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Dealing with disruptions in low-volume manufacturing: a constraint programming approach

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Unexpected events can compromise the execution of the production schedule in low-volume assembly lines. When a disruption occurs because of a delayed part supply, a quality problem or an operator absence, a reactive scheduling approach should be used in a short time in order to prevent significant deviations in final performances. In this study, we propose a new approach based on constraint programming to deal with disruptions. It is tested on a large dataset of problem instances and the obtained results are discussed.

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Keywords: low-volume manufacturing; rescheduling; constraint programming**1. Introduction**

The context of current economic development characterized by fierce global competition in manufacturing brings a lot of uncertainty to the shop floor. In particular, in low-volume manufacturing, the baseline schedules are frequently disrupted by supply delays, quality problems, and resource unavailability. If unlimited resources were available, the uncertainty would be easy to address. However, in practice the resources are limited and the consequences of a delayed product delivery may be huge especially in low-volume manufacturing of high-value products (aircraft, ships, etc). Fig. 1 presents an example of low-volume aircraft manufacturing.

When the capacity of resources are to be taken into account for scheduling the manufacturing tasks, the Operations Research literature refers to the corresponding optimization problem as the Resources Constrained Project Scheduling Problem (RCPSp). This problem is known to be NP-hard in the strong sense [1].

Since it is not possible to create policies and procedures for every eventuality that might occur, unexpected events inevitably happen and disrupt the initial plans requiring a time-pressured response. Taking too long to respond to the unforeseen can result in major losses or overruns.



Fig. 1. Assembly Line of Falcon 8X – (Courtesy of © Dassault Aviation - S. Randé).

In this paper, we focus on the development of a fast rescheduling decision support tool in order to schedule the repair actions and remaining manufacturing tasks in case of disruption. The paper is organized as follows: Section 2 reviews existing rescheduling approaches. Section 3 defines the optimization problem considered. Section 4 presents the developed planning approach. Section 5 analyses the results of a numerical experiment. Section 6 presents the conclusions and research perspectives.

2. Literature review

Unexpected events can create disruptions even if the initial schedule was considered robust since all possible problems might not be anticipated by a proactive approach. For this reason, it is also necessary to include reactive scheduling as the second protection mechanism to prevent significant deviations in performance caused by disruptions. Due to the digitalization of many processes, manufacturing data can be collected more easily in real time for many applications. The possibility of using this data in order to follow the baseline schedule offers a promising potential for the control of manufacturing process and for implementing reactive actions in a short time.

The response to a disruption must be fast because of the need to re-start manufacturing process as soon as possible [2]. A repair must also be complete in the sense of accounting for all changes that have occurred, while attempting to avoid the introduction of new changes. However, the rescheduling action may have two conflicting objectives either to minimize the number of changes in the baseline schedule or to completely re-optimize the new schedule at the cost of introducing more changes into the initial schedule. In the latter case, the problem to be solved is finally of the same type as the initial one but is smaller and with possibly different constraints because of the disruption. The former case however raises a different optimization problem, where the initial schedule is part of the input data to be taken into account at the rescheduling step.

In literature, few studies consider the rescheduling problem in case of a general disruption not related to the task processing time prolongation. Zhu et al. [3] studied three possible recovery options, namely rescheduling, mode alternation and resource alternation. They proposed a combination of MIP and CP as solution approach which consequently remain inapplicable for high-dimensional instances. Deblaere et al. [4] considered activity duration variability and resource disruption explicitly, and evaluated some dedicated exact reactive scheduling procedures, as well as a Tabu search heuristic for repairing a disrupted schedule. However, a very restrictive hypothesis was assumed that no activity could be started before its baseline starting time, reducing considerably the number of possible recovery actions. Chakraborty et al. [5] studied the dynamic features of resource inadequacy/unavailability for a general Multi Mode-RCPSp case. They considered selected sets of 10, 20 and 30-task instances from PSPLIB and introduced randomly generated disruption scenarios into them such as changes in activity duration, changes in precedence relationship, and addition of new activities. The study of Waleczik and

Mandziuk [6] formulates a generalized Stochastic Resource Constrained Project Scheduling Problem model encompassing arbitrary risks and risk response / mitigation strategies as an optimization problem and applying metaheuristics to build fully-automated decision making systems. However, their approach has a restrictive set of risks and repair actions and it has been only tested on the problem instances containing up to 100 tasks. A larger number of tasks will lead to exponentially increasing number of the states to be considered making the approach not applicable for high-dimensional projects.

The disruptions raise also the question about task interruptibility. The preempt-repeat and preempt-resume strategies can be used [7,8]. In the former case, interrupted tasks have to be restarted from the beginning, while in the latter case, only the residual portion of any interrupted task will be executed.

The analysis of the literature shows that the available approaches do not cover all the types of disruptions that occur in manufacturing environment. In the next section, we introduce formally the optimization problem considered in low-volume manufacturing context and treated in this study.

3. Problem formulation

We consider the context of low-volume manufacturing where the products to be finished pass through a paced line organized as a sequence of workstations. Since the line is paced, the time the product may spend at each workstation is limited by takt time [9]. Because of the low-volume context, a high number of tasks is to be performed at each workstation (up to several thousands) by an important team of operators (up to 40) having different skills [10-12]. A disruption may compromise the respect of the takt time and lead to a full stoppage of the line and consequently to a delay in delivery of final products related to financial penalties. Usually, in order to avoid the line stoppage, the product is transferred to the next workstation with some unfinished work. This solution generates supplementary work to be completed at the next workstation in addition to already planned tasks for the same duration of the takt time. Not only extra working hours and operators are needed in this case, but also the realization of this unfinished work has to respect the precedence and compatibility constraints with the originally planned tasks.

The following disruptions have to be taken into account by rescheduling procedure in low-volume manufacturing context:

- Supply delay: it becomes not possible to start a task since the required supply has not been provided in time.
- Operator absence: a certain time is required in order to find a qualified worker capable of replacing the absent one.
- Quality problems: either a part is defective and cannot be used or a task has been fallen with eventually some damage to already realized tasks. Usually, a quality specialist has to decide what actions need to be performed in order to come back to the regular quality state.

When the tasks have to be rescheduled in order to take into account new constraints induced by the disruption, the objective of rescheduling depends on the impact of the disruption and on the risk of violating the takt time constraint. If the disruption is local, the objective may be to minimize the changes in the current schedule. On the opposite, if the disruption is significant, the main objective will be to respect the task time i.e. to complete all the tasks by the planned deadline even if the initial schedule has to be changed a lot. In some difficult cases, when the violation of the takt time is inevitable, the objective may be to optimize the content of work to be postponed to the next workstation, i.e. to minimize the tardiness of some tasks to be preferably completed at the current workstation.

In the following, we present a mathematical model for this optimization problem with different objective functions.

3.1. Data

The following data is available for optimization:

Nomenclature

$i, j \in N$	set of tasks to be performed
d_i	duration of task i ,
t_i	start time of task i in the initial schedule,
$(p, s) \in P$	set of pairs of tasks related by a precedence constraint,
$s \in S$	set of skills required to perform tasks of set N ,
s_i	skill required for processing task i ,
$i, j \in N_s$	sets of tasks requiring skill s ,
$w \in W$	set of workers with one or multiple skills,
$s_w \subseteq S$	set of skills of worker w ,
$z \in Z$	set of manufacturing zones having capacity restrictions,
c_z	capacity of zone z ,
z_i	zone where task i has to be performed,
$i, j \in N_z$	sets of tasks to be performed in zone z ,
c_i	cost of tardiness of task i
f_i	decision variable defining the start time of task i in the final schedule,

3.2. Constraints

1. All given tasks have to be assigned respecting the demand in the number of workers and their skills.
2. The tasks cannot be interrupted and have to be performed by the same workers from the beginning to the end.
3. Each worker can perform one single task at time.
4. The *zone capacity* constraint: the number of workers present in each manufacturing zone and at each moment of time is limited.
5. *Precedence constraints* with time lags are defined by

a direct weighted graph $G(N, E)$ an edge e_{ji} with weight l_{ji} exists if for tasks $i, j \in N$ the following constraint has to be satisfied: $S_j + l_{ji} \leq S_i$, where S_j is the starting time of task j .

3.2. Objective function

As it was mentioned, the rescheduling objective may have different forms. In this study, we consider the cost of tardiness of specific tasks. Such tasks have to be performed in preference at the initial workstation for this reason if their completion time exceeds the takt time, a penalty cost c_i is applied. This cost can be different for each task i .

3.3. Disruption modelling

- Supply delay is modelled as a new task which has to precede the task waiting for the supply and whose duration is equal to the delay.
- Operator absence is modeled by modifying the resource availability.
- Quality problems are modelled by additional tasks to be scheduled and having precedence constraints to remaining tasks.

4. Solution approach

The optimization problem is modeled in terms of constraint programming with IBM CPLEX CP Optimizer. The following functions are used in the model, only the main functions are presented.

```
/*Objective: minimize tardiness cost*/
minimize sum( $i \in N$ )  $c_i * (\max(0, f_i - t_i))$ 
```

```
/* constraints*/
subject to {
```

```
/*zone capacity constraints*/
forall ( $z \in Z$ ) forall ( $i \in N_z$ ) zoneUsage[ $z$ ] <=  $c_z$ ;
```

```
/* precedence constraints*/
forall ( $(p, s) \in P$ ) endBeforeStart( $p, s$ );
```

```
/* one worker can only perform one task at a time*/
forall( $w \in W$ ) noOverlap(all( $i \in N$ ));
```

```
/* only one skill of each worker can be used at a time*/
forall( $i \in N$ ) forall( $w \in W$ ) forall( $s_w \subseteq S$ ) alternative( $s_w = 1$ );}
```

5. Numerical experiment

In this section, we present the results obtained for 3 datasets with 50, 100 and 200 tasks. Each dataset includes 250 problem instances having different density of precedence constraints (3, 4, 5, 6, 7) i.e. 50 instances for each density. Tables 1-3 presents the initial M_0 and rescheduled M_r makespans and the solution times (average, maximal and

minimal) for initial problem (T_0) and for rescheduling problem (T_r). The results were obtained with IBM CPLEX CP Optimizer.

Table 1. Solution times for instances with 50 tasks.

Prec	M_0	M_r	%	T_0 av	T_0 max	T_0 min	T_r av	T_r max	T_r min
3	136	140	3%	0.19	0.88	0.04	2.03	2.88	0.06
4	144	150	4%	0.92	20.11	0.03	5.93	25.44	0.06
5	162	164	1%	0.90	19.26	0.03	4.53	19.55	0.04
6	160	166	4%	0.96	23.12	0.03	4.06	21.87	0.06
7	175	182	4%	0.34	20.44	0.03	3.37	24.69	0.03

Table 2. Solution times for instances with 100 tasks.

Prec	M_0	M_r	%	T_0 av	T_0 max	T_0 min	T_r av	T_r max	T_r min
3	220	229	4%	3.07	32.51	0.12	13.5	38.2	0.16
4	260	272	5%	3.36	38.44	0.15	18.06	37.33	0.14
5	264	274	4%	3.88	36.31	0.15	21.26	42.89	0.27
6	258	269	4%	2.57	39.79	0.15	22	37.33	0.19
7	268	281	5%	1.1	34.8	0.17	22.21	36.03	0.23

Table 3. Solution times for instances with 200 tasks.

Prec	M_0	M_r	%	T_0 av	T_0 max	T_0 min	T_r av	T_r max	T_r min
3	413	453	10%	44.31	0.53	86.81	66.81	47.11	85.32
4	419	437	4%	41.23	0.57	87.86	67.41	3	97.18
5	406	430	6%	38.06	0.46	78.25	61.72	25.45	75.5
6	401	418	4%	35.14	0.45	80.34	64.71	5.53	88.46
7	418	437	5%	29.11	0.48	84.17	67.06	53.59	81.69

The obtained results show that the solution time increases only slightly for rescheduling problem and the instances up to 200 tasks can be solved with the proposed approach in reasonable time.

6. Conclusion

In this paper, we studied the unexpected events that may compromise the execution of the production schedule in low-volume assembly lines. In order to react to these disruptions, we developed a rescheduling algorithm based on constraint programming approach. The objective is to reschedule the remaining tasks and eventually some new ones representing repairing actions taking into account the new constraints of manufacturing environment brought by the disruption. The performances of the approach were evaluated in a numerical experiment. The obtained results show that the instances up to 200 tasks can be solved in reasonable time. Future research directions will include the consideration of cascade effect on the production line where the disruptions cannot be limited to one workstation and have to be considered for several workstations at the same time. Another important perspective is to integrate the rescheduling procedure in a complete planning method where proactive and reactive approaches are considered jointly.

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