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Multi-degree cyclic flow shop robotic cell scheduling problem: Ant colony optimization

Atabak Elmi [a,*], Seyda Topaloglu [b]

[a] Department of Industrial Engineering, Faculty of Engineering, Dokuz Eylul University, Izmir, Turkey
[b] Department of Industrial Engineering, Faculty of Engineering, Dokuz Eylul University, Izmir, Turkey

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ABSTRACT

This paper deals with the multi-degree cyclic robotic flow shop cell scheduling problem with multiple robots. All the parts are processed successively through the machines with standard processing times while single gripper robots perform the transportation operations of parts between the machines. Due to the special characteristics of the considered problem, a metaheuristic algorithm based on ant colony optimization has been proposed. The proposed algorithm simultaneously determines the optimal degree of the cyclic schedule, the robot assignments for the transportation operations, and the optimal sequence of robots' moves, which in return maximize the throughput rate. The efficiency of the proposed metaheuristic algorithm is examined by a computational study on a set of randomly generated problem instances.

1. Introduction

In this research, we focus on the sequencing and scheduling problem of a particular type of automated material handling system in cellular manufacturing: cyclic robotic cells. A robotic flow shop usually consists of an input device, an output device, a sequence of processing machines, and a crew of identical programmable robots. Parts to be processed enter the system from the input device, they are processed successively through the machines in series, and finally leave the robotic cell from the output device. Each machine can process only one part at a time. Because there are no buffers for intermediate storage between the machines and each machine can hold only one part, a robotic cell is, in essence, a flow shop with blocking, where there are single gripper robots that transfer the parts between machines.

In this paper, the multi-robot multi-degree cyclic robotic flow shop cell scheduling problem is considered, in which the same type of parts are produced in large quantities. In cyclic scheduling, the robots perform a series of material handling operations in a repetitive way in order to achieve the production target. In a single-degree cyclic schedule, a single part is completed when the robot or the robots complete the sequence of move operations. Whereas, in a multi-degree cyclic schedule (k-degree cyclic schedule), k parts are completed when the robot or the robots complete the sequence of move operations. Although shorter cycle times can be achieved with multi-degree cyclic schedules, the studies have been confined to a limited framework in the relevant literature, and mostly they have been engaged in developing one-degree cyclic schedules in single robot systems. Dawande, Sriskandarajah and Sethi [1] mentioned that when the travel times between machines are arbitrary, the problem of finding an optimal one-unit cycle is NP-hard in the strong sense. Moreover, Brauner, Finke and Kubiak [2] considered a partial case of the problem considered in [1]. In their work, it is shown that the problem of finding an optimal one-unit cycle is NP-hard in the strong sense when there is a single robot for transportation and the travel times between the machines of the cell are symmetric and satisfy the triangle inequality. As a result of these implications, when there are multiple robots and multi-degree cycle considerations that further increase the computational complexity, finding an optimal multi-degree cyclic schedule for the considered problem in this paper is also NP-hard in the strong sense. For this reason, this research proposes an ant colony optimization based algorithm that simultaneously finds the optimal degree (k, where $k \le J$) of the cyclic schedule and the optimal sequence of robots' moves corresponding to the k-degree cyclic schedule, which eventually minimize the cycle time and thus maximize the throughput rate. Here, J is a given maximum number of parts that can be processed during the cycle (maximum k-degree).

Karzanov and Livshits [3] mentioned that the transportation robots are automated guided vehicles (AGVs) moving on the shop floor from one workstation to another, the AGVs are capable to change their speeds and even stop if it is necessary, in order to let pass one another when they approach each other and, thus, to

* Corresponding author.
E-mail address: atabak.elmi@gantep.edu.tr (A. Elmi).

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avoid collisions. Also, there are other known constructive solutions that are aimed to prevent the robot collisions such as using an individual rail or a separate disjoint zone for each robot (see [4–6]). In addition, robot motion programming is used in cases that the design of manufacturing cell avoids parallel rails or other designing choices in order to fix the robot collisions problem. The robot collisions are not taken into account in this research for the availability of aforementioned solution methods that prevent the collisions.

Given the processing requirements, the objective that is most interested by manufacturers is the maximization of cell productivity. A natural and widely used measure of productivity is throughput; the number of finished parts produced per unit of time [7]. In the blocking robotic flow shop cells, a crew of computer-controlled robots performs the movements of parts between the machines. By optimally assigning the robots to these moves and sequencing the transportation operations at the same time, the throughput of the cell is maximized.

2. Literature review

Sethi, Sriskandarajah, Sorger, Blazewicz and Kubiak [8] performed the purely analytic study of a robotic flow shop cell containing two and three machines and a single robot for one-degree cyclic schedules. Logendran and Sriskandarajah [9] extended this work to cover different configurations of cells and more general times for the actions of the robot. Crama and Van De Klundert [10] and Dawande, Sriskandarajah and Sethi [1], each developed polynomial-time algorithms to find the optimal one-unit cycles considering machine numbers. More thorough reviews of the cyclic robotic flow shop cells literature can be found in surveys by Hall [11], Crama, Kats, Van de Klundert and Levner [4], and Dawande, Geismar, Sethi and Sriskandarajah [12], and in the book by Dawande, Geismar, Sethi and Sriskandarajah [7].

Agnetis [13] studied the two- and three-machine one-degree cyclic robotic cells with a single robot and developed polynomial algorithms to solve the considered problem. Levner, Kats and Levit [14] extended the same problem to m-machine using the notion of prohibited intervals. They also considered the usage of more than one robot in large robotic cells in order to eliminate material handling bottlenecks. Karzanov and Livshits [3] studied a system with parallel tracks where robots run along their respective tracks, and they proposed an algorithm to find the minimal number of robots for a given cycle time. Furthermore, Liu and Jiang [15] proposed an efficient algorithm for one-degree cyclic scheduling of two robots in a no-wait robotic cell.

Moreover, many researchers have noted and verified that multi-degree cyclic schedules usually have larger throughput than one-degree cyclic schedules. Kats, Levner and Meyzin [16] studied the k-degree cyclic robotic cells with a single robot and proposed a sieve method based algorithm to optimize the cycle time. On the basis of their problem, Che, Chu and Chu [17] proposed an exact algorithm based on branch-and-bound procedure for the no-wait robotic cells. They have noted that the proposed algorithm is polynomial for a fixed k-degree ($k>1$), but becomes exponential if k is assumed arbitrary. Lately, Che and Chu [18] showed that the no-wait multi-degree cyclic robotic cell scheduling problem with two parallel robots can be also solved in polynomial time for a fixed k-degree ($k>1$), but exponential if k is arbitrary. However, the algorithm cannot be mechanically extended to the multi-robot case because it explores some properties specific to the cells with two robots.

Furthermore, Che and Chu [19] considered the k-degree cyclic robotic cell scheduling problem with multiple robots in a no-wait system. They proposed a polynomial algorithm to find the minimum number of robots for all k-degree ($k>1$) cyclic schedules and consequently the optimal cycle time for any given number of robots. On the basis of this study, Che, Chabrol, Gourgand and Wang [20] extended the proposed method to the cyclic scheduling of a no-wait re-entrant robotic flow shop with multiple robots. Zhou, Che and Yan [21] proposed a mixed-integer programming model for the fixed k-degree cyclic robotic cells with a single robot and considering time window constraints. Therefore, to determine the optimal degree the proposed model should be solved for different values of k, separately.

Che, Feng, Chen and Chu [22] studied the cyclic hoist scheduling problem with processing time window constraints. They have proposed a method to measure the robustness of a cyclic hoist schedule as an ability of remaining stable in the presence of perturbations or variations of certain degree in the hoist transportation times. A bi-objective mixed integer linear programming model has been proposed to optimize cycle time and robustness. Feng, Che and Wang [23] considered cyclic scheduling in a robotic cell with processing time windows to minimize the cycle time and the total robot travel distance simultaneously. They have proposed an iterative ε-constraint method to solve the bi-objective MIP model. Hasani, Kravchenko and Werner [24] investigated the cyclic project scheduling problem and mentioned that the proposed graph algorithm can be extended for solving the multi-degree and multiple-robot cyclic scheduling problems.

Li, Chan and Chung [25] considered the cyclic scheduling problem in parallel machine robotic flowshops with multiple robots. They have considered the given multi-degree cycles to obtain better schedules comparing to simple cycles in parallel machine robotic flowshops with time window constraints for the first time and proposed a MIP model. Elmi and Topaloglu [26,27] investigated the hybrid flow shop robotic cell scheduling problem with one robot and multiple robots, respectively. They proposed MIP models and simulated annealing based solution approaches to minimize the makespan for the processing of multiple part types. These approaches assign the part types to the machines at each stage, and sequence the part types and the robots' transportation operations simultaneously to minimize the makespan.

To the best of authors' knowledge, there is no solution method in the literature for the multi-degree cyclic robotic flow shop cell scheduling (kDCRFSCS) problem with multiple robots and fixed processing times and free pickup condition/feature. Free pickup feature/condition enables transporting each part to the next machine any time after completing its processing on a machine. The proposed metaheuristic algorithm also assumes the degree of the cyclic schedule as a variable, and determines the optimal degree of the cyclic schedule and the optimal sequencing of the robots moves simultaneously such that the throughput rate is maximized. The researches that studied the kDCRFSCS problem are shown in Table 1. The table also illustrates the position of this research among the related literature.

3. Problem definition

The robotic flow shop under study consists of multiple computer-controlled robots for material handling, M machines assigned in a row, and the input and output stations. The machines are indexed as $m \in \{m_{In}, m_1, m_2, \ldots, m_M, m_{M+1}\}$, where m_{In} and m_{M+1} are the input and the output stations, respectively. All the parts are of same type and they are processed in the robotic flow shops by visiting the successive machines. The part flow can be described as follows: After a part is moved into the robotic flow shop from the input station m_{In}, it is processed sequentially through machines $m \in \{m_1, m_2, \ldots, m_M\}$, and it finally leaves the flow shop from the output station m_{M+1}.