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Rescheduling in job-shop problems for sustainable manufacturing systems

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Manufacturing industries are faced with environmental challenges, so their industrial processes must be optimized in terms of both profitability and sustainability. Since most of these processes are dynamic, the previously obtained solutions cannot be valid after disruptions. This paper focuses on recovery in dynamic job-shop scheduling problems where machines can work at different rates. Machine speed scaling is an alternative framework to the on/off control framework for production scheduling. Thus, given a disruption, the main goal is to recover the original solution by rescheduling the minimum number of tasks. To this end, a new match-up technique is developed to determine the rescheduling zone and a feasible reschedule. Then, a memetic algorithm is proposed for finding a schedule that minimizes the energy consumption within the rescheduling zone but that also maintains the makespan constraint. An extensive study is carried out to analyze the behavior of our algorithms to recover the original solution and minimize the energy reduction in different benchmarks, which are taken from the OR-Library. The energy consumption and processing time of the tasks involved in the rescheduling zone will play an important role in determining the best match-up point and the optimized rescheduling. Upon a disruption, different rescheduling solutions can be obtained, all of which comply with the requirements but that have different values of energy consumption. The results proposed in this paper may be useful for application in real industries for energy-efficient production rescheduling.

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1. Introduction

In manufacturing industries, there are many unexpected disruptions every day (machine breakdown, order modification, disruptive events, order cancelations, etc). After a disruption, the original schedule may become invalid due to the new conditions. In some cases, it is possible to easily modify the solution to absorb the disruption, but, in many cases, rescheduling is mandatory in order to minimize the effects of this disruption and recover the original solution as soon as possible.

In the literature, there are many dynamic scheduling methods for managing online scheduling. Arnaout (2014) tackles rescheduling for the unrelated parallel machine problem with sequence-dependent setup times and different rates of breakdowns or urgent jobs arrivals. To do this, a new repair rule, which is referred to as Minimum Weighted Cmax Difference (MWCD), was developed and compared to existing algorithms based on both schedule quality and stability. Hall and Potts (2004) work with scheduling problems where a set of original jobs has already been scheduled to minimize a cost objective when a new set of jobs arrives and creates a disruption. The decision-maker needs to insert the new jobs into the existing schedule without excessively disrupting. The authors provide either an efficient algorithm or a proof that such an algorithm is unlikely to exist. In Qi et al. (2006), the problem of updating a machine schedule is proposed when either a random or an anticipated disruption occurs after a subset of the jobs. The proposed approach differs from most rescheduling analysis in that the cost associated with the deviation between the original and the new schedule is included in the model. Vieira et al. (2000) present new analytical models that can predict the performance of rescheduling strategies and quantify the trade-off between different performance measures. To do this, three rescheduling strategies are studied: periodic, hybrid, and an event-driven strategy based on the queue size. Vieira et al. (2003) present a framework for understanding rescheduling strategies, policies, and methods in rescheduling manufacturing systems. The work explains methods for generating robust schedules and methods for

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updating schedules. In Subramaniam and Raheja (2003), the typical job-shop disruptions are studied and their repair processes are decomposed into four generic repair steps, which are achieved using a modified affected operation rescheduling (mAOR) heuristic. In Herroelen and Leus (2004), several methodologies for proactive and reactive project scheduling are reviewed. They also offer a framework that allows project management to identify the proper scheduling methodology for different project scheduling environments.

Furthermore, the main objective of manufacturing industries is to improve profitability and competitiveness. These improvements can be obtained with a good optimization of resource allocation. In the last few years, many industries have not only been facing complex and diverse economic trends of shorter product life cycles, rapidly changing science and technology, increasing diversity in customer demand, and globalization of production activities but also the enormous environmental challenges of global climate change (Mestl et al. (2005)) and rapid exhaustion of various non-renewable resources (Yusoff (2006)). Research on reducing the energy consumption of manufacturing processes has mainly focused on energy consumption optimization based at the machine level and the product level (Neugebauer et al. (2011)). Gahm et al. (2016) have developed a research framework for energy-efficient scheduling. Different proposals have been classified following different attributes and criteria. Tonelli et al. (2016) propose a centralized and distributed model for an off-line energy-aware scheduling problem. Liu et al. (2014) propose a model for the bi-objective problem, which minimizes total electricity consumption and total weighted tardiness in JSP. To this end, the Non-dominant Sorting Genetic Algorithm is used to obtain the Pareto front. In May et al. (2015), a green genetic algorithm is proposed to achieve a semi-optimal makespan with significantly lower total energy consumption in job-shop scheduling problems. The study demonstrated that wasteful energy consumption can be reduced significantly by employing complex energy-efficient machine behavior policies.

The integration of energy efficiency at both machine tool and shop floor levels could bring multiple environmental benefits. Yan et al. (2016) propose a multi-level optimization approach for energy-efficient flexible flow shop scheduling which incorporates power models of single machine and cutting parameters optimization into the energy-efficient scheduling problems. At machine tool level, the authors use cutting parameters of each machine to be optimized based on grey relational analysis, where cutting energy and cutting time are considered as the objective. Then, based on a established energy consumption model of flexible flow shop, a Genetic Algorithm is employed to optimize makespan and total energy consumption simultaneously at shop floor level. Mouzon et al. (2007) developed several algorithms and a multiple-objective mathematical programming model to investigate the problem of scheduling jobs on a single CNC machine in order to reduce energy consumption and total completion time. They pointed out that there was a significant amount of energy savings when non-bottleneck machines were turned off until needed. It is well-known that machines consume a considerable amount of energy when left idle. Therefore, many works propose a turn-on and turn-off scheduling framework to control the machines, and the overall energy consumption can be reduced. For some manufacturing systems, however, it is not possible to turn off machines completely during each of the idle intervals, either because restarting the machines requires a large amount of energy or because frequent on/off switches may damage the machine components. In these cases, the on/off control framework is not applicable (Zhang and Chiong (2016)). Therefore, an alternative to the on/off control framework is a new framework based on machine speed scaling (Fang et al., 2013 for flow shop scheduling) (Salido et al., 2013 for job-shop scheduling). In this new framework, machines are allowed to work at different speed levels when processing different jobs. Some researchers have focused their research on this framework. Zhang and Chiong (2016) propose a multi-objective genetic algorithm with enhanced local search for minimizing the total weighted tardiness and total energy consumption. Fang et al. (2013) propose mathematical programming and combinatorial approaches to consider a flow shop scheduling problem with a restriction on peak power consumption.

One of the most important production scheduling problems studied in the literature is the job-shop scheduling problem (JSP), which represents a problem in which some tasks are assigned to machines with a specific processing time. In comparison, studies on the JSP with energy-saving objectives are limited, although some works currently consider this feature in JSPs.

This paper works with an extension of the job-shop scheduling problem where each machine can work at different rates (JSMS) (Salido et al. (2013)). It is assumed that when a job is processed at a higher speed, its processing time decreases, while its power consumption increases (Fang et al. (2013)). Power consumption is the energy consumption per unit of time. Thus, the energy consumption of a task is given by the formula Energy = Power × Time. In tasks that are related to manufacturing processes, it is usually assumed that the higher the power in machines, the lower the processing time required. This relationship is not lineal since it depends on the efficiency rate, which usually decreases from a certain point of the power supplied (Draganescu et al. (2003); Morillo et al. (2016)). Therefore, even though the power consumption increases, the energy consumption may be lower, equal to, or higher depending on what efficiency rate the machine is working at. For instance, if all machines can use less energy at maximum speed for all tasks, the problem remains trivial with respect to power consumption, since only this machine speed (from those available) will be selected. In this case, the problem is considered a classical job-shop scheduling problem with the only objective of minimizing makespan. Indeed, if a machine uses less energy at maximum speed (and therefore the lowest processing time), the other available machine speeds can be removed from the list in a preprocessing step, since they will not be part of a solution. Therefore, the case in which there is a tradeoff between energy consumption and machine speed is considered so all available machine speeds can be part of a solution based on operator preferences.

Thus, without loss of generality, and taken into account the above formula Energy = Power × Time, it is considered energy consumption instead of power consumption, since the processing time of each pair machine-task is fixed and known in advance for each machine speed. Similar to Zhang and Chiong (2016), the processing time in JSMS depends on the machine speed and therefore on the energy consumption. Thus, it is assumed that increasing the machine speed will lead to higher energy consumption despite the shorter processing time.

Furthermore, most of the existing research on reducing energy consumption in JSP has focused on static scheduling models (Zhang and Chiong (2016); May et al. (2015); Liu et al. (2014)). To the best of our knowledge there is no interactive rescheduling method that takes into account energy consumption in job shop scheduling. Therefore, new techniques are needed to address rescheduling and to reduce the energy consumption in job-shop scheduling problems. In this paper, a new rescheduling technique is proposed to recover the original solution by minimizing energy-consumption within the rescheduling zone.

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