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An optimization model for carbon efficiency of a job-shop manufacturing system

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Abstract

Carbon emissions of a job-shop manufacturing system consist of processing and non-processing carbon emissions. Processing carbon emissions are caused by the processing process of machines used for the operation of a job. To select the most suitable one from all alternative machines for the operation provide a chance to reduce this type emission. Non-processing carbon emissions are caused by idle (unload) state process of all individual machines. To generate the optimal operation sequences also provide a chance to less these non-processing emissions. Considering both types of emissions, a two stage carbon efficiency optimization model using two optimal strategies is proposed.

Keywords: Low-carbon manufacturing; Carbon emission dynamics; Carbon efficiency; Optimal strategy; Job-shop manufacturing system

1. Introduction

Manufacturing industry has an important role in the reduction of carbon emissions by measuring, characterizing and optimizing the performance of manufacturing system. International energy agency (IEA) indicated that the manufacturing industry contributes over 33% of total carbon emissions and more than 40% of the total energy consumption [1]. Manufacturing process is naturally energy intensive and electricity generated from fossil fuels is a major carbon emission contributor [2]. Existing researches on optimizing the environmental dimension of manufacturing focused on developing more energy and resource efficient machines and processes [3-6]. However, majority of energy is consumed by functions that are not directly related to the production of components and the efficiency improving efforts focusing solely on the machines or processes thus may miss a significant energy saving opportunity [7-8]. More and more researches began to focus on the energy reducing margin on the system-level, especially the operational methods. For example, Fang *et al*. presents a new mathematical programming model of the flow-shop scheduling problem that considers peak power load, energy consumption, and associated carbon footprint in addition to cycle time [9]; Bruzzone *et al*. based on advanced planning and scheduling system that does not consider energy saving proposed an energy-aware scheduling of manufacturing processes to optimally plan energy saving for a give schedule [10]; Dai *et al*. proposed an energy efficient model for flexible flow shop scheduling based on an energy-efficient mechanism using an improved genetic-simulated annealing algorithm [11].

This paper will focus on the optimization of carbon efficiency of a job-shop manufacturing system. A two stage optimization approach aiming at best carbon efficiency thus is established based on two optimization strategies with genetic algorithm solution.

2. Problem Definitions

In a job-shop manufacturing system, a finite set of n jobs ($J_1, J_2, \ldots J_i, \ldots J_n$) are to be processed on a finite set of m machines ($M_1, M_2, \ldots M_j \ldots, M_m$) following a

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predefined order. Each job is defined as a finite set of N_i ordered operations where O_i^k (k=1, …, N_i) is the kth operation of job J_i processed on machine M_j and requiring a processing time p_{ij}^k. The kth operation O_i^k of job J_i processed on machine M_j is determined by a decision variable x_{ij}^k which is $x_{ij}^k = 1$ if the operation O_i^k is assigned to machine M_j. In addition, the manufacturing system is subject to the following constraints: (1) more than one machine fit the kth operation of job J_i; (2)each machine can perform only one operation at a time on a product; (3) each machine is constantly available for assignment, without being kept idle while products are waiting; (4) jobs are simple sequences of operations and they consist of strictly ordered operation sequences; (5) once an operation starts in an equipment, it must be completed without interruption; (6) a job can be in process on at most one operation at any time; (7) jobs between equipment are assumed to be negligible; (8) the processing time and power of the operation can be determined based on the experiments.

This paper aims at optimizing the carbon efficiency of a job-shop manufacturing system, which can be shown by equation (1). Where, the comprehensive production output is the numerator while the denominator is the total carbon emissions of the shop.

$$\text{Max:}\quad \overline{CE} = \sum_{i=1}^{n} Q_i \cdot W_i \Big/ CE_{shop} \qquad (1)$$

or Min:

$$CE_{shop} = \sum_{i}^{n}\sum_{k=1}^{N_i}\sum_{j=1}^{m} X_{ij}^k \cdot \Big(\int_0^{t_{i,k}} P_{ijk}^{work} \cdot \zeta_e dt + am_{ij}^k(t)\cdot \zeta_{am} + w_{ij}^k(t)\cdot\zeta_w\Big) + \sum_{j=1}^{m}\int_0^{t_{idle}} P_j^{idle}\cdot\zeta_e dt \qquad (2)$$

Where, Q_i is the production output of the ith type job, W_i is the weight of the ith job for calculating the comprehensive production output, $\overline{CE}$ is the comprehensive carbon efficiency of the job-shop with the total carbon emissions CE_{shop}. X_{ij}^k is the task allocation matrix for the kth operation of job J_i assigned in equipment M_j, P_{ijk}^{work} is the processing power of M_j for the operation O_i^k, $am_{ij}^k(t)$ is the consumption of the auxiliary material such as coolant with the carbon emission coefficient ζ_{am}, $w_{ij}^k(t)$ is the waste of M_j for the operation O_i^k and its carbon emission coefficient is ζ_w, P_j^{idle} is the idle power of M_j.

3. Optimization Strategies for Carbon Efficiency

Carbon emissions dynamic characteristics are the dynamic changes of carbon emissions over time. They are also determined by production or scheduling plan. In this paper, two optimization strategies were proposed based on the following two considerations:

- More than one machine may fit the kth operation of job J_i, while these individual machines are featured with different performance. There is an optimal task allocation scheme with the best machine for the kth operation of job J_i.
- Once the machine for the kth operation of job J_i is determined, the processing time and carbon emission rate is fixed (namely the processing carbon emissions is constant). However, the non-processing carbon emissions are varied for different sequence schemes of all operations.

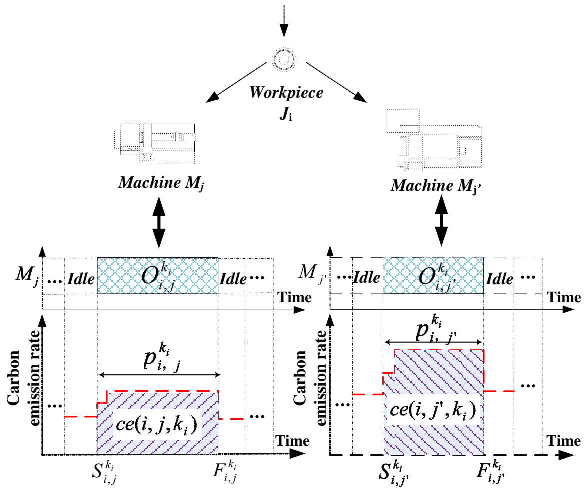

Fig. 1. Carbon emissions comparison for the same operation in different machines

Take the kth operation O_i^k of job J_i, for example, it can be processed by two machines (maybe more than two in the actual production workshop) M_j and $M_{j'}$. The corresponding carbon emissions profiles of both machines used for the operation O_i^k are shown in Fig.1. It shows that in spite of $F_{i,j}^{k_i} - S_{i,j}^{k_i} > F_{i,j'}^{k_i} - F_{i,j'}^{k_i}$, namely processing time $p_{i,j}^{k_i} > p_{i,j'}^{k_i}$, the carbon emissions $ce(i,j,k_i)$ of machine M_j is significantly less than the carbon emissions $ce(i,j',k_i)$ of machine $M_{j'}$ shown by slash shadow in Fig.1.The main reason is that the carbon emission rate of M_j is significantly smaller than $M_{j'}$ even though the processing time of M_j is longer. Their carbon emission rate is determined by their processing power, auxiliary materials utilization such as cutting fluids and waste exclusion *etc*. Therefore, it cannot reduce the carbon emissions of shop floor only by the