Journal of Cleaner Production 156 (2017) 124–136

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

# Multi-objective co-operative co-evolutionary algorithm for minimizing carbon footprint and maximizing line efficiency in robotic assembly line systems

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A R T I C L E  I N F O

*Article history:*
Received 30 November 2016
Received in revised form
5 April 2017
Accepted 5 April 2017
Available online 8 April 2017

*Keywords:*
Robotic assembly line balancing
Carbon footprint
Multi-objective optimization
Co-evolutionary computation

A B S T R A C T

Methods for reducing the carbon footprint is receiving increasing attention from industry as they work to create sustainable products. Assembly line systems are widely utilized to assemble different types of products and in recent years, robots have become extensively utilized, replacing manual labor. This paper focuses on minimizing the carbon footprint for robotic assembly line systems, a topic that has received limited attention in academia. This paper is primarily focused on developing a mathematical model to simultaneously minimize the total carbon footprint and maximize the efficiency of robotic assembly line systems. Due to the NP-hard nature of the considered problem, a multi-objective co-operative co-evolutionary (MOCC) algorithm is developed to solve it. Several improvements are applied to enhance the performance of the MOCC for obtaining a strong local search capacity and faster search speed. The performance of the proposed MOCC algorithm is compared with three other high-performing multi-objective methods. Computational and statistical results from the set of benchmark problems show that the proposed model can reduce the carbon footprint effectively. The proposed MOCC outperforms the other three methods by a significant margin as shown by utilizing one graphical and two quantitative Pareto compliant indicators.

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## 1. Introduction

Assembly lines are flow-oriented systems of great importance in the automotive and consumer electronics industries. Robots have in recent years been widely applied in these types of systems, replacing manual labor (Gao et al., 2009). Robots are capable of operating 24 h a day without worries of fatigue and can perform different tasks by re-programming. The effective utilization of robot assembly lines evolves into the need to solve the robotic assembly line balancing (RALB) problem, in which two sub-problems; task assignment and robot allocation, are addressed simultaneously.

Assembly line balancing is an important issue that must be addressed when considering the design of such systems. The literature study presented in this paper, shows that there is no research addressing the optimization of carbon footprint and line efficiency of robotic assembly line systems. This paper provides a method to simultaneously tackle the carbon footprint and line efficiency for a robotic assembly line system. The research contains two significant contributions to the field of robotic assembly line balancing. (1) A multi-objective generic model is developed to optimize the total carbon footprint and line efficiency. This is the first time the carbon footprint is considered in robotic assembly line systems. (2) A multi-objective co-operative co-evolutionary algorithm (MOCC) is developed to simultaneously handle the task assignment and robot allocation. Multi-objective optimization is applied since the criteria of carbon footprint optimization and the line efficiency potentially conflict. MOCC is a new co-evolutionary method suitable for handling several sub-problems simultaneously and this algorithm suits this problem very well. MOCC is compared with three other multi-objective algorithms and a comprehensive study is carried out to test the superiority of the proposed MOCC.

The remainder of the paper is structured as follows. Section 2 presents a detailed literature review of the considered problem. Section 3 provides the problem assumptions and the mathematical

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http://dx.doi.org/10.1016/j.jclepro.2017.04.032
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model. Section 4 gives a detailed explanation of the proposed method along with a small-sized numerical example. Section 5 details the computational and statistical results. Finally, conclusions and future research avenues are presented in Section 6.

## 2. Literature review

Robotic assembly line balancing (RALB) problem was first introduced by Rubinovitz and Bukchin (1991). In Rubinovitz and Bukchin (1991) the allocation of the best available robot to the workstation to perform the allocated tasks is done based on the criteria of minimizing the number of workstations. Later, Rubinovitz et al. (1993) design and balance robotic assembly lines using branch-and-bound algorithm. Levitin et al. (2006) and Gao et al. (2009) solve RALB problems with the objective of minimizing cycle time through the use of genetic algorithms due to the NP-hard nature of the problem. Yoosefelahi et al. (2012) develop a multi-objective model and provide three multi-objective evolutionary strategies, while Dang et al. (2012) uses genetic algorithms to solve a multi-criteria problem of mobile robot scheduling. Most recently Nilakantan et al. (2015c) and Nilakantan and Ponnambalam (2016), utilize particle swarm optimization (PSO) algorithms and variants of PSO (Li et al., 2016a) to address different types of robotic assembly line balancing problems (one-sided, U-type and two-sided robotic assembly lines) with the objective of minimizing cycle time. Nilakantan et al. (2017) focuses on solving RALB problem with the objective of minimizing total assembly line cost and they utilized differential evolution algorithm to solve the problem. Most of the research is focused on RALB for single model assembly lines. However, Aghajani et al. (2014) consider the mixed-model two-sided RALB problem with a cycle time minimization criterion using a simulated annealing algorithm (Lee et al., 2001). The above mentioned literature mainly focused on RALB and different objectives analyzed over the years. The following paragraph discusses the literature related to energy consumption with respect to assembly line and manufacturing systems.

Research on automotive assembly by Fysikopoulos et al. (2012) report that energy costs contribute about 9–12% of the total manufacturing costs. Energy consumption cost is one of the major expenses for robotic assembly lines and one of the primary forms of energy used in the manufacturing sector is electricity. The manufacturing of electricity typically leads to emission of $CO_2$ which amounts to 20% of total emission in the factories (Dai et al., 2013). Recently, Nilakantan et al. (2015a) investigate the energy consumption in straight robotic assembly lines and developed two models to minimize the cycle time and energy consumption. Due to the problem's NP-hard nature they utilized particle swarm optimization to solve the problem. Nilakantan et al. (2016) propose a set of new evolutionary algorithms for designing an energy efficient straight robotic assembly line. Nilakantan et al. (2015b) minimize the energy consumption of a U-shaped robotic assembly line. Li et al. (2016b) subsequently investigate the reduction of total energy consumption in two-sided robotic assembly lines and develop a multi-objective restarted simulated annealing algorithm to obtain Pareto solutions. Their results indicate that the optimization of line balancing and the minimization of energy consumption in some situations were conflicting. Recently, researchers propose meta-heuristic approaches such as the genetic-simulated annealing algorithm (Tang and Dai, 2015) and the artificial bee colony algorithm to solve the scheduling problem of a flexible flow shop with the objective of reducing energy consumption. The reported results show that the proposed approaches could achieve on average a 10% reduction in the energy consumption when tested on small and medium sized problems.

Apart from the financial benefit of reduced energy consumption, the reduction also beneficially influences industry's impact on the environment. Yi et al. (2012) consider the carbon footprint in job-shop scheduling and a carbon footprint-aware model was developed to optimize makespan and carbon footprint. Liu (2014) develop a genetic algorithm to minimize total weighted tardiness and minimizing $CO_2$ emissions. Li et al. (2015) analyze the carbon emissions of CNC-based machining systems and consider the carbon footprint caused by cutting fluid, wear of cutting tools and material consumption. Lin et al. (2015) optimize the makespan and carbon footprint in turning processes using a multi-objective algorithm. Both the processing parameter optimization and flow-shop scheduling were addressed and the carbon footprints due to cutting fluids, disposal of worn tools and material consumption were considered. From literature it can be seen that minimal work has been reported to-date with respect to carbon footprint reduction and multi-objective optimization in robotic assembly line systems. Extensive searching has been done in Scopus database with the following keywords: robotic assembly line balancing, carbon footprint and multi-objective and the search resulted in no relevant literature. The focus of this paper will be to develop a mathematical model and solution technique that simultaneously optimizes the carbon footprint and line efficiency.

## 3. Mathematical formulation

This section presents the mathematical model and the assumptions considered when solving the proposed problem.

### 3.1. Model assumptions

In robotic assembly lines, robots are allocated to each workstation and each performs a set of different assembly tasks. The balance of the assembly line and the allocation of the robots are two separate sub-problems that should be considered during the line balancing process. It is assumed that the carbon footprint is composed of energy consumptions by a variety of different activities such as direct energy consumption, disposal of worn tools and material consumption (Lin et al., 2015). The disposal of worn tools and material consumption in robotic assembly lines can to some extent be regarded to be fixed as the same number of activities must be completed regardless of the number of robots used. This paper focuses on the carbon footprint caused by energy consumption. In this study, two types of energy consumption are considered. The first type of energy consumption is the energy consumed while performing the operation and the second type of energy consumption is the energy consumed while the robots are kept idle between operations. The following assumptions are similar to those presented in Gao et al. (2009) and Nilakantan et al. (2015c):

1. Robots can be allocated to any workstation and can perform any task.
2. The number of workstations is equal to the number of available robots and each robot is allocated to exactly one workstation.
3. The operation times of tasks depend on the type of robots assigned and the operation times for a task vary depending on the robot completing the operation.
4. A task can be allocated only when the cycle time and the precedence constraint(s) are satisfied.
5. Only one kind of product is assembled in straight assembly lines and parallel workstations are not considered.
6. Setup times, work-in-process inventory and material handling are negligible.

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