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Discrete Optimization

Job-shop production scheduling with reverse flows

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A B S T R A C T

In this paper, we conduct a study of the job-shop scheduling problem with reverse flows. This NP-hard problem is characterized by two flows of jobs that cover the same machines in opposite directions. The objective is to minimize the maximal completion time of the jobs (i.e., the makespan).

We start by analyzing the complexity and identifying particular cases of the problem. Then, we provide a mathematical model that we use in conjunction with a solver to determine the computational times. These times are often too long because the problem is NP-hard. Thus, in this paper, we present a new heuristic method for solving the NP-hard 3-machine case. We evaluate the performance of this heuristic by computing several lower bounds and conducting tests on a Taillard-based benchmark. These tests give satisfying results and show that the heuristic ensures good performance when the two flows have comparable numbers of jobs. Then, we suggest a hybrid method that consists of a combination between a heuristic and a solver-based procedure to address the *m*-machine problem.

1. Introduction

Growing environmental concerns and other economic challenges have led many companies to take into account the return and recycling of their end-of-life products (Amaro & Barbosa-Povoa, 2008). This is reflected by a new type of physical flow in supply chains: reverse flows. In classical supply chains, the flows move from the suppliers to the plants, and the finished products are then delivered to customers. In contrast, the end-of-life products move from their typical final destination (customers, in most cases) back to the manufacturer, which decides whether the products should be reintroduced to the production process or sent to waste disposal systems, such as *incinerators*. Over the last 15 years, research activities on reverse logistics have made visible progress. Material recycling has become an important issue in a large number of areas: the glass industry (Salema, Barbosa-Povoa, & Novais, 2010), electronic devices (Krikke, Bloemhof-Ruwaard, & Van Wassenhove, 2003), carpet materials (Realff, Ammons, & Newton, 2004), etc.

Reverse flows can also be considered within a single production unit, as is the case in the assembly/disassembly plants (Brennan, Gupta, & Taleb, 1994) that handle products having reverse sequences in their operating process. However, despite applications in various industrial sectors (the automotive industry, electronic devices, weapon systems, etc.), the literature on this type of reverse flow is less extensive. Most of the research deals with the return of products in a supply chain (Krikke, Bloemhof-Ruwaard, & Van Wassenhove, 2003; Salema, Barbosa-Povoa, & Novais, 2009), where the optimization criteria are often economic and the proposed solutions concern long-term planning problems (i.e., establishing the role of each supply chain entity in terms of production).

In this paper, we study one of these factory configurations, specifically the case where the operating range of the products to disassembly is exactly the opposite of the one to assembly and products of both flows use the same machines. After a brief literature review on flow-shop and job-shop scheduling, we provide a mathematical formulation and analyze the complexity of the problem. Then, we determine various particular cases that can be solved by known methods, and we identify dominance rules for this problem. After setting the limits of exact solutions using a mixed integer linear programming (MILP) model, we present an algorithm based on the Nawaz, Enscore and Ham (NEH) approach (Nawaz, Enscore, & Ham, 1983) to solve the NP-hard 3-machine case. The performance of this method is evaluated by computing lower bounds and carrying out an experimental study on a Taillard-based benchmark. Then, we develop a hybrid approach based on the NEH heuristic and mathematical optimization to solve the *m*-machine problem.

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Fig. 1. Workshop with reverse flows and three machines.

Table 1
Durations of the jobs on each machine.

Machine	Job					
	J1	J2	J3	J4	J5	J6
M1	3	7	2	1	4	3
M2	2	1	5	8	2	6
M3	4	2	3	4	6	5

2. Problem description

The problem we address in this study consists of a workshop where n jobs must be scheduled on m machines. Only two operating ranges are available here: the first one skims through the machines in the order M1, M2, ..., Mm (direct jobs), and the second one covers them in the opposite direction (reverse jobs). We define E1 as the set of direct jobs and E2 as the set of reverse jobs (Fig. 1).

The other assumptions for this problem are as follows:

- All jobs are independent and available for processing at time 0.
- There is only one machine of each type.
- All machines are continuously available.
- Each machine can process at most one job at a time, and each job can be processed only on one machine at a time.
- The processing of a given job on a machine cannot be interrupted once started (no preemption is allowed).

The aim then consists of finding the best scheduling sequence of n jobs on m machines to minimize the completion time of the last job on the last machine (the makespan). We give below an illustrative example (Ex1) with three direct (J1, J2 and J3) and three reverse (J4, J5 and J6) jobs to schedule on three machines. Table 1 displays the durations of the jobs on each machine, and Fig. 2 shows a feasible solution.

3. Literature review

As mentioned, most of the existing research deals with reverse flows in supply chains. Major works concern the design of these supply chains and the planning decisions involved. Initially, forward and reverse flows were treated separately as a two-echelon problem, but this may result in higher costs due to the design of a reverse network independently of the forward chain (Uster, Easwaran, Akcali, & Cetinkaya, 2007). Recent research has attempted to address the two flows simultaneously. Cardoso, Barbosa-Povoa, and Relvas (2013) developed a mixed integer linear programming formulation for the design and planning of supply chains with reverse flows and studied its applicability to a European supply chain case study. Salema, Barbosa-Povoa, and Novais (2010) validated a multi-period and multi-product network model for a real Portuguese glass company. The supply chain is made up of factories, warehouses, customers and sorting centers, and the glass returns to the factories after use.

In this paper, we focus on the reverse flows within an assembly/disassembly unit and address the operational (short-term) decisions. Disassembly problems are an important part of the research on product recovery activities. Kim, Lee, and Xirouchakis (2007) present a literature review on the disassembly planning problems. Brennan, et al. (1994) review the development of methodologies that address the disassembly operations planning. Kim, Lee, Xirouchakis, and Kwon (2009) provide a branch-and-bound algorithm to satisfy the demand of end-of-use product components over a horizon time by determining the quantity and timing for the disassembly of these parts. Kizilkaya and Gupta (1998) present a Flexible Kanban System technique to control material flow in a disassembly environment. Some articles dealing with the disassembly scheduling focused on the quality of the components for reuse. Wan and Gonnuru (2013) used a radio-frequency identification method to track data throughout a product's lifecycle, and they then proposed a genetic algorithm that provides a disassembly sequence to maximize the benefits by taking into account the recovery value and the disassembly cost. Ilgin and Gupta (2011) worked on the sensors implanted in products. They evaluated the impact of the information provided by these sensors on the performance of a washing machine disassembly line. Among the other works dealing with the sequencing and scheduling aspects in the disassembly problems, we can mention the research of Adenso-Diaz, Garcia-Carbajal, and Gupta (2008) in which the authors present a path-relinking-based heuristic that seeks the optimal disassembly sequence plan; Duta, Filip, and Popescu (2008), which provides a genetic algorithm for finding the disassembly sequence with the best financial income; and McGovern and Gupta (2007), where a genetic algorithm is also developed for disassembly line balancing problems. We also note that the particular problem we are dealing with can be perceived as a particular case of the job-shop problem or as two combined flow-shop problems. The literature on these optimization problems is abundant. Below, we give a brief summary of

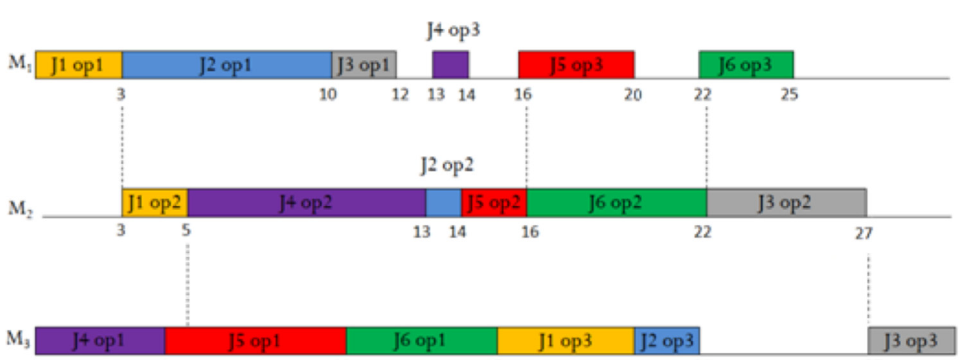

Fig. 2. A feasible schedule of the jobs for the example (Ex1).