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Carbon-efficient scheduling of flow shops by multi-objective optimization

Jian-Ya Ding, Shiji Song*, Cheng Wu

Department of Automation, Tsinghua University, Beijing 100084, PR China

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ABSTRACT

Recently, there has been an increasing concern on the carbon efficiency of the manufacturing industry. Since the carbon emissions in the manufacturing sector are directly related to the energy consumption, an effective way to improve carbon efficiency in an industrial plant is to design scheduling strategies aiming at reducing the energy cost of production processes. In this paper, we consider a permutation flow shop (PFS) scheduling problem with the objectives of minimizing the total carbon emissions and the makespan. To solve this multi-objective optimization problem, we first investigate the structural properties of non-dominated solutions. Inspired by these properties, we develop an extended NEH-Insertion Procedure with an energy-saving capability. The accelerating technique in Taillard's method, which is commonly used for the ordinary flowshop problem, is incorporated into the procedure to improve the computational efficiency. Based on the extended NEH-Insertion Procedure, a multi-objective NEH algorithm (MONEH) and a modified multi-objective iterated greedy (MMOIG) algorithm are designed for solving the problem. Numerical computations show that the energy-saving module of the extended NEH-Insertion Procedure in MONEH and MMOIG significantly helps to improve the discovered front. In addition, systematic comparisons show that the proposed algorithms perform more effectively than other tested high-performing meta-heurisitics in searching for non-dominated solutions.

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1. Introduction

In recent decades, global warming and climate change have gained increasingly more public attention. As is widely acknowledged, global warming is caused by the increasing amount of worldwide greenhouse gas emissions, particularly the carbon dioxide (CO_2) produced in the fossil fuel combustion process. Since fossil fuels are the main source of energy generation, rationalized energy consumption will significantly reduce carbon dioxide emissions, and thereby slowing down global warming. According to Fang, Uhan, Zhao, and Sutherland (2011), the industrial sector contributes about one-half of the world's total energy consumption. Thus, manufacturing enterprises have become a major source of global warming and their carbon footprints are likely to be restricted by high taxes and related regulations in the future. Faced with this situation, manufacturers will have to seek for practical approaches to reduce energy consumption and carbon footprints in the production process.

One natural approach for reducing carbon footprints in the manufacturing process is to develop power-efficient machines (Li, Zein, Kara, & Herrmann, 2011; Mori, Fujishima, Inamasu, & Oda, 2011) and to design embodied product energy framework (Kara, Manmek, & Herrmann, 2010; Rahimifard, Seow, & Childs, 2010). However, the above energy improvement methods require considerable financial and personnel costs, which are not applicable for most small- and medium-sized manufacturing enterprises. In the meantime, some researchers observed that the reduction of carbon emissions can also be achieved by some operational strategies and advanced scheduling schemes (Drake et al., 2006; Gutowski, Dahmus, & Thiriez, 2006). This approach is much more practical for improving carbon efficiency in the production systems and has attracted growing research interests and attentions.

Among the increasing research attempts to reduce environmental impact through production scheduling, the work by Mouzon, Yildirim, and Twomey (2007) is one of the most well known. They collected the operational statistics of four CNC machines in a machine shop and observed that a significant amount of energy is consumed when the non-bottleneck machines are left idle. Therefore, they proposed a machine turn-on and turn-off scheduling framework to reduce energy cost while optimizing other scheduling objectives. This framework is further explored in a follow-up work of Mouzon and Yildirim (2008) for a single machine problem to minimize the total tardiness and the total energy consumption. More recently,

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* Corresponding author. Tel.: +86 10 62796805.
E-mail addresses: ding-jy12@mails.tsinghua.edu.cn (J.-Y. Ding), shijis@mail.tsinghua.edu.cn (S. Song), wuc@mail.tsinghua.edu.cn (C. Wu).

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Dai, Tang, Giret, Salido, and Li (2013) extended this "ON–OFF" strategy to the flexible flow shop scheduling problem (FFSP) to make a trade-off between the makespan and the total energy consumption.

Although turning on and off the machines can achieve the reduction of energy consumption, this strategy may not be practical in some workshops, where the machines and appliances cannot be switched off completely during the manufacturing process (Luo, Du, Huang, Chen, & Li, 2013). Recently, a new speed scaling framework is proposed for the scheduling problem (Fang, Uhan, Zhao, & Sutherland, 2013). In this framework, machines are allowed to run at varying speed levels when processing different jobs. When a machine is processing at a higher speed, the processing time decreases while the electricity consumption increases. These settings would lead to an obvious contradiction between the total processing time and the total carbon emissions. Under this framework, several scheduling problems have been investigated. Fang, Uhan, Zhao, and Sutherland (2012) considered a flow shop scheduling problem with a restriction on peak power consumption. They proposed two mixed integer programming formulations for this problem and investigate their computational performance. Liu and Huang (2014) studied a batch-processing machine scheduling problem and a hybrid flow shop problem, both of which involve the economic- and environmental-related criteria.

The permutation flow shop (PFS) problem is one of the most widely discussed scheduling model over the decades (Gupta & Stafford, 2006). However, little attention has been paid to the energy perspective in this model (Fang et al., 2011; 2012). To fill in the gap, we consider the problem of minimizing the completion time (makespan) and the total carbon emissions in a m-machine PFS problem. The speed scaling strategy is also considered in the presented model to achieve a better trade-off between the two objectives. However, obtaining the Pareto optimal sets for this problem is quite difficult. The traditional m-machine PFS problem with makespan criterion is already known to be NP-hard when $m \geq 3$ (Garey, Johnson, & Sethi, 1976) and solving the considered problem with speed scaling and multiple objectives is expected to require much more computational efforts. Thus, it is impractical to solve the problem optimally with mixed integer programming for the medium- and large-sized instances.

Meta-heuristics, on the other hand, can provide an optimal or near-optimal solution with acceptable time consumption. They are widely adopted for combinatorial optimization. One of the most famous meta-heuristics for multi-objective optimization is the non-dominated sorting genetic algorithm II (NSGA-II) (Deb, Pratap, Agarwal, & Meyarivan, 2002). It has been proved to be the most effective algorithm for several benchmark problems (Zhihuan, Yinhong, & Xianzhong, 2010). However, the "No Free Lunch" principle (Wolpert & Macready, 1997) suggests that, without utilizing the specific information of a problem, all algorithms will perform no better than random blind search when averaged across all possible problems. In addition, most of the meta-heuristics are very time-consuming for large-scale problems, which leads to slow convergence and low efficiency. Therefore, we may develop a more efficient and effective algorithm than the NSGA-II and other high-performing meta-heuristics if some structural properties of the problem and some accelerating techniques are considered in the searching progress.

Research on using problem properties and acceleration techniques to improve the performance of meta-heuristics is rather scarce for the carbon-efficient scheduling problems. Most research works concerning this topic design a sophisticated evolutionary computation algorithm for the multi-objective optimization problem and validate its performance through computational analysis. The nature of the problem is usually not fully utilized in the search progress. On the other hand, there is a considerable amount of literature on how the problem structural properties and speedup methods can help to improve the performance of meta-heuristics for the traditional PFS problem with a single objective (Grabowski & Pempera, 2001; Nowicki & Smutnicki, 1996; Taillard, 1990). The Taillard's acceleration method for makespan evaluation (Taillard, 1990) is one of the most well-known speedups for the PFS problem. It can evaluate a total of $n+1$ candidate solutions generated by the NEH-Insertion procedure (Nawaz, Enscore, & Ham, 1983) within $O(mn)$ computational time. Inspired by the process of Taillard's method, we notice that the NEH-Insertion procedure is also well-suited for the considered multi-objective PFS problem if we make a proper extension to it. This extension is based on the problem property that there could be some energy reduction if we slow down some operations of the inserted job while keeping the makespan unaffected. Use of this property in the energy saving process can result in the exclusion of a large number of dominated candidate solutions in $O(1)$ time without evaluating these solutions exactly. Therefore, the extended NEH-Insertion procedure can lead the search process to more promising regions in the solution space efficiently. Based on the above results, we develop and implement a multi-objective NEH (MONEH) algorithm and a modified multi-objective iterated greedy (MMOIG) algorithm for the considered problem to minimize the makespan and the total carbon emissions.

The contribution of this work is at least threefold:

- A multi-objective optimization framework is presented for the flowshop scheduling problem when considering machine energy consumption cost.
- We make a good extension to the well-known NEH-Insertion Procedure. Incorporated with a novel energy saving process, the extended procedure can help to improve the discovered fronts significantly for the considered problem.
- An efficient constructive heuristic algorithm (MONEH) and a high-performing meta-heuristic algorithm (MMOIG) are proposed for the problem. The high-quality non-dominated solutions generated by these algorithms can help decision makers to balance between the productivity-related criterion and the sustainability-related criterion in production.

The rest of the paper is organized as follows. In Section 2, the problem to be studied is stated, and some useful problem properties are investigated. In Section 3, we develop the extended NEH-Insertion procedure for the problem. Section 4 presents the MONEH algorithm and the MMOIG algorithm. In Section 5, computational results are provided to show the effectiveness of the proposed procedure and algorithms. In Section 6, we give some concluding remarks and highlight some future research directions.

2. Problem description and properties

2.1. Problem statement

The multi-objective PFS problem is described as follows.

- Each of the n jobs from the set $\mathcal{J} = \{1, 2, \ldots, n\}$ is to be processed sequentially through m machines denoted by $\mathcal{M} = \{1, 2, \ldots, m\}$ in the same order with respect to the indices of machines. One job $j \in \mathcal{J}$ may start its processing at machine $i \in \mathcal{M}$ only after its operation on the previous machine $(i-1) \in \mathcal{M}$ has been completed. In addition, each machine is allowed to process at most one job at a time.
- There is a finite and discrete set of s different processing speeds $\mathcal{S} = \{v_1, v_2, \ldots, v_s\}$ for each machine, and the processing speed of a machine cannot be changed during its execution of a job. Every job $j \in \mathcal{J}$ has a given processing requirement p_{ij} on every machine $i \in \mathcal{M}$. When a job $j \in \mathcal{J}$ is processed on machine $i \in \mathcal{M}$ at speed $v \in \mathcal{S}$, the corresponding processing time is $p_{ijv} = p_{ij}/v$ and the corresponding power consumption per unit time is PP_{iv}.
- The machines will not be turned off completely until all jobs are finished. Instead, each machine $i \in \mathcal{M}$ will be running at the

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