Industrial Rescheduling Approaches: Where Are We and What is Missing?

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Abstract. Scheduling is a very complex decision-making activity that takes place on a routine basis in industrial environments. Intrinsically uncertain parameters and unexpected events force schedulers to update agendas over time, making this activity even more difficult. Despite recent advances, the deployment of scheduling solutions in industry is still preliminary and has many open demands, especially those regarding rescheduling capabilities. In order to take full advantage of the Industry 4.0 paradigm progress has to be made on several dimensions. This contribution examines rescheduling proposals pertaining to the discrete manufacturing domain and points out their main weaknesses. In addition, it stresses some of the requirements that a rescheduling framework must fulfill to be applicable in industry within the context of digital transformation.

Keywords: Industrial rescheduling · Disruptive events · Industry 4.0

1 Introduction

Predictive industrial scheduling addresses the generation of agendas by supposing that all the manufacturing orders and resources are given and there is no uncertainty in their behavior. Experience demonstrates that there are (i) intrinsically uncertain parameters, like processing times and costs, setup/changeover times, etc., and (ii) unforeseen events, such as machine breakdowns, rush orders, order cancellations/modifications, lack of personnel, late arrival of raw materials, etc. In fact, industrial environments are part of a globalized and competitive economy that needs to tackle volatile markets, sharp fluctuations in fuel pricing, and that is strongly affected by the perturbations of the COVID pandemic, wars, and extreme climatic incidents. This situation raises important challenges to the scheduling function, calling for proficient rescheduling abilities. On the other hand, the tremendous advances in a variety of digital know-hows, led to advanced manufacturing technologies, such Smart Manufacturing and Industry 4.0. If such technologies are properly adopted and articulated, they can pump up current reactive scheduling capabilities. Therefore, in the current context, the rescheduling domain faces both tremendous difficulties and enormous opportunities.

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Despite the great interest of the field, an analysis of the open literature reveals that (i) contributions only address certain problem elements, leaving aside some important ones, and (ii) scheduling and rescheduling are not envisioned as critical parts of a digitalized industrial environment yet. This work deals with these challenges by making a critical analysis of the academic literature, which is focused on discrete manufacturing environments. The analysis tackles the many dimensions of the problem, which are previously examined and organized (Sect. 2). This contribution also points out the dichotomy that exists between the industrial and academic worlds. Conclusions are drawn, pointing out some of the requirements that a scheduling decision support system needs to satisfy to take full advantage of the Industry 4.0 paradigm.

2 Conceptual Elements of the Rescheduling Problem

The rescheduling problem is a very complex one, demanding a variety of aspects to be taken into account. Its treatment also depends on the type of industrial process (continuous, batch, discrete manufacturing). This work addresses it for discrete manufacturing environments. On the other hand, the scope of the existing rescheduling approaches varies greatly and there is no standard classification scheme. According to Vieira et al. [1], rescheduling strategies, policies, and methods, need to be addressed.

2.1 Rescheduling Strategies, Policies and Methods

A *rescheduling strategy* describes whether or not production schedules are generated [1]. The two most common strategies are: (i) *dynamic*, the one that never generates a schedule and mainly adopts dispatching rules, and (i) *predictive-reactive*, the one that relies on an initial schedule that it is updated when a specific event is triggered or a time period has elapsed. In this contribution the second strategy is addressed.

Since revisions are inherent to the predictive-reactive strategy, this approach requires a *rescheduling policy* to specify when and how rescheduling is executed. The policy may also prescribe the events that would trigger revisions. Four policies have been recognized in the literature: (i) *event-driven*, which activates the schedule revision when specific events occur; (ii) *periodic*, which adjusts the agenda every τ time units; (iii) *hybrid*, which combines the first two policies; and (iv) *enhanced,* which is an evolution of the hybrid one [2].

The *event driven policy* is by far the most commonly adopted. It is based on the possibility of recognizing events that would trigger a rescheduling process in case of taking place. Some of these events are: due date changes, machine breakdowns, arrival of urgent jobs, job cancelations, serious deviations on processing times, material quality problems, lack of resources/personnel, etc. Since disruptive events can happen at any time and their probability of occurrence is independent of the previous events, this approach may cause shop floor instability if every identified event triggers a revision, regardless of its severity.

The *periodic policy* is also widely used. It has the advantage of attempting to preserve the stability of the agenda and minimizing the shop floor nervousness. However, if a serious disruption occurs in between two consecutive rescheduling points, T−1 and T, the scheduler does not have the opportunity to react until T is reached. The longer the time period τ, the more serious the problem, especially if the event takes place right after $T-1$. Moreover, the literature does not tackle the rationale behind the assignment of a proper value to τ and neither provides a systematic approach to update this value according the way the schedule is materialized.

The *hybrid policy* considers both triggering events and predefined time points where revision is conducted. It can be seen as an evolution of the periodic policy because an agenda adjustment will be triggered if a disruption happens in between the planned revision points. In comparison with the first two policies, the hybrid one may lead to many more revisions if all disruptions turn into triggering events, thus causing instability on the shop floor. One of the drawbacks of this approach is its lack of memory, which can be illustrated by the following situation. Let's suppose that an unforeseen event takes place at time $T-\varepsilon$ (with ε being a very short amount of time and T a planned revision point). This event will lead to a revision, but at time T another schedule modification will take place, despite the fact that probably nothing has changed on the shop floor. Finally, the *enhanced policy* is an improvement of the hybrid one. Under this approach, every time a rescheduling action is triggered (for whatever reason), the time points associated with periodic revisions are updated. Then, rescheduling is performed when: (i) an unexpected event is detected, or (ii) the elapsed time since the last revision is equal to τ.

Regarding *rescheduling methods*, they are procedures for generating and repairing schedules. They span from partial or local repair techniques to complete regeneration methodologies.

Due to lack of space, a more detailed analysis of other relevant problem aspects cannot be included and can be found in the most important reviews of the field [1, 3, 4]. Among them, it is worth remarking the elements that characterize uncertainties in terms of the following four dimensions: *Cause*, *Context*, *Impact* and *Inclusion* [4]. Despite their significance, the *context* – the environmental situation at the time when something happens – and the *impact* associated with the unforeseen events have been left aside by most of the proposals. In fact, for a given type of disruptive event in a certain job-shop, the reaction should not be always the same. For instance, a machine breakdown needs to be treated differently when it occurs at the beginning of the planning horizon than when it occurs at the end. Very few contributions have focused on these issues and more work needs to be done.

2.2 Performance Measures

A literature analysis reveals that two types of performance measures have been mainly adopted for the rescheduling problem. One is associated with schedule efficiency and the other one with its stability. Regarding efficiency, the most common metrics are makespan and different measures of tardiness. On the other hand, rescheduling policies that yield fewer and less aggressive revisions improve stability and reduce shop floor nervousness. With respect to stability quantification, some of the adopted measures are: (i) the number of times rescheduling takes place in a given period [5]; (ii) deviations of the task start/completion times between the original and revised schedule; (iii) difference of job/task sequences between the two schedules, etc. In the context of flexible shops, it is not only important to account for changes in the sequence of operations, but also to consider modifications in the assignment of tasks to machines. This aspect is missing in most of the rescheduling proposals devoted to flexible job shops.

Another relevant issue, which is generally omitted, is the fact that the impact of changes increases as they are made closer to the current time. This notion has been captured by defining the *actuality* of the modifications caused by a disruption [6]. It has been specified as a penalty function associated with the deviation of the start time of a job with respect to the current time. It makes evident that a change having an impact in the next hour is not as critical as another one that will take place in 10 min.

When revising a schedule, it is important to consider both efficiency and stability under a multiobjective approach. These two metrics can be combined *a priori* in a single utility function by means of weights [7] or with other methods, e.g. lexicographic or goal programming. They can also be addressed in *a posteriori* fashion by means of approaches that generate all the Pareto optimal solutions or a representative subset of them, such as the ε-constraint method, or some evolutionary algorithms. This second group is better for decision making purposes, but is highly demanding from a computational perspective. Approaches belonging to this group are almost incompatible with the fast response that is required by rescheduling problems. On the other hand, the first group is less demanding but needs information associated with weights or the relative importance of the objectives, which is not easy to establish prior to reaching any solution. In addition, any proposal would require the metrics to be normalized in order to be properly treated, which in turn needs to know the possible range of values of each objective function.

Finally, it is necessary to stress that despite the strong link that exists between the adopted rescheduling strategy and the chosen performance measures, these two aspects have been addressed almost independently, which is clearly incorrect.

3 Literature Analysis

Table 1 summarizes the main characteristics of the problem that were taken in account by the contributions that have been thoroughly examined. All of them have adopted a predictive-reactive strategy, like most of the articles in the academic literature. However, none of them has addressed in a formal way how the predictive and reactive solution approaches relate to each other.

In terms of the chosen policy, there is a mix of event-driven and periodic, being the former the most common one. The solution methodologies that follow an event-driven approach [8–13], have adopted an overly simplified vision of the problem. Most proposals omit the consideration of the *context* and *impact* associated with the unforeseen events. Therefore, the implicit assumption is that all the disruptions of the same type occur under the same circumstances and have identical consequences on the schedule, which is certainly not true in practice. Another strong supposition of all event-driven approaches is the fact that they assume that disturbing events are properly identified and correctly informed in real time. However, this is not generally the case in the industrial practice. The same happens with the status of the active schedule at the rescheduling point. If this information is taken into account, which is not always the case, it is presumed to be available online, in a format that can be directly fed into the solution methodology. These strong hypotheses, which are far away from reality, derive from the implicit supposition of interoperability between the scheduling tool and the IT and OT applications that host the relevant data required to solve the scheduling problems. Academic contributions omit any systems' interplay aspects, taking them for granted. As pointed out by Harjunkoski [14], this interplay does not occur in industry in full fashion yet. In addition to the complications of having different time scales and information granularities, there are serious problems associated with the different domain representations that are employed, which in many cases do not interoperate [15].

Another common simplifying assumption of the event-driven approaches [8–13] is that only one disruptive event occurs at a time, which is not always the case. Even if this takes place, it is possible that other minor changes might have affected the active agenda (e.g., small variations in the machine processing and setup times) and need to be considered when revising the ongoing schedule. This issue calls for updated and continuous production progress data that can be seamlessly fed to the scheduling system. In addition, it calls the attention the lack of consideration of stochastic processing times (See Table 1) by the academic proposals.

Regarding the adoption of the periodic policy, three different length periods were experienced by [7]. This work performed an ANOVA test to study how τ affects the efficiency and the stability measures; however, no clues on why the 100, 200 and 300 time units have been chosen.

With respect to the performance measures, Table 1 shows that the adopted metrics cover efficiency – makespan, tardiness – and stability – starting time and/or completion time deviations, actuality –, as well as a combination of them in some cases. Usually these metrics are combined by means of a series of factors. However, the proposals do not explain how the values of these weighing factors are adopted.

4 Conclusions

Within the realm of scheduling approaches, the academic proposals that attempt to address rescheduling are ones of the less mature, preventing their adoption by industry. There are a variety of reasons for this gap, which have been pointed out in previous sections. Apart from these elements, in order to be well accepted by industry, any reactive scheduling methodology needs to provide timely responses. Many contributions do not supply enough information regarding their computational load. Some others do, but leave aside all the work needed to prepare the necessary models and to select the proper parameter values. Academic models, which are not standard ones and are context dependent, are manually built and tuned. This approach is not accepted in industry due to a variety of reasons: lack of personnel with skills in mathematical programming, need to have solutions in short times, etc. Hence, the automatic development of rescheduling models is another requirement to be addressed. Finally, most solution approaches lack an explicit representation of the schedule [16] that would be of great help in the Industry 4.0 context. Having a domain model would allow implementing explicit reasoning procedures in order to: (i) compare the planned schedule with what actually has happened at the shop floor, (ii) analyze context and impact of disruptive events on the active agenda, (iii) automatically setup the models to be solved, (iv) enable scheduler-system interactions by means of high-quality graphical user interfaces, etc.

Table 1. Characteristics of the problem that have been addressed by the solution approaches

	Environment			Rescheduling Strategy		Rescheduling Policy			Schedule Repair		Disruptions			Performance Measures				
	Job Shop	Flow Shop	Flexible Shop	Dynamic	Predictive-Reactive	Periodic	Event Driven	Hybrid	Partial	Complete	Machine Breakdown	Stochastic Processing Time	Urgent Orders Arrival	Makespan	Tardiness	Starting Time Deviation	Actuality	Sequence Deviation
Abumaizar & Svetska, 1997 [8]	x				x		x			x	x			x		x		x
Dong &Jang, 2012 [9]	x				x		x			x	x			x	x	x		
Fattahi &Fallahi, 2010 [10]	x		x		x		x			x				x		x	x	
Jensen, 2001 [11]	x				x		x				x				x			
Rahmani & Ramezanian, 2016 [12]		x	x		x		x			x			x		x	x		
Rangsaritratsamee et al., 2004 [7]	x				x	x				x				x	x	x		
Suwa, 2007 [2]		x			x			x		x			x					
Shen & Yao, 2015 [13]	x		x		x		x			x	x		x	x	x	x	x	

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