Computers in Industry 81 (2016) 82–95

Contents lists available at ScienceDirect

Computers in Industry

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

Energy-efficient dynamic scheduling for a flexible flow shop using an improved particle swarm optimization

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ARTICLE INFO

Article history:
Received 30 April 2015
Received in revised form 15 August 2015
Accepted 1 October 2015
Available online 23 October 2015

Keywords:
Dynamic scheduling
Energy consumption
Flexible flow shop
Particle swarm optimization

ABSTRACT

Due to increasing energy requirements and associated environmental impacts, nowadays manufacturing companies are facing the emergent challenges to meet the demand of sustainable manufacturing. Most existing research on reducing energy consumption in production scheduling problems has focused on static scheduling models. However, there exist many unexpected disruptions like new job arrivals and machine breakdown in a real-world production scheduling. In this paper, it is proposed an approach to address the dynamic scheduling problem reducing energy consumption and makespan for a flexible flow shop scheduling. Since the problem is strongly NP-hard, a novel algorithm based on an improved particle swarm optimization is adopted to search for the Pareto optimal solution in dynamic flexible flow shop scheduling problems. Finally, numerical experiments are carried out to evaluate the performance and efficiency of the proposed approach.

1. Introduction

Nowadays manufacturing industry is facing the enormous environmental challenge as well as strong economic pressure due to the increasing energy requirements and associated environmental impacts. An important aim of manufacturing companies is to reduce energy consumption for cost-saving and environment-friendly modes in terms of the development of sustainable manufacturing [1]. Research on reducing the energy consumption of manufacturing processes has mainly focused on the energy consumption optimization based on the machine level and the product level, respectively [2–6]. Besides, from the manufacturing system-level perspective, optimizing the objectives of production scheduling is a feasible and efficient approach for manufacturing companies to decrease energy consumption without any machine or product redesign. Recently, many interesting efforts have been performed to investigate production-scheduling problems that take into account energy efficiency. Most of these research works are primarily concerned with developing a mathematical model for solving the static scheduling problem. Only few works [7,8] are focused on reactive approaches for sustainable operations scheduling. However, scheduling problems are dynamic in nature and complex due to uncertain events occurring in real-world production scheduling. It is evident that the previous static decision-making models of scheduling problems have some severe limitations for real production environments. Some general multi-objective scheduling models to minimize makespan and energy consumption have proven to be effective in the flexible flow shop [9]. However, uncertain events, such as new job arrivals and machine breakdown are not taken into consideration. In this paper the energy consumption and makespan are analyzed while considering dynamic factors in the flexible flow shop. A dynamic scheduling strategy based on predictive-reactive scheduling approach is adopted to represent the multi-objective optimization problem. Furthermore, due to the fact that dynamic scheduling problem is well known as NP-hard, different methods are employed to solve the scheduling problem. Thus, two improved particle swarm optimizations (i.e., NS-PSO and NIW-PSO) are proposed for the dynamic flexible flow shop problem.

The remaining sections of this paper are organized as follows. Section 2 introduces related works. Section 3 states the research problem. Section 4 presents an approach for solving the dynamic flexible flow shop scheduling problem. Section 5 presents numerical experiments and case studies and finally Section 6 presents the conclusions.

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http://dx.doi.org/10.1016/j.compind.2015.10.001
0166-3615/

2. Related works

In recent years, there has been growing interest in production scheduling in order to get energy savings. May et al. [10] addressed a multi-objective scheduling model related to energy consumption and makespan in a job-shop system and obtained a series of different Pareto front solutions based on a green genetic algorithm. Escamilla et al. [11] developed a genetic algorithm to minimize energy consumption and makespan in an extended version of the job-shop scheduling problem where each machine can work at different rates. Jiang et al. [12] built a multi-objective optimization model involving makespan, processing cost, processing quality and energy consumption for a flexible job-shop scheduling problem and designed a modified on-dominant sorting genetic algorithm to solve it. Liu et al. [13] established a scheduling model that minimized the total non-processing electricity consumption and total weighted tardiness for the job shop problem, and the non-dominant sorting genetic algorithm was employed to solve the problem. Bruzzone et al. [14] provided an energy-aware scheduling algorithm based on a mixed integer programming formulation to account for the energy consumption for a given flexible flow shop where original job assignment and sequencing were required to keep fixed. Fang et al. [15] proposed a new mixed integer linear programming model for the flow shop scheduling problem that considered the peak total power consumption, the carbon footprint, and the makespan. At the same time, the authors [9] also explored the energy-efficient scheduling problem with two objectives, the makespan and energy consumption for the flexible flow shop. To sum up, it can be found that most of the state-of-the-art papers focused on energy-efficient scheduling for various shop floor environments (job shops, flow shops, flexible job/flow shops, etc.) in the perspective of static scheduling. However, owning to frequently inevitable unpredictable dynamic factors (such as new job arrivals and machine breakdown) occurring in most real-world production environments, a previously feasible schedule could not be executed.

In the literature on dynamic scheduling problems, predictive-reactive scheduling strategies have been widely used in manufacturing systems, where schedules are revised in response to dynamic factors [16]. Most of them only consider efficiency of the schedule like makespan. However, reducing energy consumption in production scheduling considering dynamic factors has been rather limited. Pach et al. [7] proposed a reactive scheduling model based on potential fields in flexible manufacturing systems, which considered three indicators: makespan, energy consumption and the number of resource switches in a dynamic context. Zhang et al. [8] proposed a new goal programming mathematical model to solve the dynamic rescheduling problem in a flexible manufacturing system, which addressed the energy consumption and the schedule efficiency as multi-objective optimization functions. Zeng et al. [17] introduced the idea of idle time window based on busy and idle states of each machine for the dynamic scheduling of multi-task with the objective of minimizing the energy consumption in a hybrid flow-shop.

In addition, dynamic scheduling problems are more complex than static scheduling problems and they are strongly NP-hard [18,19]. Various techniques such as heuristic/meta-heuristic algorithms and hybrid techniques have been introduced to solve this kind of problems. In particular, meta-heuristic approaches, such as genetic algorithm (GA), simulated annealing (SA), and particle swarm optimization (PSO) have been successfully employed to generate optimized results in recent years. Nevertheless, these works do not address energy efficiency issues. For example, Rossi and Dini [20] proposed a real-time genetic algorithm for dynamic job-oriented scheduling in flexible manufacturing systems, and the proposed approach greatly reduces the makespan. Whereas, Chryssolouris and Subramaniam [21] employed genetic algorithms for a dynamic job shop with performance indicators such as job tardiness and job cost in the presence of machine breakdown and alternate job routine. The results showed that the proposed GA outperforms the common dispatching rules. Chou et al. [22] investigated an improved simulated annealing approach for the dynamic scheduling problem of semiconductor with the objective of minimizing the total weighted completion time. The computational experiments indicated the proposed method can effectively and efficiently obtain optimized solutions. On the other hand, Visalakshi and Sivanandam [23] designed four different PSO approaches for solving the dynamic task scheduling problem. Wang et al. [24] presented a new hybrid discrete PSO for addressing the dynamic job shop scheduling problem by inserting new jobs and machine failures. Pacini et al. [25] proposed the PSO for studying the dynamic scheduling of cloud-based scientific experiments in online environments. These cases have confirmed that the PSO has good performance in solving dynamic scheduling problems.

However, there exist some limitations in the literature that must be tackled. First, further improvement with regard to the optimization algorithms is required to make it more adaptive to meet the various objective requirements in practical environments. Second, the optimization algorithms need to be more effective and efficient for dynamic scheduling problems. Due to the advantages of the PSO algorithm, in terms of simple structure, immediate applicability to practical scheduling problems and quick optimal solutions, a novel PSO is proposed to explore the dynamic flexible flow-shop scheduling problem with new job arrivals and machine breakdown to minimize energy consumption and makespan in contrast to the described background.

3. Problem statement

A dynamic flexible flow-shop scheduling (DFFS) with unrelated parallel machines can be defined as follows. The DFFS is a multi-stage production process that consists of two or more stages in series. There is at least one machine in each stage, and at least one stage has more than one machine. Assume that there is a set $J = \{1, 2, 3, ..., n\}$ of n jobs, a set $S = \{1, 2, 3, ..., s\}$ of s stages, and a set $M_t = \{1, 2, 3, ..., m_t\}$ of $m_t(t \in S)$ machines at each stage $t(t \in S)$ in manufacturing system. All jobs to be processed on machines need to go through all the stages in the same order. Moreover, there is a set $V = \{1, 2, 3, ..., d\}$ of d spindle speeds for one machine at stage $t(t \in S)$ and each job $j(j \in J)$ must be processed on machine $m(m \in M_t)$ at an assigned speed $v(v \in V)$. Hence, at each stage, tasks of different jobs could have different processing times with their corresponding energy consumptions. Due to the fact that unexpected events occur during the production scheduling, two dynamic factors are considered. First, there is a set $J' = \{1, 2, 3, ..., n'\}$ of n' new jobs, which must arrive after the start of the original scheduling plan and they may arrive continuously at any time. Second, there is a set $M'_t = \{0, 1, 2, ..., m'_t\}$ of m'_t machines suffering a breakdown during the production scheduling. The breakdown can occur during either idle time or operational time of one machine. Additionally, the required conditions for the DFFS are shown in Table 1. Additionally, a description of the notations used along the rest of the paper is presented in Table 2.

The formal mathematical model for the DFFS is proposed in Appendix. It is an extension of the mathematical model presented in [9] to cover rescheduling.

There have been diverse approaches to solve multi-objective optimization problems in the literature, which can be divided into two groups: a priori approach and a posteriori approach. The former assigns weights to each objective. Hence, the multi-objective problem is converted to form a single objective problem.