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Hybrid discrete differential evolution algorithm for biobjective cyclic hoist scheduling with reentrance

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ABSTRACT

Cyclic hoist scheduling problems in automated electroplating lines and surface processing shops attract many attentions and interests both from practitioners and researchers. In such systems, parts are transported from a workstation to another by a material handling hoist. The existing literature mainly addressed how to find an optimal cyclic schedule to minimize the cycle time that measures the productivity of the lines. The material handling cost is an important factor that needs to be considered in practice but seldom addressed in the literature. This study focuses on a biobjective cyclic hoist scheduling problem to minimize the cycle time and the material handling cost simultaneously. We consider the reentrant workstations that are usually encountered in real-life lines but inevitably make the part-flow more complicated. The problem is formulated as a biobjective linear programming model with a given hoist move sequence and transformed into finding a set of Pareto optimal hoist move sequences with respect to the bicriteria. To obtain the Pareto optimal or near-optimal front, a hybrid discrete differential evolution (DDE) algorithm is proposed. In this hybrid evolutional algorithm, the population is divided into several subpopulations according to the maximal work-in-process (WIP) level of the system and the sizes of subpopulations are dynamically adjusted to balance the exploration and exploitation of the search. We propose a constructive heuristic to generate initial subpopulations with different WIP levels, hybrid mutation and crossover operators, an evaluation method that can tackle infeasible individuals and a one-to-one greedy tabu selection method. Computational results on both benchmark instances and randomly generated instances show that our proposed hybrid DDE algorithm outperforms the basic DDE algorithm and can solve larger-size instances than the existing ε-constraint method.

1. Introduction

In the past few decades, computer-controlled material handling devices are widely applied in the automated manufacturing industry. Typical applications are in the automated electroplating lines and surface processing shops where hoists as material handling devices are responsible for transporting parts, such as printed circuit boards (PCBs), aerospace parts, spectacle and jewelry, from one workstation to another [1]. A part transportation operation usually includes three suboperations: unloading the part from a workstation, transporting it to another workstation, and loading it onto the workstation. The parts receive surface electroplating or metallurgical treatments on workstations or tanks filled with chemicals or electrolytic solutions. In such manufacturing systems, hoists are shared by all the workstations and material handling times among the workstations cannot be neglected. Therefore, efficiently scheduling the hoists' transportation operations plays an important role in improving their productivity [1,2].

Due to the specifics of electroplating treatments, the processing time of parts on each workstation is not a constant but bounded by a pair of minimum and maximum values. If the actual processing time of a part is shorter than the minimum bound or longer than the maximum bound, the part is defective. Therefore, scheduling problem in such a manufacturing system needs not only to determine the hoist move sequence but also to determine the part processing time in each workstation. The scheduling problem in such automated manufacturing systems is referred to as *hoist scheduling problem* in the literature and was proved to be NP-hard by Lei and Wang [3]. In 1976, Phillips and Unger [4] first formulated the problem as a mixed integer programming (MIP) model, where a single hoist repeatedly carries out a fixed hoist move sequence and the system returns to the initial status when

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this fixed sequence is completed. The duration for performing this fixed sequence is referred to as *cycle time* and maximizing the productivity is equivalent to minimizing the cycle time [5–12]. Comprehensive surveys of the hoist scheduling problems and their algorithms are presented by [1,5,8,13,14].

In automated electroplating lines and surface processing shops, material handling operation is usually expensive. In some manufacturing system, material handling cost can take up a significant portion, even as high as 80%, of the total manufacturing cost [15,16]. In practice, production managers concern not only on the productivity but also on the material handling cost. However, these two criteria usually conflict with each other. Reducing the material handling cost affects the productivity of the system and vice versa [17]. So the scheduling problem in this study is to seek for a set of solutions that balances the productivity and the material handling cost.

This study considers optimizing the productivity and material handling cost simultaneously in an *extended* automated electroplating line [18] with reentrance where parts visit some workstations more than once. This type of workstations is referred to as *reentrant workstations* [18–20] and is common in real electroplating and surface treatment shops. For example, in PCB electroplating lines, PCBs need to visit a rinsing workstation and a drying workstation more than once. The two workstations are both called as reentrant workstations and determined as soon as the parts' processing recipes are known. The parts flow in an extended automated electroplating line is depicted in Fig. 1. In such extended lines, the conflicts between the processing stages that share the same reentrant workstation need to be additionally considered. Kats and Levner [21] proposed a strongly polynomial algorithm for extended electroplating lines with fixed part processing times. Liu et al. [18] formulated the problem as a comprehensive MIP model where the reentrant workstations and parallel workstations were considered together. Their MIP model can handle the problem with no more than 20 workstations. Che and Chu [19] developed an efficient branch and bound (B&B) algorithm to solve large-size problems. Recently, Li and Fung [22] proposed an extended MIP model to deal with the multi-degree cyclic case, where more than one part is produced in each cycle.

The studies mentioned above focused on finding an optimal hoist schedule to minimize the cycle time. Several researchers have paid their attentions to biobjective hoist scheduling problem where the manufacturing cost or environment factors are considered. Kuntay et al. [23] studied the cyclic hoist scheduling problem with both the economic and environmental objectives. They first obtained the minimum cycle time by solving a single-objective scheduling problem. Then, they minimized chemical and water consumption for the corresponding minimum cycle time. Subaï et al. [24] also considered the environment cost in their biobjective hoist scheduling problem where the non-linear environment cost as a function of the processing times is formulated. Their algorithm consisted of two stages. In the first stage, it found all optimal sequences of hoist moves by solving a cyclic hoist scheduling model only to minimize the cycle time. In the second stage, it minimized the environment cost with the given cycle time as a constraint in the second optimization model. As the two studies first optimized one objective and then optimized the other with a given bound of the first objective, the complete Pareto front is hard to find. Recently, Feng et al. [17] proposed a biobjective MIP model for the hoist scheduling problem to minimize the cycle time and the hoist traveling time simultaneously. An iterative ε-constraint method was proposed to find the exact Pareto optimal front for small-size instances. To the best of our knowledge, there are no meta-heuristics reported in the existing literature to deal with a biobjective cyclic hoist scheduling problem with reentrance.

This paper proposes a hybrid discrete differential evolution (DDE) algorithm [25–31] to find the Pareto optimal or near-optimal solutions for cyclic hoist scheduling problems with the objectives of minimizing the cycle time and the material handling cost simultaneously. To simplify the formulation of the material handling cost, we formulate it as a sum of the hoist traveling time in a cycle with the assumption that the material handling cost is linear with hoist traveling time. The main contribution of this paper is twofold. First, we study biobjective hoist cyclic scheduling problem in more practical lines with reentrant workstations, which is not reported in the existing literature. The reentrant part-flow makes the corresponding biobjective scheduling problem harder to solve. Second, an efficient hybrid DDE is proposed to deal with the mid- and large-size problems that cannot be solved by existing ε-constraint method proposed by Feng et al. [17].

The rest part of this paper is organized as follows. Section 2 gives the problem description and formulation. Section 3 introduces the main idea of our proposed hybrid DDE and the main components of the algorithm. In Section 4, computational results on both benchmark instances and randomly generated instances are given to demonstrate the effectiveness and efficiency of our algorithm. We conclude our work and discuss the further study in Section 5.

2. Problem description and formulation

2.1. Problem description

In this study, an automated electroplating line, as depicted in Fig. 1, is composed of M workstations and one dummy workstation that is used both as loading and unloading devices. A computer-controlled hoist transports the parts from one workstation to another. The parts are identical and have N processing stages. Some processing stages share the same reentrant workstation and without loss of generality, we assume that $M \leq N$. The part processing time of each stage should be controlled within a *time-window* with given minimum and maximum bounds. The workstations and the hoist can service only one part at any time. To guarantee the quality of the surface treatment on the parts, the *no-wait* constraints is imposed, which requires that when a part

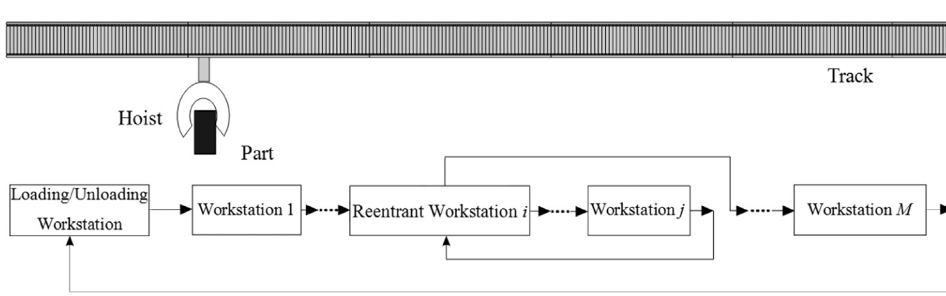

Fig. 1. The parts flow in a PCB electroplating line with reentrance.