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Two-machine flowshop scheduling with flexible operations and controllable processing times

Zeynep Uruk [a], Hakan Gultekin [b,*], M. Selim Akturk [a]

[a] Department of Industrial Engineering, Bilkent University, 06800 Ankara, Turkey
[b] Department of Industrial Engineering, TOBB University of Economics and Technology, 06560 Ankara, Turkey

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ABSTRACT

We consider a two-machine flowshop scheduling problem with identical jobs. Each of these jobs has three operations, where the first operation must be performed on the first machine, the second operation must be performed on the second machine, and the third operation (named as flexible operation) can be performed on either machine but cannot be preempted. Highly flexible CNC machines are capable of performing different operations. Furthermore, the processing times on these machines can be changed easily in albeit of higher manufacturing cost by adjusting the machining parameters like the speed and/or feed rate of the machine. The overall problem is to determine the assignment of the flexible operations to the machines and processing times for each operation to minimize the total manufacturing cost and makespan simultaneously. For such a bicriteria problem, there is no unique optimum but a set of nondominated solutions. Using ϵ-constraint approach, the problem could be transformed to be minimizing total manufacturing cost for a given upper limit on the makespan. The resulting single criterion problem can be reformulated as a mixed integer nonlinear problem with a set of linear constraints. We use this formulation to optimally solve small instances of the problem while a heuristic procedure is constructed to solve larger instances in a reasonable time.

1. Introduction

In this paper, we study the problem of scheduling n identical jobs each of which has three operations to be performed on two machines placed in series. One of the operations can only be performed on the first, the other one by the second machine. The third operation is flexible meaning that it can be performed by either one of the machines. Besides such flexible operations, we also consider the controllability of the processing times of each operation on these machines. In the scheduling literature, there are a number of studies considering flexible operations and controllable processing times separately. However, this is the first study that considers both of these simultaneously through a bicriteria objective.

In most of the deterministic scheduling problems in the literature, job processing times are considered as constant parameters. However, various real-life systems allow us to control the processing times by allocating extra resources, such as energy, money, or additional manpower. Under controllable processing times setting, the processing times of the jobs are not fixed in advance but chosen from a given interval. The processes on the CNC machines are well known examples of how the processing times can be controlled. By adjusting the speed and/or feed rate, the processing times on these machines can easily be controlled. Although reducing the processing times may lead an increase in the throughput rate, it incurs extra costs as well. Controllability of processing times may also provide additional flexibility in finding solutions to the scheduling problem, which in turn can improve the overall performance of the production system. Therefore, in such systems we need to consider the trade-off between job scheduling and resource allocation decisions carefully to achieve the best scheduling performance.

Study of the controllable processing times in scheduling was initialized by Vickson [16]. He drew attention to the problems of least cost scheduling on a single machine in which processing times of jobs were controllable. Nowicki and Zdrzalka [9] worked on two-machine flowshop scheduling problems, for which Janiak [4] showed that the problem of minimizing makespan is NP-hard for a two-machine flowshop with linear compression costs. Karabati and Kouvelis [6] discussed simultaneous scheduling and optimal processing time decision problem for a multi-product, deterministic flow line operated under a cyclic scheduling approach. Yedidsion et al. [18] considered a bicriteria scheduling problem of controllable assignment costs and total resource consumption. Wang and Wang [17] studied a single machine scheduling problem to minimize total convex resource consumption cost for a given upper bound on the total

* Corresponding author.
E-mail address: hgultekin@etu.edu.tr (H. Gultekin).

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weighted flow time. Shabtay et al. [13] studied a no-wait two-machine flowshop scheduling problem with controllable job-processing times under the objective of determining the sequence of the jobs and the resource allocation for each job on both machines in order to minimize the makespan. Gultekin et al. [2] considered a cyclic scheduling environment through a flowshop type setting in which identical parts were processed. The parts were processed with two identical CNC machines and transportation of the parts between the machines was performed by a robot. Both the allocations of the operations to the two machines and the processing time of an operation on a machine were assumed to be controllable. Shabtay et al. [12] proposed a bicriteria approach to maximize the weighted number of just-in-time jobs and to minimize the resource consumption cost in a two-machine flowshop environment. Shabtay and Steiner [14] provided a survey of the results in the field of scheduling with controllable processing times.

There are several studies on decision rules for the assignment of the flexible operations in fixed processing time production environment. Gupta et al. [3] studied a two-machine flowshop processing nonidentical jobs that the buffer has infinite capacity. Each job had three operations, one of which was a flexible operation. The assignment of the flexible operations to the machines for each job was determined under the objective of maximizing the throughput rate. They showed that the problem is NP-Hard and developed a 3/2-approximation algorithm and a Polynomial Time Approximation Scheme (PTAS). Crama and Gultekin [1] considered the same problem for identical parts, under different assumptions regarding the number of jobs to be processed and the capacity of the buffer in between the machines. For each problem, alternative polynomial time solution procedures are developed. Ruiz-Torres et al. [11] studied a flowshop scheduling problem with operation and resource flexibility to minimize the number of tardy jobs.

Our study is the first one that considers both assignment of the flexible operations and the controllability of processing times at the same time through a bicriteria objective. We assume the processing times to be controllable with nonlinear manufacturing cost functions. As a consequence of the controllability of the processing times and the dynamic assignment of the flexible operations from one part to the other, although the jobs are assumed to be identical they may have different processing times on the machines. Consequently, they are identical in the sense that, they all require the same set of operations. The problem is to determine the assignment of flexible operations to one of the machines along with the processing time of each operation under the bicriteria objective of minimizing the total manufacturing cost and makespan.

The rest of the paper is organized as follows. In the next section, we state the problem definition and formulate it as a nonlinear mixed integer problem to determine a set of efficient discrete points of makespan and manufacturing cost objectives. In Section 3, we demonstrate some basic properties for the problem which will be used in the development of the algorithm that will be discussed in Section 4. We perform a computational study in Section 5 to test the performance of our proposed algorithm by comparing it with an exact approach. Section 6 is devoted to concluding remarks and possible future research directions.

2. Problem definition and modeling

There are n identical jobs requiring three operations to be performed by the two machines placed in series. There is always space for the new parts in the buffer space between the machines and preemption is not allowed. All jobs are first processed by the first machine and then by the second machine. The first (second) operation can only be performed by the first (second) machine. The third operation can be performed by either one of the machines. Due to the flowshop nature of the problem, the third operation must be performed after the first or before the second operation as in Gupta et al. [3] and Crama and Gultekin [1]. The assignment of the flexible operation to one of the machines for each job is a decision that should be made.

Furthermore, the processing times are not fixed predefined parameters, but they are controllable and can take any value in between a given lower and an upper bounds. For job j, the processing times of the fixed operations on the first and the second machines are denoted by f_j^1 and f_j^2, respectively and the processing time of the flexible operation is denoted by s_j. These denote the actual processing times on the machines. The parts are identical in the sense that their processing time functions are job independent. However, actual processing times of the parts on the machines may differ from one job to another. The second decision is to determine the values of these processing times.

The manufacturing cost of an operation for the CNC machines can be expressed as the sum of the operating and the tooling costs. Operating cost of a machine is the cost of running this machine. Tooling cost can be calculated by the cost of the tools used times tool usage rate of the operation. Kayan and Akturk [7] showed that manufacturing cost of a turning operation can be expressed as a nonlinear function of its processing time. Although we consider the manufacturing cost incurred for a CNC machine, our analysis is valid for any convex differentiable manufacturing cost function.

We present the notation used throughout the paper below. Note that, since the jobs are identical, the index j denotes the job in the jth position.

Decision variables

f_j^i	processing time of the preassigned operation of job j on machine i, $i=1,2$ and $j=1,..,n$
s_j	processing time of the flexible operation of job j on the assigned machine
x_j	decision variable that controls if flexible operation of job j is assigned to machine 1 or not
$T_{j,i}$	starting time of the jth job on machine i
$C_{j,i}$	completion time of the jth job on machine i

Parameters

J	set of jobs to be processed
n	number of jobs to be processed, $\lvert J \rvert = n$
O	operating cost coefficient of machines ($/time unit)
$F^i(f_j^i)$	manufacturing cost function incurred by job j on machine i
$S(s_j)$	manufacturing cost function incurred by the flexible operation of job j on the assigned machine
f_l^i, f_u^i	processing time lower and upper bounds of the preassigned operations on machine i, respectively
s_l, s_u	processing time lower and upper bounds for the flexible operations, respectively
b	tooling cost exponent (note that, $b<0$)
A^1, A^2, A^s	tooling cost multipliers for the 1st, 2nd, and the flexible operations, respectively

Having these notations, the manufacturing cost functions for the preassigned and flexible operations can now be written as follows:

$$F^i(f_j^i) = O \cdot f_j^i + A^i \cdot (f_j^i)^b \quad \text{for } i=1,2 \text{ and } j=1,\ldots,n \tag{1}$$