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RECYCL-3430; No. of Pages 17
ARTICLE IN PRESS
Resources, Conservation and Recycling xxx (2016) xxx–xxx
Contents lists available at ScienceDirect
Resources, Conservation and Recycling
journal homepage: www.elsevier.com/locate/resconrec

Full length article

Minimizing total carbon footprint and total late work criterion in flexible job shop scheduling by using an improved multi-objective genetic algorithm

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ARTICLE INFO

Article history:
Received 15 May 2016
Received in revised form 27 October 2016
Accepted 2 December 2016
Available online xxx

Keywords:
Bi-objective flexible job shop scheduling
Environmentally sustainable operations management
Carbon emission
Late work criterion
Multi-objective genetic algorithm

ABSTRACT

In scheduling, previous research attention has been directed towards classical-based objective functions, while ignoring environmental-based objective functions. The purpose of this research is to present a multi-objective flexible job shop scheduling problem with the objectives of minimizing total carbon footprint and total late work criterion, simultaneously, as sustainability-based and classical-based objective functions, respectively. In order to solve the presented problem effectively, an improved multi-objective genetic algorithm is proposed to obtain high quality non-dominated schedules. This work has three main scientific contributions that are: (1) This is a novel and pioneer research that addresses carbon footprint reduction in flexible job shop scheduling, (2) This is also the first research that addresses the total late work criterion in multi-objective flexible job shop scheduling, and (3) This research proposes an improved multi-objective evolutionary algorithm for solving the newly extended bi-objective problem. Stepwise delineation of the proposed algorithm is provided and fifteen newly extended test instances are solved by the proposed approach. Computational outcomes of the proposed algorithm are compared with two most representative and well-known multi-objective evolutionary algorithms, namely, non-dominated sorting genetic algorithm II and strength Pareto evolutionary algorithm 2. The principal results show that: (1) The proposed algorithm is superior in finding high quality non-dominated schedules, (2) It performs better in four averaged comparison metrics as compared to the other algorithms, and (3) Carbon footprint has an impact on the optimum solutions. As conclusions, the proposed algorithm is useful for production managers to schedule their operations in a way that can reduce carbon emission while minimizing late work. Production managers will also have the flexibility in selecting a schedule from amongst a set of non-dominated schedules.

1. Introduction

Public awareness on climate change and global warming has increased mainly due to changes in weather patterns, increased global temperatures, hurricanes, etc. Stocker et al. (2013) reported that the concentration of greenhouse gases including carbon dioxide, methane, nitrous oxide, etc., has significantly increased in the atmosphere as compared to the past decades. Carbon dioxide, with a high heat-trapping capacity, is primarily produced through combustion processes of fossil fuels, particularly in electricity generation, and is considered as a major greenhouse gas contributing to global warming. The concentration of carbon dioxide has already exceeded the safe limit where its concentration has increased by 40% as compared to the pre-industrial period (Stocker et al., 2013), and it stays in the atmosphere longer than other higher heat-trapping greenhouse gases. Manufacturing enterprises by means of direct or indirect emission of carbon dioxide are one of the dominant sectors accountable for global warming. Hence, the need to address eco-efficiency and environmental sustainability practices can be increasingly observed in manufacturing enterprises in order to decrease environmental impacts while increasing economic benefits (May et al., 2016; Peng and Xu, 2014; Schinko et al., 2014).

One of the problem-solving approaches for carbon footprint reduction is the cutting-edge and innovative design of manufacturing machineries, equipment, and processes (Li and Kara, 2011; Li et al., 2012c; Mori et al., 2011). In addition, embodied product energy viewpoint and life cycle assessment have also been adopted in carbon footprint assessment and reduction in a manufacturing system (Kara et al., 2010; Laurent et al., 2010; Rahimifard et al., 2010). These perspectives, technological and

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http://dx.doi.org/10.1016/j.resconrec.2016.12.001
0921-3449/

product viewpoints, support eco-efficiency practices in a manufacturing enterprise; however, they may not be appropriate for small to medium sized firms due to the considerable financial requirements. On the other hand, from an operations management viewpoint, operational strategies and decision making approaches such as advanced scheduling and planning techniques can be significant drivers in carbon footprint reduction. These approaches are much more efficacious in carbon footprint reduction, and growing research attempts can be seen in this area of research (Liu and Huang, 2014; Zheng and Wang, 2015).

In the scheduling area, previous researchers have primarily focused on classical-based objective functions such as makespan, tardiness, lateness, earliness, workload of machines, etc. (Gao et al., 2014a; Kaplanoğlu, 2016; Zhao et al., 2014), while ignoring environmental-based objective functions. In this research, flexible job shop is chosen as a manufacturing type, in which it is considered important from two points of view. Firstly, from the academic point of view, environmental-based objective functions have not been investigated in flexible job shop scheduling, where this gap can be filled in this research. In addition, previous researchers have mostly focused on batch scheduling (Liu, 2014; Liu and Huang, 2014), hybrid flow shop scheduling (Liu and Huang, 2014), and resource constrained project scheduling (Zheng and Wang, 2015). Secondly, from the practical point of view, a flexible job shop manufacturing system is more practical in real-world applications as many companies adopt this model. Thus, the following research questions will be addressed: (1) How the reduction of total carbon footprint and total late work criterion can be simultaneously considered in flexible job shop scheduling? (2) How this multi-criteria scheduling problem can be solved? (3) How schedules can be affected by carbon footprint reduction?

In order to answer these research questions, the main motivation or aim of this research is to model a low-carbon multi-objective flexible job shop scheduling problem to minimize two objectives in the operational decision level. The total late work criterion and total carbon footprint are minimized, simultaneously, as classical-based and sustainability-based objective functions, respectively. In retrospect, most previous research has neglected these aspects. Generally, objective functions in scheduling problems are in conflict with each other; therefore, an improved multi-objective genetic algorithm, named MOGA, is proposed to obtain a set of Pareto optimal schedules for the proposed multi-objective model. This work is the first novel attempt, with a three-fold scientific contribution, at modeling a multi-objective flexible job shop scheduling problem to minimize carbon footprint emission and late work criterion by applying MOGA. In addition, it is useful for flexible manufacturing job shops to schedule their operations in a manner that can reduce carbon footprint and late work. This will contribute to environmental sustainability and customer satisfaction. The obtained results of the proposed approach are compared against the most representative and well-known multi-objective evolutionary algorithms (Coello, 2006), namely, Non-dominated Sorting Genetic Algorithm II (NSGA-II) and Strength Pareto Evolutionary Algorithm 2 (SPEA2).

The remaining contents of this research are organized as follows. In Section 2, a brief literature review on the current studies is conducted. In Section 3, a bi-criterion flexible job shop scheduling problem is described, and its mixed-integer programming model is constructed. In Section 4, the proposed algorithm, MOGA, is explained in details. In Section 5, the data sets, performance criteria, parameter settings, and computational results are discussed. Managerial implications are discussed in Section 6 and finally, concluding remarks, limitations, and future research opportunities are provided in Section 7.

2. Literature review

In the parlance of Operations Research, carbon footprint reduction is considered as an inventory control problem, where it can be tackled at different decision levels (long term to short term decisions) including strategic (Badri et al., 2013; Chaabane et al., 2012; Wang et al., 2011), tactical (Absi et al., 2013; Hua et al., 2011), and operational (Liu and Huang, 2014). In the operational decision level, limited research attempts aimed at minimizing total carbon footprint can be observed, specifically in the flexible job shop scheduling environment. Liu (2014) developed an ε-archived genetic algorithm for the multi-objective batch scheduling problem in order to minimize carbon footprint and total weighted tardiness of the schedule, simultaneously. Liu and Huang (2014) presented two types of different manufacturing scheduling problems, which were bi-objective batch-processing machine scheduling and multi-objective hybrid flow shop scheduling, to simultaneously minimize carbon emission, energy consumption, and total weighted tardiness. In addition, they have implemented a non-dominated sorting genetic algorithm and an adaptive multi-objective genetic algorithm to generate the approximate solutions and reference Pareto fronts, respectively.

Zheng and Wang (2015) investigated a low-carbon bi-criterion resource constrained project scheduling problem by applying a Pareto-based estimation of distribution algorithm to minimize makespan and carbon footprint, simultaneously. Lei (2009) performed a survey of the state of the art on multi-objective manufacturing scheduling problems, including flexible job shop scheduling, that interested readers can refer to for more details. Based on the existing literature, it is only recently that low-carbon manufacturing scheduling problems have attracted more research attention due to global warming concerns and environmental-based regulations. Interestingly, there is no research, to the authors' best knowledge, that has contributed to low-carbon flexible job shop scheduling, where carbon emission can be considered in two levels, including job routing and sequencing, with recirculation.

Tardiness-based, lateness-based, and late work-based objective functions are useful classical manufacturing scheduling criteria involving due dates. The late work-based objective functions, including total weighted late work criterion and total late work criterion, were first introduced in parallel processors scheduling. The total late work criterion, unlike other classical objective functions, is calculated based on the late parts of each task being executed after their due dates, i.e. late parts of each task are significant in its calculation (Sterna, 2011). This objective function is a special case of total tardiness and is considered to be at least as difficult as maximum lateness (Sterna, 2011). Research attempts at minimizing this criterion can be found, specifically in single objective scheduling, for instance, parallel identical machines scheduling (Abasian et al., 2014; Chen et al., 2015; Xu et al., 2015), resource constrained project scheduling (Ranjbar et al., 2013), single machine scheduling (Wang et al., 2015; Wu et al., 2015; Yin et al., 2016), open shop scheduling (Błażewicz et al., 2004), job shop scheduling (Blazewicz et al., 2007; Piroozfard and Wong, 2015a), flexible manufacturing scheduling (Sterna, 2007), and flow shop scheduling (Błażewicz et al., 2005; Blazewicz et al., 2008; Pesch and Sterna, 2009). A survey of the state of the art has been presented by Sterna (2011) where interested readers can refer to for more details. However, there is not any published research that has considered the total late work criterion in multi-objective scheduling, to the authors' best knowledge, specifically in multi-objective flexible job shop scheduling.

Basically, multi-objective flexible job shop scheduling problems are complex and non-deterministic polynomial-time (*NP*) hard, most of which cannot be solved by exact techniques, due to the problem scale, susceptibility to the shape of the Pareto

Please cite this article in press as: Piroozfard, H., et al., Minimizing total carbon footprint and total late work criterion in flexible job shop scheduling by using an improved multi-objective genetic algorithm. Resour Conserv Recy (2016), http://dx.doi.org/10.1016/j.resconrec.2016.12.001