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Minimizing energy consumption and cycle time in two-sided robotic assembly line systems using restarted simulated annealing algorithm

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ABSTRACT

Two-sided assembly lines are usually utilized to produce large-sized high-volume products. Recently robots are widely utilized in this line to replace the manual handling and manage the allocated tasks. For a robotic assembly line, the energy consumption is a major expense and the increased energy cost draws much more attentions from manufacturing enterprises. To the best knowledge of the authors, there is no research reported on the energy consumption of two-sided robotic assembly line. This paper presents a new mixed-integer programming model to minimize the energy consumption and cycle time simultaneously. A restarted simulated annealing algorithm is developed to deal with the complexity of the model, which utilizes new local search with three neighbor structures and restart phase based on the crowding distance assignment procedure to obtain well-spread Pareto-optimal set. Testing cases are designed to measure the performance of the proposed method and the restarted simulated annealing algorithm is compared with the fast elitist non-dominated sorting genetic algorithm. The computational results demonstrate that the proposed model is useful to reduce the total energy consumption and the restarted simulated annealing algorithm outperforms the non-dominated sorting genetic algorithm in both convergence and spread criteria.

1. Introduction

Two-sided assembly lines are widely utilized to assemble cars, trucks, automobiles and buses. This line differs from the traditional one-sided assembly line. In two-sided lines, both left and right sides are utilized in parallel. Some tasks are preferred to be operated on the left side (L-type) or right side (R-type) while others should be operated on either side (E-type). In the face of a competitive market and diverse customers' demands, the demand of flexible production becomes urgent. Robots are the essential parts to increase flexibility by being programmed to perform different tasks, and thus robots are allocated to the stations to replace the manual resource (Gao et al., 2009). Robots can perform the tasks continually without worries of fatigue and the assembly lines with robots are called robotic assembly lines.

A layout of two-sided robotic assembly line is depicted in Fig. 1. In this line, each mated-station is composed with two facing stations, and each station is allocated with a robot to operate different tasks. Two-sided assembly lines have several advantages over the traditional one-sided assembly lines, such as a shorter line length, less material handling, and reduced cost of tools (Bartholdi, 1993). To balance this line, two-sided robotic assembly line balancing (TRALB) problems are designed. TRALB problems are divided into two types. Type I TRALB problem deals with minimizing the number of stations with a given cycle time whereas type II TRALB minimizes the cycle time on a set of mated-stations (Kim et al., 2009; Purnomo et al., 2013).

Robotic assembly lines have several advantages over manual assembly lines, such as high productivity, manufacturing flexibility, less skilled labor and good quality of products (Levitin et al., 2006). In a robotic assembly line, the energy consumption is a major expense, and the increase of the energy price makes it non-ignorable. Fysikopoulos et al. (2012) indicate that the energy cost during a car manufacturing process is about 9–12% of the total manufacturing cost, and 20% reduction in energy consumption results in about 2–2.4% reduction in the final manufacturing cost.

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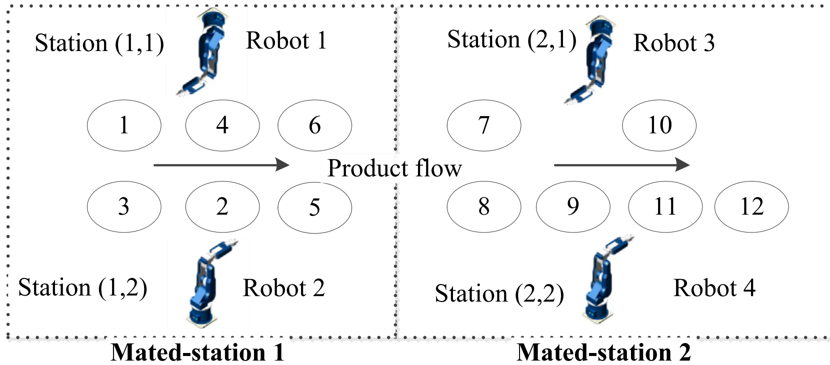

Fig. 1. The layout of two-sided robotic assembly line.

Reduced usage of energy can also keep the industries competitive and reduce pollution.

However, the research on the reduction of energy consumption in the assembly line systems is limited, and they are only related to one-sided or U-type assembly lines (Nilakantan et al., 2015a,b, 2016). To the author's best knowledge, there is no research reported where energy consumption in a two-sided robotic assembly line is considered. In addition, the energy consumption and the balance of the assembly line are not positively correlated strictly and they may be conflicted as proven in the research of Nilakantan et al. (2015a), but no multi-objective optimization algorithm is applied to obtain a Pareto-optimal set. Therefore this paper focuses on the two-sided robotic assembly line with the objectives of minimizing the energy consumption and cycle time simultaneously. Three main contributions of this research are:

(1) A new type II two-sided robotic assembly line with the objective of minimizing the energy consumption is defined and new benchmark problems are generated.
(2) A new mixed-integer programming model is developed to minimize the energy consumption and cycle time simultaneously. Nilakantan et al. (2015a) proposed a model to minimize the maximum of the energy consumptions on all stations in a straight robotic assembly line. In this paper, the sum of energy consumption on all stations is minimized. This new objective is more practical when there is no limitation on the peak energy consumption of the stations.
(3) A restarted simulated annealing (SA) algorithm as a metaheuristic method is developed to solve the multi-objective type II two-sided robotic assembly line balancing (TRALB-II) problem. New local search and a restart phase are put forward to enhance the performance of the SA algorithm. The SA is selected due to its simplicity and effectiveness, which are proved in literature (Arkat et al., 2007; Khorasanian et al., 2013; Özcan and Toklu, 2009b; Özcan, 2010).

The remainder of this paper is organized as follows. Section 2 presents the literature review, and the mathematical model is described in Section 3. Section 4 provides the encoding, decoding and the proposed SA algorithm. Section 5 gives the computational results and the findings of this research are concluded in Section 6.

2. Literature review

The literature review in this part consists of three categories: two-sided assembly line balancing, robotic assembly line balancing and the energy consumption in production.

Since the two-sided assembly line balancing (TALB) problem is first presented by Bartholdi (1993), an increasing number of methods are developed, which can be divided into exact methods, heuristic methods and metaheuristic methods. For exact methods, Hu et al. (2008) presented a station-oriented enumerative algorithm, Wu et al. (2008) and Hu et al. (2010) developed branch-and-bound algorithms. For heuristic methods, Lee et al. (2001) proposed a group assignment procedure and Özcan and Toklu (2010) developed a heuristic approach based on sequencing operations for assembly lines. Among the metaheuristic methods, Kim et al. (2000) developed a genetic algorithm, Özcan and Toklu (2009a) utilized a tabu search algorithm, Özbakir and Tapkan (2011) proposed a bee algorithm, Khorasanian et al. (2013), Özcan and Toklu (2009b) and Özcan (2010) utilized simulated annealing algorithms to solve two-sided balancing problems with different objectives.

Faced with diverse customers' demands, the concept of robotic assembly line draws growing attentions in recent days. In this line, robots rather than human beings assemble the products on each station, which was first come up by Rubinovitz and Bukchin (1991). Later, Rubinovitz et al. (1993) extended a branch-and-bound algorithm based heuristic approach to design and balance the robotic assembly line. Tsai and Yao (1993) utilized a heuristic approach for series-type robotic assembly line and Kim and Park (1995) developed a cutting plane algorithm for the robotic assembly line balancing with the objective of minimizing the total number of robot cells. Levitin et al. (2006) considered the type II robotic assembly line balancing (RALB-II) problem and they proposed a genetic algorithm. Gao et al. (2009) also considered the RALB-II problem and a genetic algorithm hybridized with local search was utilized to solve it. Yoosefelahi et al. (2012) proposed an evolution strategies algorithm for a multi-objective RALB-II. More recently, Aghajani et al. (2014) balanced the robotic mixed-model two-sided assembly line with robot setup times. Among all the above researches, only the paper by Aghajani et al. (2014) dealt with the two-sided robotic assembly line.

With regard to the energy consumption in manufacturing systems, the research is limited (Dai et al., 2013) and the research on energy consumption on an assembly line is very minimal. Fysikopoulos et al. (2012) presented a study of energy consumption in an automotive assembly and they showed that modeling an assembly by including energy considerations can save energy and cost. He et al. (2012) provided modeling method of task-oriented energy consumption for machining manufacturing system and they utilized SIMULINK simulation