of integrated scheduling of production and delivery on a single machine. Though the completed jobs are delivered in batches, but they only considered a single customer. Agnetis, Aloulou, and Fu (2014) considered coordinated production and interstage batch delivery scheduling problems, where a third-party logistics provider delivers semi-finished products in batches from one production location to another production location belonging to the same manufacturer. Li, Jia, and Leung (2015) considered an integrated production and delivery on parallel batching machines. They assumed that several jobs can be batched together and processed by a machine, provided that the total size of the jobs in the batch does not exceed the machine capacity. The third-party logistics provider picks up the jobs at a series of time points. Though the papers considered the batch delivery, the routing optimization in a batch was ignored.

As the vehicle routing problem is an extension of the classical Traveling Salesman Problem (TSP), it is NP-hard. Since our problem has a vehicle routing problem as a subproblem, our problem is indeed more complex. Li (2005) considered the coordination scheduling problem of production–distribution with a single machine. A routing optimization method is used to minimize the customer waiting time. Geismar, Laporte, Lei, and Sriskandarajah (2008) assumed that the manufacturer produces a certain product and researched the coordination scheduling problem with a vehicle routing method to minimize the maximum customer waiting time. Calvete, Galé, and Oliveros (2011) studied a two-layer coordination scheduling problem, in which the distributor is the leader to pursue the distribution in time and vehicle routing, and the manufacturer is just in a subordinate position to produce products on demand of the distributors. Zhong, Chen, and Chen (2010) assumed that distribution is performed by a third-party logistics (3PL) provider, and delivery cost is a linear increasing function of the order size, and linear decreasing function of the delivery time; the objective is to minimize the total distribution cost. They proposed a polynomial-time approximation algorithm to solve the problem. Armentano, Shiguemoto, and Løkketangen (2011) considered the problem of minimizing the production and inventory with homogeneous vehicles that has capacity constraints. They constructed a Tabu Search algorithm. Leung and Chen (2013) studied coordination scheduling on a single machine. Their objective is to minimize the weighted sum of maximum delay time and the number of distribution vehicles. Averbakh (2010) considered the online scheduling with a limit on the distribution batch size.

To solve a complex integrated production and delivery problem with multi-objectives, the paper mentioned above transformed the problem to an optimization problem with single objective. The current mainstream direction of solving multi-objective optimization problem is to design an efficient heuristic, such as a multi-objective evolutionary algorithm, to generate Pareto optimal solution set for the multi-objective problem. Among these, genetic algorithm and its variations, such as NSGA-II (Non-dominated Sorting Genetic Algorithm), have been widely used in solving multi-objective scheduling problems. For example, Saremi, Jula, ElMekkawy, and Wang (2015) used the method of NSGA-II to schedule patients with stochastic service times and heterogeneous service sequences with bi-objectives of minimizing the waiting time of patients and the completion time of the facility. Parente, Cortez, and Gomes Correia (2015) viewed an earthwork construction as a production line, where the goal is to optimize resources under two crucial criteria (costs and duration) and focused NSGA-II on compaction allocation, using linear programming to distribute the remaining equipment.

In the field of production scheduling, Lei (2011) considered a job shop scheduling problem in which the goal is to minimize the makespan and total tardiness simultaneously. A simplified multi-objective genetic algorithm was proposed for the problem. Qingdao-er ji, Wang, and Wang (2013) considered a multi-objective