



Scheduling in flowshops with flexible operations: Throughput optimization and benefits of flexibility

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ARTICLE INFO

Article history:

Received 15 June 2011

Accepted 9 July 2012

Available online 22 July 2012

Keywords:

Flexible manufacturing systems

Flowshop scheduling

Makespan

Operation allocation

ABSTRACT

This study considers the throughput optimization in a two-machine flowshop producing identical jobs. Unlike the general trend in the scheduling literature, the machines are assumed to be capable of performing different operations. As a consequence, one of the three operations that a job requires can only be processed by the first and another operation can only be processed by the second machine. These are called fixed operations. The remaining one is called the flexible operation and can be processed by any one of the machines. The machines are assumed to have different technological properties, i.e. non-identical, so that the processing time of the flexible operation has different values on the two machines. We first consider the problem of assigning the flexible operations to the machines for each job in order to maximize the throughput rate. We develop constant time solution algorithms for infinite and zero capacity buffer spaces in between the machines. We then analyze the benefits of flexibility. Managerial insights are provided regarding the changes in the makespan as well as the associated cost with respect to the increase in the level of flexibility.

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1. Introduction

In order to be successful in today's highly competitive world requiring high levels of productivity and adaptability to changes, firms increase levels of flexibility in their manufacturing systems. Flexibility in manufacturing is defined as the ability to change or react with little penalty in time, effort, cost or performance (Upton, 1994). There are many different types of manufacturing flexibilities such as the machine flexibility defined as the ability of the machines to perform different operations and the operation flexibility defined as the ability to produce a product in different ways (Browne et al., 1984). In order to get the maximum available benefit from flexibility some important problems must be tackled such as the determination of the "optimal" levels of flexibility and the determination of operational rules (e.g. schedules) for such systems. This study considers a flowshop consisting of two workstations which possess machine flexibility. Such situations arise in many different practical settings. For example, if the workstations consist of Computer Numerical Control (CNC) machines which can perform different operations as long as the necessary cutting tools are loaded on their tool magazines or if the workstations consist of manual operators equipped with the necessary tooling and cross-trained to perform different operations. From now on we will refer to the workstations as machines.

We assume identical jobs requiring three operations are to be processed on these machines. The first operation can only be processed by the first machine and the third operation can only be processed on the second machine. These operations are called fixed operations. On the other hand, both of the machines are capable of performing the second operation, which is called the flexible operation. Let f^1 denote the processing time of the fixed operation on machine 1 and f^2 denote the processing time of the fixed operation on machine 2. The machines are assumed to have different technological properties (non-identical machines) so that the processing time of the flexible operations take different values depending on the machine it is processed. We denote the processing time of the flexible operations on the first machine by s^1 and on the second machine by s^2 . If the flexible operation is assigned to the first machine for a job, then the total processing time of this job on the first machine is $f^1 + s^1$ and on the second machine is f^2 . If it is assigned to the second machine then the processing times are f^1 and $f^2 + s^2$, respectively. The problem is to determine the assignment of the flexible operations of each job to the machines that maximizes the overall throughput rate (or equivalently minimizes the makespan). Another problem considered in this study is determination of the optimal level of flexibility. Here the decision involves the maximization of the throughput rate while taking the cost of increasing the level of flexibility into account.

There are certain cases in industrial practice that directly correspond to the design mentioned above. For example, the CNC machines are capable of performing different operations

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provided that the required cutting tools are loaded on their tool magazines. However, having multiple copies of each tool and loading to the magazines of the machines may not be physically possible and/or economically feasible. This is because the total number of tools required to process different operations involved in a job is usually larger than the available magazine storage capacity (Gray et al., 1993). Further, especially the tools used in metal cutting industry may be very expensive. Therefore, because of such tradeoffs some tools may have multiple copies, while some others have only a single copy. Here, operations requiring tools which have multiple copies may be treated as flexible, whereas the others as fixed operations (Gultekin et al., 2006). A similar discussion also applies to manual operations. It may be possible to train operators to perform some of the necessary operations that a job requires, but training for all the necessary operators may not be possible (Daniels et al., 2004). Another example is automotive manufacturing where spot welding robots are used extensively. Due to part geometry, some welding operations can only be performed by special welding guns loaded on specific robots, whereas some other operations can be performed by different gun types. In the assembly of printed circuit boards (PCB), presence or absence of feeder tapes that hold the electronic components to be inserted on machines may lead to a similar circumstance (Crama et al., 2002).

There is an extensive literature on manufacturing flexibility which can be reviewed from the survey of Beach et al. (2000). Daniels and Mazzola (1994) consider a flowshop with manual operators. The operators are crosstrained to perform all the necessary operations that the jobs require. This situation is called complete flexibility. In another study, Daniels et al. (2004) consider a flowshop with partial resource flexibility meaning that the operators are trained to perform a subset of all the operations that a job requires. They assume that the assignment of the operators can be changed dynamically from one station to another and the process times at the stations are functions of the number of operators working on that station. Gultekin et al. (2006) make a similar assumption in a robotic cell consisting of two CNC machines and producing identical parts whereas Batur et al. (2012) consider the same problem with multiple parts. They aim to determine the assignment of flexible operations to the machines and the robot move cycle that maximizes the throughput rate. Anuar and Bukchin (2006) consider a flowshop where the assignment of the tasks can be changed dynamically. They aim to balance the line in the long term and investigate the performance of a number of operating rules. Burdett and Kozan (2001) consider an m -machine preemptive flowshop producing multiple jobs. The tasks are assumed to be shifted to adjacent stations. Mathematical formulation of the problem and heuristic procedures are provided. They show that considerable benefits can be obtained by applying task redistribution methodology for a wide range of problem instances, different flowshop types, and task shifting scenarios.

Daniels et al. (2004) prove that a large portion of the available benefits associated with labor flexibility can be realized with a relatively small investment in crosstraining. Their results suggest that in order to obtain high-quality solutions, scheduling and resource assignment decisions must be coordinated. Similar conclusions are also made by Jordan and Graves (1995), who consider the process flexibility and Nomden and van der Zee (2008), who consider routing flexibility. Process flexibility is defined as being able to manufacture different types of products in the same production facility at the same time. Routing flexibility, on the other hand, is defined as the ability to produce a product using different routes. Assuming that the cost of increasing the level of flexibility is directly proportional with the level of flexibility, a low level of flexibility where most

of the performance improvements are achieved is the best decision. However, this assumption is not necessarily true under the settings of the current study as shown in Example 2 in Section 4.

In a closely related study Gupta et al. (2004) consider a two-machine flowshop with infinite buffer capacity in between the machines that produce multiple jobs having fixed and flexible operations. They prove that the problem is NP-hard, suggest heuristic algorithms and develop a polynomial time approximation scheme (PTAS). Another closely related study is by Crama and Gultekin (2010) who consider the problem with identical jobs and identical machines (i.e. $s^1 = s^2 = s$). They develop polynomial or polynomial pointwise algorithms for different assumptions regarding the buffer capacity in between the machines. However, as shown in Example 1 in Section 3.1, their results are not applicable to the non-identical machines case which is a more realistic production setting.

Main contributions of the current study are the development of constant time algorithms for the non-identical machines problem with no-buffer and infinite capacity buffer assumptions and demonstration of the benefits of machine flexibility. Furthermore, the managerial insights towards deciding on the optimal level of flexibility can also be stated as a major contribution of this study. In the next section we define our problem in detail. In Section 3 we develop solution procedures for the no-buffer and infinite capacity buffer cases. Section 4 considers the benefits of flexibility and provides managerial insights. Section 5 is devoted to concluding remarks and future research directions.

2. Problem definition and preliminary results

In this section we define the problem more formally. There are n identical jobs to be processed on two machines. Let $N = \{1, 2, \dots, n\}$ denote the set of jobs to be processed. All jobs are first processed by machine 1 and then by machine 2. The buffer space between the machines is denoted by B . In this study we consider both the no-buffer case ($B=0$) and the infinite capacity buffer case ($B \rightarrow \infty$). In infinite buffer capacity systems, it is assumed that there is always space for an additional part in the buffer between the first and the second machines. Therefore, after the first machine completes processing a part, this part can be placed to the buffer and the machine can start processing the next part immediately. On the other hand, in no-buffer systems, after the processing of a part is completed on the first machine if the second machine is still busy processing another part, first machine cannot be unloaded. As a consequence, this machine cannot start processing the next part. Preemption is not allowed, which means, if one job has started its operation on any machine it must be completed before it leaves the machine. Additionally, each machine can process one job at a time and a job can only be processed by one machine at any time. Each of the identical jobs consists of three operations: the first operation is processed by machine 1 and the third operation is processed by machine 2. The second operation can either be processed by machine 1 or 2. The problem is to determine the assignment of the flexible operations to the machines for each job. These assignments can differ from one job to another. The objective is to minimize the completion time of the last job in the sequence on the second machine that is, the makespan.

We use the following notation and decision variables throughout the text:

- p_i^j : Total processing time of job $i \in N$ on machine $j=1,2$. Depending on the assignment of the flexible operation, p_i^j can either be equal to f^j or $f^j + s^j$,

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