Computers & Operations Research 40 (2013) 1420–1434

Contents lists available at SciVerse ScienceDirect

Computers & Operations Research

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

Two-machine robotic cell scheduling problem with sequence-dependent setup times

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ARTICLE INFO

Available online 2 October 2012

Keywords:
Robotic cell scheduling
Sequence-dependent setup times
Mixed-integer linear programming
Simulated annealing
Branch and bound
Taguchi

ABSTRACT

In this paper, we introduce a new and practical two-machine robotic cell scheduling problem with sequence-dependent setup times (2RCSDST) along with different loading/unloading times for each part. Our objective is to simultaneously determine the sequence of robot moves and the sequence of parts that minimize the total cycle time. The proposed problem is proven to be strongly NP-hard. Using the Gilmore and Gomory (GnG) algorithm, a polynomial-time computable lower bound is provided.

Based on the input parameters, a dominance condition is developed to determine the optimal sequence of robot moves for a given sequence of parts. A mixed-integer linear programming (MILP) model is provided and enhanced using a valid inequality based on the given dominance condition. In addition, a branch and bound (BnB) algorithm is exploited to solve the problem, and due to the NP-hardness, an improved simulated annealing (SA) algorithm is proposed to address large-sized test problems.

All the solution methods are evaluated using small-, medium- and large-sized test problems. The numerical results indicate that the optimal solution of the MILP model is attained for the medium- and some large-sized test problems, and the proposed SA, tuned using the Taguchi technique, provides an acceptable, near-optimal solution with markedly reduced CPU time. Moreover, the lower bound is observed to be significantly near the optimal solution. Thus, this lower bound is exploited to validate the results of the SA algorithm for large-sized test problems.

1. Introduction

Today, the application of robots in manufacturing systems and in cyclic production strategy is increasingly becoming an interesting area of research. Robots can work in various fields such as spot welding, handling, assembling and operations [1]. In this paper, as in almost all previous studies, the handling robot is mainly considered. Robotic cells consist of one input device, a series of machines, one output device and robots that handle the parts between the stations [1]. There is no buffer storage between machines, such that each part is being processed or blocked on a machine or being handled by the robot [2]. The objective is to simultaneously determine the optimal sequence of robot moves and the sequence of parts in a one-unit cyclic problem to minimize the long-run average cycle time or equivalently, to maximize the throughput [3].

1.1. Aims and contributions

The aim of this paper is to introduce a new practical case of the two-machine robotic cell scheduling problem and to present efficient solution methods. As the quantity and variety of products increase, setup times, particularly those depending on previous settings, increasingly influence cell performance. This fact raises the need for consideration of sequence-dependent setup times (SDST) in robotic cell scheduling.

The issue of setup times in a robotic cell is different from setup times in traditional scheduling. Without loss of generality, the SDST consists of two sets of activities, i.e., the setup and setdown operations that are required for each job. A robotic cell also needs these activities, denoted as loading and unloading operations, before and after each processing. Therefore, this paper focuses on SDST in robotic cells, particularly when loading times are naturally defined as sequence-dependent operations. Later, the concept and relevance of SDST in robotic cells will be provided with more details. The contributions of this paper are summarized as follows:

- A new two-machine robotic cell scheduling problem of one-unit cycle with sequence-dependent setup times (2RCSDST) is

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http://dx.doi.org/10.1016/j.cor.2012.09.006

Nomenclature

$P_1,P_2,\ldots,P_k$	part types that must be manufactured
$r_1,r_2,\ldots,r_k$	minimum ratio of parts (in one MPS, r_k units of type k are produced)
$n=r_1+\cdots+r_k$	total number of finished parts in the MPS (size of the MPS)
M_1, M_2	machines
a_j	processing time of part j on machine M_1
b_j	processing time of part j on machine M_2
I, O	input and output hoppers, respectively
ε_j^0	grasping time of part j at the input hopper (I)
ε_{ij}^{m1}	loading time of part j on the mth machine after part i, where $m=1,2$
ε_j^{m2}	unloading time of part j from the mth machine, where $m=1,2$
ε_j^3	dropping time of part j at the output hopper (O)
δ	traveling time of the robot between I and M_1, M_1 and M_2, M_2 and O
2δ	traveling time of the robot between M_2 and I, O and M_1
3δ	traveling time of the robot between O and I
w_i^m	waiting time of the robot before unloading part i from the mth machine

introduced. This paper proves that the problem is NP-hard in the strong sense.

- Using the Gilmore and Gomory (GnG) algorithm, a lower bound with time complexity of $O(n^2)$ for the aforementioned problem is developed. The lower bound is used for a branch and bound (BnB) algorithm. In addition, the lower bound is used to verify the performance of simulated annealing (SA), another solution method. The SA algorithm is proposed because due to intractability, the optimal solutions of large-sized test problems are not provided in a reasonable time.
- A novel mixed-integer linear programming (MILP) model, simultaneously addressing the problems of determining the best sequence of robot moves and the best sequence of parts, is developed.
- A valid inequality is developed based on the dominance condition to enhance the MILP model. Utilizing CPLEX as a commercial solver for solving MILP models, the medium- and some large-sized test problems can be solved in a reasonable time. SA is also enhanced by the inclusion of the dominance condition as well as a well-tuning scheme obtained using the Taguchi technique.

Three newly generated sets of data are used to evaluate the proposed solution methods, the lower bound and the MILP model by solving a wide range of test problems with different sizes. The numerical results indicate the appropriate closeness of the lower bound to the optimal solution. Furthermore, the solution of the proposed SA is suitably close to the optimal solution, which confirms its usefulness in solving larger test problems.

The remainder of the paper is organized as follows. The following sub-sections review the existing literature and demonstrate how the idea originates. In Section 2, the problem definitions, notations and formulations are presented. Section 3 presents the lower bound and proves its accuracy. The proposed solution methods are described in Section 4. Section 5 presents the numerical experiments, and Section 6 concludes the paper.

1.2. Literature review

The most recent comprehensive survey and classification of robotic problems belong to Dawande et al. [1]. According to their classification scheme, the problem discussed in this paper is represented as $RF_2|(free,\ A,\ MP,\ cyclic\text{-}1)|\mu$, which means two-machine simple robotic cells with one single-gripper robot, free pickup criterion, additive travel-time metric, multiple part-types, producing one unit per cycle and aiming to maximize the throughput. Bagchi et al. [4] have also presented a detailed review of robotic flowshops from the traveling salesman problem (TSP) point of view. The remaining two substantial surveys in this area discuss cyclic scheduling problems in robotic flowshops [5] and identical part production in robotic cells [6].

Despite the aforementioned studies, there is still the need for an up-to-date survey including the most recent studies. This paper attempts to briefly classify the related works in Table 1. The classification criteria, mainly obtained from [1], are represented as the number of machines (*M*), single part type (*SP*), multiple part types (*MP*), units per cycle (*U/C*), robot moves sequence problem (*RMS*), parts sequence problem (*PS*) and the main contributions.

Studies addressing robotic problems are more extensive than those listed in Table 1; however, other studies, such as those conducted by Suárez and Rosell [31], Soukhal and Martineau [32], Alcaide et al. [33], Brucker and Kampmeyer [34], Yoosefelahi et al. [35] and Levner et al. [36], use different criteria, production strategies, number of robots, cell layouts, types of machines and types of robot applications than those used in this paper and the papers discussed in Table 1. For related applications of TSP to this work, the reader is referred to Bagchi et al. [4], Deineko et al. [37], Zahrouni and Kamoun [29] and Laporte et al. [38].

1.3. The necessity of 2RCSDST in theory and practice

There has been increasing attention provided to scheduling problems with setup time considerations. Allahverdi et al. [39] present a survey and classification of scheduling problems with sequence-dependent and sequence-independent setup times (costs). Gupta and Darrow [40], Logendran et al. [41], Liao and Juan [42] and Salmasi and Logendran [43] also consider sequence-dependent setup times. Despite the importance of SDST, to the best of the authors' knowledge, no study has addressed the robotic cell scheduling problem with sequence-dependent setup times.

In addition, in the real environment, the modern technology of a single-gripper robot with higher degrees of freedom may lead to sequence dependencies in peaking up and releasing down object activities. A comprehensive, up-to-date study of robot grippers was conducted by Monkman et al. [44]. Modern grippers usually utilize vision-guided grasping systems such as the cameras and sensors used for image processing and visual serving technologies (see [45,46]). When the manufacturing parts differ in sizes and dimensions, the required time for image recognition, jaw setting of the gripper, grasping and unloading the part will also change.

However, when the robot is going to load an object, it takes some time to recognize the position and dimension of the fixture, turn the held part if needed, load the part on the machine, wait for any necessary adjustments and settings on the part and finally release the object. The importance of time savings in loading objects becomes more apparent when computer numerical control (CNC) machines are present in the cell executing multi operations such as welding, drilling, cutting and punching.