Computers & Industrial Engineering 100 (2016) 72–87

Contents lists available at ScienceDirect

Computers & Industrial Engineering

journal homepage: www.elsevier.com/locate/caie

Robot move sequence determining and multiple part-type scheduling in hybrid flexible flow shop robotic cells

G. Didem Batur [a,*], Serpil Erol [a], Oya Ekin Karasan [b]

[a] Department of Industrial Engineering, Gazi University, 06570 Ankara, Turkey
[b] Department of Industrial Engineering, Bilkent University, 06800 Ankara, Turkey

ARTICLE INFO

Article history:
Received 4 March 2015
Received in revised form 10 August 2016
Accepted 11 August 2016
Available online 17 August 2016

Keywords:
Parallel machine scheduling
Hybrid flow shops
Robotic systems
Mathematical modeling
Simulated annealing

ABSTRACT

We focus on the scheduling problem arising in hybrid flexible flow shops which repeatedly produce a set of multiple part-types and where the transportation of the parts between the machines is performed by a robot. The cycle time of the cell is affected by the robot move sequence, part/machine assignments and part sequences. In a hybrid flexible flow shop in which there exist one machine in the first and two machines in the second stage, the problem of determining the best cycle time is modeled as a traveling salesman problem. In order to provide a solution methodology for realistic problem instances, a Simulated Annealing based heuristic is constructed and the problem is solved using two different neighborhood structures. The results are also compared against an effective proposed lower bound value.

1. Introduction

The point of origin of this research is the increase in the level of automation in manufacturing industries. As pointed out by Kamoun, Hall, and Sriskandarajah (1999), since setup times are reduced to improve flexibility, material handling time and cost become bottleneck, and efficient material handling becomes very important. A robotic cell is a manufacturing cell which consists of a number of machines and a material handling robot. In such systems, a part is taken from the input buffer, carried to the related machine and left to the output buffer after its processing is completed.

Robots are commonly used in many different cell formations. In this study, we focus on the robot usage in hybrid flow shops (HFSs). In a classical flow shop, all jobs are processed by the same set of machines in a linear fashion, from the first to the last stage and one machine performs all the processing for each stage. In order to extend the capacity of a single stage, additional parallel machines may be purchased. This extension of a flow shop to allow multiple (usually identical) machines in stages transforms the flow shop into a HFS (Kurz & Aşkın, 2003).

In the literature there are many studies under the interrelated topics of 'flow shops with parallel machines', 'hybrid flow shops' and 'flexible flow shops'. These research fields contain both similar and different aspects. The studies on hybrid flow shops (HFSs) usually focus on non-identical jobs and identical parallel machines, whereas the interest of studies on flow shops with parallel machines is in the identical job and uniform parallel machine environment (Dessouky, Dessouky, & Verma, 1998). Hybrid flexible flow shop problem which is the focus of this study, is obtained from classical flow shop with parallel machines problem by introducing a few specific additional assumptions (Nowicki & Smutnicki, 1998). In hybrid cells, it is possible to produce parts of different types and a job might skip any number of stages provided it is processed in at least one of them, whereas, in flexible flow shops, all jobs are processed following the same production flow: stage 1, stage 2, ..., stage m (Kurz & Aşkın, 2003).

Though the underlying optimization problems in a HFS are challenging, they have received a lot of attention in the literature due to the practical relevance of the inherent problems. Vignier, Billaut, and Proust (2010), Linn and Zhang (1999), Wang (2005) and Quadt and Kuhn (2007), and more recently Ruiz and Vazquez-Rodriguez (2010) present reviews on HFS problems.

Under the topics of hybrid flow shops or flexible flow lines there are many studies considering setup operations which are similar to the robot operations considered in our study.

Yaurima, Burtseva, and Tchernykh (2009) focus on hybrid flow shops with unrelated machines and sequence-dependent setup time. Taking the availability constraints and limited buffers into account, they present a genetic algorithm. Jabbarizadeh, Zandieh, and Talebi (2009) also consider sequence-dependent setup times and machine availability constraints on hybrid flexible flow shops.

* Corresponding author.
E-mail address: dbatur@gazi.edu.tr (G.D. Batur).

http://dx.doi.org/10.1016/j.cie.2016.08.006
0360-8352/

They propose heuristic methods and present computational experiments to evaluate the efficiencies of the algorithms.

Zandieh and Karimi (2011) consider a multi-objective group scheduling problem in a hybrid flexible flow shop setting with sequence-dependent setup times by minimizing the total weighted tardiness and the maximum completion time, simultaneously. They propose a multi-population genetic algorithm for the problem and compare it with the multi-objective genetic algorithm and the non-dominated sorting genetic algorithm.

Sawik (2012) provides mixed-integer programming models for cyclic or batch scheduling of a flexible flow shop with finite in-process buffers and continuous or limited machine availability, and compares the cyclic and batch scheduling modes. The computational experiments reported in the paper indicate that when setup times are negligible, cyclic scheduling outperforms batch scheduling for both continuous and limited machine availability. Based on these promising results, we also focus on cyclic schedules in our study.

As manufacturers implement larger and more complex robotic cells, more challenging optimization problems arise in handling such systems. To face this challenge, there have been many studies as early as dating back to late 1970s. We would like to draw the attention of the interested reader to surveys such as Crama, Kats, Van de Klundert, and Levner (2000), Lee, Lin, and Ying (2010), Dawande, Geismar, Sethi, and Sriskandarajah (2005) and Brauner (2008).

In robotic cells, different types of parts can be processed in lots. Parts typically differ from each other by having different processing times on a given machine. In multiple part type scheduling, a Minimal Part Set (MPS), i.e., the smallest possible set of parts having the same proportions as the overall production target, is produced repetitively. During an MPS cycle, all the parts in an MPS are taken from the input, get processed on appropriate machines and leave the system in its original starting state. Considering this cyclic production environment, the objective in multiple part type scheduling is to minimize the average time to produce one MPS. Multiple part-type problems are harder than their identical part-type counter problems even for small number of machines.

Machines in our robotic cell have the ability to handle a mixture of operations, which is defined as the process flexibility together with the ability to interchange the ordering of several operations for each part type, which is defined as the operational flexibility. Therefore, studies taking these definitions into account also play an important role in our study.

Gültekin, Aktürk, and Karaşan (2006) consider a robotic cell scheduling problem with two machines. Due to tooling constraints, some operations of identical parts can only be processed on certain machines. They find the allocation of the flexible operations to the two machines and the robot move cycle in order to minimize the cycle time.

The scope in Gültekin, Karaşan, and Aktürk (2009) is an m-machine flexible robotic manufacturing cell consisting of CNC machines. Using the advantage of the flexibility of the machines, the authors define a class of robot move cycles, namely pure cycles, and prove that, in most of the regions, one of these cycles is optimal.

Kamalabadi, Gholami, and Mirzaei (2007) consider multiple part type 3-machine robotic cells possessing operational flexibility that allow the operations to be performed in any order. They develop a mathematical model which is based on Petri nets and then, due to the difficulty of obtaining optimal solutions in reasonable computational times, they implement the particle swarm optimization heuristic for solving the problem.

Batur, Karaşan, and Aktürk (2012) focus on the scheduling problem arising in 2-machine flexible robotic cells which repeatedly produce a set of multiple part-types. As a result of the flexibility properties of the system, they try to find the robot move sequence as well as the processing times of the parts on each machine that minimize the cycle time.

The study of Elmi and Topaloglu (2013) is similar to ours. They deal with using multiple robots in hybrid flow shop robotic cells. A mixed integer linear programming model minimizing the makespan is proposed along with a simulated annealing based heuristic as solution methodologies. Although the cell formation considered in this study is close to the robotic cell in this study, our system becomes more complex when taking flexibility and sequencing of the robots moves into account. Additionally, we are able to provide a very effective lower bound value for our problem.

In hybrid flow shop scheduling, there are two inherent problems that have to be jointly solved, namely, the sequencing of parts on the stages and the allocation of parts to the different machines at each stage (Gupta, 1988). Considering these two problems together with the robotic cells, there are three main problems of this study; part input sequencing, part/machine allocation for each stage and the robot move sequencing.

In this study we focus on the scheduling problem observed in hybrid flexible flow shops where multiple part-types are produced and the transportation of these parts is performed by the help of a robot. Such systems necessitate multi-stage environments which may contain more than one machine and are commonly used in industries such as food processing, chemical, textile, metallurgical, printed circuit board and automobile manufacturing. Within our scope is an in-line robotic cell formation in which the first stage has only one machine whereas the second stage has two identical machines.

In the following section, the notation and basic assumptions pertinent to this study are introduced. Section 3 presents the proposed mathematical model. In Section 4, a simulated annealing approach is proposed as a solution methodology and two different neighborhood structures are distinguished. In Section 5 the results of the heuristic methodology are compared against a proposed lower bound value. Section 6 summarizes the contributions and concluding remarks of this study.

2. Notation and assumptions

As is mentioned before, in the literature, there are studies under the topics of 'flow shops with parallel machines', 'hybrid flow shops' and 'flexible flow shops'. Although there are differences, following characteristics are in common:

(1) The number of processing stages k is at least 2.
(2) Stage k has $m_k \geqslant 1$ machines in parallel and in at least one of the stages $m_k > 1$.
(3) All jobs are processed following the same production flow: stage 1, stage 2, …, stage m. A job might skip any number of stages provided it is processed in at least one of them.

In this study we have used the following assumptions which are also used in the "standard" form of the HFS problem (Ruiz & Vazquez-Rodriguez, 2010);

(1) All jobs and machines are available at time zero.
(2) Machines at a given stage are identical.
(3) Any machine can process only one operation at a time and any job can be processed by only one machine at a time.
(4) Setup times are negligible.
(5) Preemption is not allowed.
(6) The capacity of buffers between stages is unlimited.
(7) Problem data is deterministic and known in advance.