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Robust scheduling for multi-objective flexible job-shop problems with random machine breakdowns

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A B S T R A C T

This study addresses robust scheduling for a flexible job-shop scheduling problem with random machine breakdowns. Two objectives – makespan and robustness – are simultaneously considered. Robustness is indicated by the expected value of the relative difference between the deterministic and actual makespan. Utilizing the available information about machine breakdowns, two surrogate measures for robustness are developed. Specifically, the first suggested surrogate measure considers the probability of machine breakdowns, while the second surrogate measure considers the location of float times and machine breakdowns. To address this problem, a multi-objective evolutionary algorithm is presented in this paper. The experimental results indicate that, compared with several other existing surrogate measures, the first suggested surrogate measure performs better for small cases, while the second surrogate measure performs better for both small and relatively large cases.

1. Introduction

The job-shop scheduling problem (JSP) has been well studied in the manufacturing systems field during the past few decades. The classic JSP, which is a combinatorial optimization problem, is strongly NP-hard (Garey et al., 1976). An extension of the JSP, the flexible job-shop scheduling problem (FJSP) has received considerable attention in the field. The FJSP consists of two subproblems, including machine assignment and operation sequence. Thus, the FJSP is a more complex version of the JSP and is also strongly NP-hard. Bruker and Schlie (1990) were among the first to address the FJSP and proposed a polynomial algorithm to the problems with two jobs. Most existing research addressed this problem with the assumption that the parameters are known and deterministic. However, in real-world manufacturing systems, schedules are often confronted with uncertain or stochastic factors. For example, resource shortages and machine breakdowns can delay a schedule's completion time.

In this study, we focus on the FJSP while considering uncertainty, referred to as the stochastic FJSP (S-FJSP). The methodology of *robust scheduling* (de Vonder et al., 2008) is employed to solve the S-FJSP. In robust scheduling, robustness is usually the objective for the schedules. According to the existing literature, the measure robustness is mainly classified into two categories (Herroelen and Leus, 2005): *quality robustness* and *solution robustness*. The former is often used to indicate the insensitivity of the schedule performance under uncertainty in terms of the objective value, such as makespan (Leon et al., 1994; Jensen, 2003; Lin and Liao, 2007) and tardiness (Wu et al., 1999; Tseng et al., 2009), while the latter usually refers to the insensitivity of activity start (or complete) times to the uncertainty. Usually, the measure of *solution robustness* can be considered the *stability* of the schedule (Goren and Sabuncuolu, 2008). *Quality robustness* indicates the ability to preserve a specified level of solution quality in the presence of uncertainty. Because makespan is the most important objective in the FJSP, which is also one of the objectives of our research, for a predesigned schedule, we are interested in the preservation of makespan when uncertainty is present. Moreover, in most cases, *solution robustness* of a schedule is not large enough to accommodate all possible changes (Goren and Sabuncuolu, 2008), so investigation of the *quality robustness* of a schedule in the presence of uncertainty is required. Thus, in this research, we focus on *quality robustness* rather than *solution robustness*. For the remainder of this paper, the term "robustness" refers to *quality robustness*.

With simultaneous consideration of makespan and robustness, the FJSP holds a multi-objective nature. The multi-objective approaches for the S-FJPS are seldom reported in the literature. Usually, the two objectives are combined, and the problem is transferred to a single-objective problem, such as that described by Al-Hinai and ElMekkawy (2011). However, providing a wide

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range of solutions to decision makers might be more useful. Then, decision makers can determine trade-offs between makespan and robustness for their schedules. Thus, in this work, we study the S-FJSP in a multi-objective optimization framework.

Because the uncertainty is "unknown", it is difficult to evaluate the effects of uncertainty of the baseline schedule. One approach for evaluating uncertainty is to simulate the uncertainty scenarios. However, exhausted simulations may have large time requirements (Liu et al., 2007). To tackle this problem, certain surrogate measures (SMs) are usually employed to approximate the robustness of a schedule. Slack-based SMs are often employed in approaches for robust scheduling (Leon et al., 1994; Al-Fawzan and Haouari, 2005). Another assumption for robust scheduling is that the uncertainty is *bounded*, suggesting that some uncertainty information is available in advance and could be utilized when constructing the baseline schedule. However, most slack-based SMs neglect this information. To utilize the information about uncertainty, we propose two surrogate measures and investigate their performances within a multi-objective framework. In the first suggested surrogate measure, the workload information for each machine is utilized, and the robustness is measured as the weighted sum of the float time for each operation. For the second suggested surrogate measure, the machine breakdown locations are incorporated in the calculation of robustness. Computational results suggest that the proposed surrogate measures are effective for the S-FJSP.

The rest of the paper is organized as follows. In Section 2, we briefly review the literature on robust scheduling. The problem formulation and multi-objective optimization for FJSP are presented in Sections 3 and 4, respectively. In Section 5, we examine several robust measures for S-FJSP and suggest two new surrogate measures. The details of proposed multi-objective evolutionary approach are presented in Section 6. Experimental results are reported in Section 7. Finally, some conclusion and future work are given in Section 8.

2. Robust scheduling

According to the existing literature, in job-shop scheduling problems, uncertainty is attributed to two main aspects: the job processing times, as described by Wu et al. (1999), Xia et al. (2008), Tseng et al. (2009), and Lei (2010) and the machine breakdowns or maintenance (Liao and Chen, 2003; Liu et al., 2007; Goren and Sabuncuolu, 2008; Lei, 2011; Dong and Jang, in press). Regarding the generation of robust schedules, the approaches can also be divided into two categories: buffering and non-buffering approaches.

Several studies (Mehta and Uzsoy, 1998, 1999; O'Donovan et al., 1999) have shown that advanced insertion of appropriate idle times is effective for handling disruptions. However, there are two main difficulties for buffering strategies (Al-Hinai and ElMekkawy, 2011): (1) the strategies must decide the locations for inserting idle times and (2) they must decide the number of idle times. In non-buffering approaches, a robustness measure based on the baseline schedule is usually an objective for optimization. Although extensive methods have been reported in the literature, the concept and definition of robustness of a schedule is still an open issue. Leon et al. (1994) used the average float time as the surrogate model of robustness. Wu et al. (1999) used expected weighted total tardiness as the robustness measure to study the job-shop scheduling problem with process time variability. In Liao and Chen (2003), minimizing the maximum tardiness was taken as the optimization objective. Tseng et al. (2009) also focused on total tardiness in the single machine problem with controllable process times. Gu et al. (2010) proposed a competitive co-evolutionary quantum genetic algorithm for the stochastic job shop scheduling problem while minimizing the expected value of makespan. A similar research was presented by Lei (2011), where minimizing the stochastic makespan was taken as the objective for the job-shop scheduling problem subject to random breakdowns. Dong and Jang (in press) considered the performance measures of mean tardiness and mean flow time under machine breakdowns for production scheduling at a job shop.

Compared to the classic JSP, few studies have addressed the FJSP under uncertainty. Mahdavi et al. (2010) described a simulation-based decision support system for production control of a stochastic flexible job shop manufacturing system. Wang and Yu (2010) proposed a filtered beam search based heuristic algorithm to solve the FJSP with machine availability constraint considerations. Lei (2010) presented an FJSP with fuzzy processing time and proposed a decomposition-integration genetic algorithm (DIGA) to minimize the maximum fuzzy completion time. Moradi et al. (2011) investigated an integrated FJSP with preventive maintenance activities under the multi-objective optimization approaches. Al-Hinai and ElMekkawy (2011) studied the FJSP with random machine breakdowns using a two-stage hybrid genetic algorithm. In their paper, robustness and stability of a schedule were investigated with a bi-objective approach, and three stability measures were suggested.

Because of its practical importance, robust scheduling is widely used in other scheduling problems, such as production planning (Daniels and Kouvelis, 1995; Aytug et al., 2005) and project scheduling (Herroelen and Leus, 2005). Most literatures regarding robust project scheduling are focused on resource-constrained project scheduling. Al-Fawzan and Haouari (2005) proposed a robustness measure of a given schedule that is based on the total amount of free slack for all activities. Kobylański and Kuchta (2007) proved the deficiencies of the robustness measure in Al-Fawzan and Haouari (2005) and modified this measure to be the minimum of all the free slack or the minimum of the ratios of free slack/duration. Chtourou and Haouari (2008) followed the approach of Al-Fawzan and Haouari (2005) but assigned weights to the free slack of an activity, considering the number of its successors and/or the sum of its required resources. In their work, 12 surrogate robustness measures based on free slack were proposed and assessed. Lambrechts et al. (2008) measured the robustness with the weighted deviation between the planned and actual activity starting times during project execution and employed a free slack-based objective function in the tabu search procedure. Hazir et al. (2010) introduced surrogate measures to estimate the schedule robustness for a discrete time/cost trade-off problem. The surrogate measures were also based on slack, including weighted slack, slack utility function and dispersion of slack.

3. Problem formulation

3.1. Deterministic FJSP

FJSP is a generalization of the classic job-shop scheduling problem (JSP). Similar to the JSP, FJSP takes into account the assignment of each operation to a machine and sets its starting and ending times. However, the task is more challenging than the classic one because it requires a proper selection of a machine from a set of machines to process each operation. Then, the FJSP can be described as follows:

- There are n independent jobs that are indexed by i.
- There are m machines indexed by k.