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Integrated production scheduling and maintenance policy for robustness in a single machine

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ABSTRACT

This paper addresses the problem of finding robust production and maintenance schedules for a single machine with failure uncertainty. Both production and maintenance activities occupy the machine's capacity, while production depletes the machine's reliability and maintenance restores its reliability. Thus, we propose a proactive joint model which simultaneously determines the production scheduling and maintenance policy to optimize the robustness of schedules. Then, a three-Phase heuristic algorithm is devised to solve the mathematic model. Computational results indicate that the performance of solution can be significantly improved using our algorithm compared with the solutions by the traditional way. Furthermore, the balance of quality robustness and solution robustness and the impact of jobs' due dates are explored in detail.

1. Introduction

In the past decades, production scheduling has been an interesting topic to many researchers and practitioners. The majority of production scheduling literature assumes that machines are available for processing jobs at all times during the planning horizon. However, in many realistic situations, machines may be unavailable during the scheduling horizon for different reasons, such as unexpected breakdowns and scheduled maintenances in typical industrial settings.

The production scheduling and maintenance activities interrelate with each other, since both of them have impacts on the machine's capacity and reliability: they both occupy the machine's capacity, while production depletes the machine's reliability and maintenance restores its reliability. With the development of traditional production scheduling and maintenance theories, many researchers begin to pay attention to the integration of production scheduling and maintenance in the near decades considering its practical significance. In the related literatures, two important research tracks can be identified in the field of integrated production scheduling and maintenance planning.

Some researchers focus on the capacity of machine. In these literatures, unavailability intervals and availability constraints are proposed in some of them, or the preventive maintenance (PM) is introduced in the others. The unavailability intervals can be envisaged as the PM activities in those papers, since both of them are the same in substantial. They consider that performing PMs consumes the run time of machine and reduces the capacity of machine. The machine failure is ignored in these papers. PMs as deterministic constraints are introduced into the production scheduling, which makes it a deterministic combinatorial optimization problem. And there are two types of PMs. (i) A given fixed period of PM. Comprehensive reviews about this type of PMs are provided in [1–4]. (ii) Flexible PMs that can be scheduled by the operator. In the field about this type of PMs, there are two kinds of assumptions about PM period. Some researchers assume that the machine must be maintained after it continuously works for a period of time and the maximum allowed continuous working time is T. This kind of model can be found in [5–12]. The other researchers assume that the PM must be executed in a predefined interval $[u, v]$ whose length is longer than the maintenance time t. This kind of model can be found in [13–16].

The other researchers focus on the reliability of machine. They consider that there are unexpected random breakdowns during the execution of the scheduling plan and the corrective maintenance (CM) is executed when the breakdown occurs. This uncertain element of machine makes it a stochastic optimization problem. In general, there are two methodologies to deal with the uncertainties in scheduling problems: proactive and reactive approaches. Incorporating the knowledge of uncertainty at the decision stage, proactive approaches focus on generating more robust predictive schedules to minimize the effects of disruptions. On the other hand, reactive scheduling algorithms are implemented at execution time to adjust the schedule according to the real-time situation when the uncertainty is realized or disruptions occur. The detailed introduction of these papers can be found in Aytug et al. [17], which reviews the literatures on executing production schedules in the presence of unforeseen disruptions on the shop floor.

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Besides, some other researchers study the integration of production scheduling and PMs for a single machine with failures. Cassady and Kutanoglu [18] propose an integrated model that simultaneously determines production scheduling and PMs for a single machine in terms of the total expected weighted tardiness of jobs. Then the model is extended by Sortrakul et al. [19], Pan et al. [20], Wang and Liu [21]. But, all these papers neglect the probability distribution of the breakdowns and do not consider the robustness of the system. They just use the expectation of breakdowns to replace the actual values in their models. From the viewpoint of the model and algorithm, it is actually a deterministic optimization problem, which is not reasonable considering the problem's stochastic attribute.

To the best of our knowledge, the papers considering both production scheduling and PM do not consider the breakdowns which affect the stability of machine. Besides, although some proactive scheduling approaches assume random breakdowns, they do not use the reliability information of machine. None of them coordinates the production scheduling and the entire maintenance policy to provide an integrated decision system for the operators. The purpose of this paper is to establish a joint model for a single machine with stochastic failure uncertainty to integrate the production scheduling and maintenance policy containing PMs and CM reactions, and to optimize the bi-objective of quality robustness and solution robustness simultaneously.

The remainder of this paper is organized as follows. The problem definition and the proactive joint model are described in Section 2. In Section 3, a three-Phase heuristic is proposed to solve the model. Section 4 details two different methods to insert the buffer times at the second phase of the algorithm. Computational experiments are then given in Section 5 to demonstrate the effectiveness of these algorithms, followed by the conclusions and discussions on future research in Section 6.

2. Problem definition

The following notations are used throughout this study:
Model parameters:

t_r: time required to repair the machine.
t_p: time required to perform PM on the machine.
θ: the scale parameter of the Weibull probability distribution.
β: the shape parameter of the Weibull probability distribution.

Decision variables:

x_{ij}: the jobs' sequence decision variable; if job j is processed in the i^{th} position, $x_{ij}=1$; otherwise, $x_{ij}=0$.
$y_{[i]}$: PM decision variable; if PM is performed immediately prior to the i^{th} job, $y_{[i]}=1$; otherwise, $y_{[i]}=0$.
$buffer_{[i]}$: the size of the buffer time inserted immediately before the i^{th} job; obviously, $buffer_{[1]}=0$.

Auxiliary variables:

$p_{[i]}$: processing time of the i^{th} job.
$d_{[i]}$: due date time of the i^{th} job.
$s^0_{[i]}$: the planned start time of the i^{th} job.
$s^r_{[i],\omega}$: the actual start time of the i^{th} job in the actual scenario ω.
$C^r_{[i],\omega}$: the actual finish time of the i^{th} job in the actual scenario ω.

2.1. The problem description

A set of jobs $J=\{j_1,j_2\ldots j_n\}$ with deterministic processing times p_i and due date times d_i $(i\in J)$ is to be scheduled in a single machine. All jobs are available at time zero and no preemption is allowed. Suppose the machine used to process the jobs is subject to failure, and the time to failure for the machine is run-based and governed by a Weibull probability distribution, where the failure rate is proportional to a power of time. Since the distribution was described in detail by Waloddi Weibull in 1951, it has been widely used in Reliability hazard analysis, Failure mode and effects analysis.

Obviously, it is practical to perform PM on the machine during production horizon in order to reduce the risk of unexpected machine failures. We assume that PM restores the machine to the “as good as new” condition, i.e., the machine's age becomes zero. Since the unexpected machine failure can't be eliminated by PM, reactions should be taken once the machine fails. Minimal repair policy is adopted, i.e., the machine is restored to an operating condition, but the machine's age is not changed. And the jobs are resumable, i.e., the job interrupted by machine failure can be resumed after repair without any additional time penalty.

Let $j_{[i]}$ be the job processed in the i^{th} position. $b_{[i]}$ denotes the machine's age immediately prior to $j_{[i]}$ and $a_{[i]}$ denotes the machine's age immediately after $j_{[i]}$. Since the failure function is subject to Weibull probability distribution, the following conclusions about the information of machine breakdowns can be obtained from Ebeling [22]. Let $\xi_{[i]}$ be a discrete random variable which describes the number of breakdowns when processing $j_{[i]}$. Then, $\xi_{[i]}$ is governed by a Poisson probability distribution with λ, i.e., $\Pr(\xi_{[i]}=k)=\lambda^k e^{-\lambda}/k!$, where $\lambda=(a_{[i]}/\theta)^\beta-(b_{[i]}/\theta)^\beta$. Whenever a random breakdown occurs, the original plan is interrupted, since an additional amount of time will be occupied for the corrective maintenance. As a result, some reactive decisions have to be made, which makes the entire problem a multistage stochastic programming problem. At the first stage, we need to determine the initial schedule including the jobs' start times and positions of PMs. Then, when the machine fails, the right-shifting rescheduling policy is adopted as follows. The jobs' sequence and positions of PMs cannot be changed, the queuing jobs are postponed for a sufficient amount of time to just accommodate the repair duration, and jobs cannot be started before its planned start time. This rescheduling policy is quite reasonable in practices since the initial schedule serves as a basis for planning external activities such as tools change and material procurement.

In the scheduling literature, the performance of a schedule is usually measured by regular measures, such as makespan, the total flow time, the total tardiness, etc. But, the schedule robustness is subscribed by many experienced schedulers when the uncertainties are considered. Herroelen and Leus [23] divide schedule robustness into two groups: solution robustness and quality robustness. They define solution robustness as the insensitivity of the activity start times to variations in the input data, and quality robustness as the insensitivity of schedule performance (such as project makespan or cost) with respect to disruptions. The baseline schedule is the starting point for communication and coordination with external entities in the company's inbound and outbound supply chain [24]. The schedule is the basis for planning external activities such as material procurement, tool changes and delivery of orders to customers, etc. Schedule modification may increase the line-side inventory cost or render infeasibility of the external activities. Thus, the solution robustness is more and more important nowadays, especially for the JIT production system. A predictive schedule σ^0 is generated at the beginning of the planning horizon. σ^0 is executed on the shop floor and revised using the rescheduling policy when breakdown occurs. At the end of the planning horizon, we have a actual schedule $\sigma^r(\omega)$. For the solution robustness, the measure of $\sum_{i=1}^{n}(s^r_{[i],\omega}-s^0_{[i]})$ is selected to minimize the total deviation between the jobs' start time of actual schedule and that of the initial schedule. For the quality robustness, the performance measure of