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A novel mathematical model and multi-objective method for the low-carbon flexible job shop scheduling problem

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ABSTRACT

Most conventional scheduling problems use production efficiency, cost and quality as their preeminent optimization objectives. However, because of increasing costs of energy and environmental pollution, “low-carbon scheduling” as a novel scheduling model has received increasing attention from scholars and engineers. This scheduling model focuses on reducing energy consumption and environmental pollution at the workshop level. In this paper, a new low-carbon mathematical scheduling model is proposed for the flexible job-shop environment that optimizes productivity, energy efficiency and noise reduction. In this model, the machining spindle speed — which affects production time, power and noise — is flexible and is treated as an independent decision-making variable. The methods of evaluation of productivity, energy consumption and noise are presented. A multi-objective genetic algorithm based on a simplex lattice design is proposed to solve this mixed-integer programming model effectively. The corresponding encoding/decoding method, fitness function, and crossover/mutation operators are designed specifically for the features of this problem. Three example problem instances with different scales and one Engineering case study illustrate and evaluate the performance of this method. The results demonstrate the effectiveness of the proposed model and method for the low-carbon job shop scheduling problem.

1. Introduction

Currently, the environmental and energy crises have become worldwide problems that are receiving increasing attention in most countries. Future energy consumption will increase as societies continue to develop. As shown in Fig. 1 [1] for example, by 2040 China and India will consume twice as much energy as in 2013. Along with increasing energy consumption, environmental problems are becoming increasingly serious. Thus, how to effectively reduce carbon emissions from energy consumption has become a popular research topic. Since the beginning of the industrial revolution, industry has consumed considerable amounts of energy for production [1]. Manufacturing enterprises are responsible for approximately 50% of global total energy consumption, 38% of greenhouse CO_2 emissions and serious pollution [2–4]. Therefore, manufacturing enterprises urgently need sustainable practices to achieve economic, ecological and social goals [5,6].

A manufacturing system is an input-output system that converts energy and material resources into products. Scheduling is one of the most important sub-systems in a manufacturing system. With the process plans of jobs as inputs, a scheduling task schedules the operations of all jobs on machines while satisfying precedence relationships in the process plans. Scheduling is the link of two production steps: preparing the processes and putting them into action. Conventional process research focuses mostly on productivity and cost and rarely addresses other aspects, particularly environmental issues. However, Gutowski et al. [7,8] noted that more than 85% of energy is not directly used for actual processing. This implies that efforts to improve energy efficiency by focusing solely on the machines or processes may miss a significant energy savings opportunity [9]. In fact, scheduling can significantly affect the energy consumption of the entire manufacturing system. Thus, appropriate scheduling plans can not only improve productivity but also reduce energy consumption and emissions [4,10,11]. Additionally, compared to other methods such as redesigning machines or processes, shop floor scheduling and plant operation strategies require little capital investment and can be easily applied to existing systems [12,13]. Currently, “low-carbon scheduling” as a novel scheduling model has become a topic of great interest in the scheduling area because of the costs of increased energy consumption and environmental pollution [14,15].

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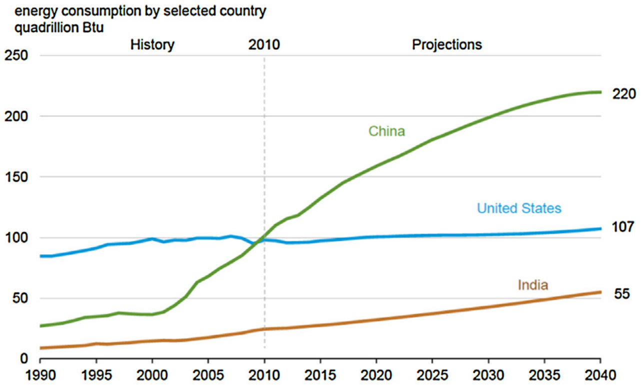

Fig. 1. Energy consumption in China, USA and India, 1990–2040 [1].

Research on "low-carbon scheduling" has been gradually increasing [4]. For a single-machine scheduling environment, Mouzon et al. [3] proposed a multi-objective mathematical programming model and several algorithms for a single CNC machine scheduling problem with the goals of reducing both energy consumption and total completion time. Mouzon and Yildirim [15] applied a greedy randomized adaptive search algorithm to a single-machine multi-objective optimization scheduling problem with the objective of minimizing the total energy consumption and total tardiness. Rager et al. [16] proposed an evolutionary algorithm for energy-oriented parallel machine scheduling. For the flow-shop environment, Fang et al. [17,18] presented some new mathematical programming models of its scheduling problem that consider peak power load, energy consumption, and associated carbon footprint in addition to cycle time. Bruzzone et al. [19] proposed an approach that relies on a mixed-integer programming model in which the reference schedule was modified by an advanced planning and scheduling (APS) system to consider energy consumption without changing the jobs' assignments and sequencing. Dai et al. [20] proposed an energy-efficient model for flexible flow-shop scheduling and developed a genetic-simulated annealing algorithm to solve it. Luo et al. [21] proposed a new ant colony optimization meta-heuristic for production efficiency and electric power cost for a hybrid flow shop scheduling problem. Keller et al. [22] developed a heuristic method for the hybrid flow-shop scheduling problem considering energy flexibility. For the job-shop scheduling environment, Liu et al. [9] developed a multi-objective scheduling method for the classical job-shop scheduling problem (JSP) with total energy consumption and total weighted tardiness as objectives.

The above review illustrates that current research has not sufficiently investigated low-carbon flexible job-shop programming (FJSP). Most studies of low-carbon scheduling are oriented toward single machines and flow shops [9]. However, job shops are an important workshop type in the discrete manufacturing industry. All of these manufacturing workshops urgently need new methods to improve sustainability at the system level. Research on low-carbon FJSP has only just started, and considerable progress has yet to come. The motivation of this paper is two-fold. From the academic perspective, the models and methods of low-carbon FJSP have not been studied well. From the application perspective, most workshops in the discrete manufacturing industry are focused on the flexible job-shop model. In this paper, a new low-carbon mathematical scheduling model is proposed for the flexible job shop environment with spindle speed flexibility that takes into account productivity, energy efficiency and noise reduction. In this model, the machining spindle speed, which affects production time, power and noise, is flexible and is taken as an independent decision-making variable. The evaluation methods of productivity, energy consumption and noise are presented. A multi-objective genetic algorithm based on a simplex lattice design is proposed to solve this mixed-integer programming model effectively. From the features of this problem, the corresponding encoding/decoding method, fitness function, and crossover/mutation operators are designed. The results of this paper can be used in the flexible job shop environment and may significantly reduce energy consumption and noise emission as well as improve productivity.

The remainder of the paper is organized as follows. The problem formulation is discussed in Section 2. A novel multi-objective algorithm for low-carbon FJSP is proposed in Section 3. Experimental studies are reported in Section 4. Section 5 is an engineering case study. Section 6 offers the discussion. Section 7 presents the conclusion and suggests avenues for future research.

2. Problem formulation

This paper selects productivity, energy consumption and noise emission as the three low-carbon scheduling optimization objectives. First, the evaluation models for these three objectives are proposed. The mixed-integer programming model for low-carbon FJSP is then presented based on the proposed evaluation models.

2.1. Evaluation models of productivity, energy consumption and noise emission

The usual productivity indicators for the workshop scheduling problem include makespan, total flow time, and average/maximum tardiness. The makespan, the most popular indicator, is chosen here to evaluate productivity [23,24]. The following will describe the evaluation models of energy consumption and noise emission in detail.

2.1.1. Evaluation model of energy consumption

When a machine is not actively engaged in machining operation, its total input power is used for idling: $p^l = p^u$; when it is being used to process parts, some power is used to maintain idling while the remainder is used for processing, and part of this power is lost to loading conditions of the machine. This lost power is termed loading power loss.

$$p^l = p^u + p^c + p^a \quad (1)$$

where

p^l — Input power of the machine;
p^{μ} — Idling power of the machine;
p^c — Output power of the machine (machining power);
p^{α} — Loading power loss.

Assuming that the time to process part *j* on machine *i* is *t*, according to Eq. (1), the energy consumption can then be expressed as e_{ij}:

$$e_{ij} = \int_0^{t_{ij}} p^l_{ij}(t)\cdot dt = \int_0^{t_{ij}} p^u_{ij}(t)\cdot dt + \int_0^{t_{ij}} p^c_{ij}(t)\cdot dt + \int_0^{t_{ij}} p^a_{ij}(t)\cdot dt \quad (2)$$

In practical applications, the idling power consumption of a machine is often used in place of the output power consumption of machining to facilitate the calculation and the actual operation, and an energy consumption matrix can be established after practice [25,26].

The loading power loss is caused by the loading conditions of the machine, which is proportional to the output power p^c in the allowable range. The power balance equation of machining can be expressed as

$$p^l = p^u + (1+\alpha)p^c \quad (3)$$