A proactive-reactive approach to schedule an automotive assembly line

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1 Introduction and problem statement

The assembly of bodywork parts for the automotive sector is operated in dedicated assembly lines implementing the sequence of assembling operations through specific joining technologies (e.g., spot welding, clinching, hemming, etc.). These assembly lines are organized as a set of stations executing assembly operations, input/output stations to load components and unload final parts, and a transportation device moving parts within the line. The latter is usually a *7-axis* robot shared among the stations. In this paper we consider an assembly line where a batch of parts has to be processed. Assembly operations are executed by automatic devices while load/unload operations are executed manually. The line has a single transportation robot to be shared among the stations and the proposed approach aims at scheduling its missions. Due to the manual execution of load/unload operations, uncertain process times must be considered, thus, the problem under study is a *Stochastic Resource-Constrained Flow-Shop Scheduling Problem* to minimize the time needed to complete a batch of products, i.e., the makespan. In the need to address uncertainty, specific approaches must be adopted. Examples are the ones optimizing the expected value of the makespan (Fernandez 1995, Igelmund and Radermacher 1983). Nevertheless, the minimization of the expected value does not protect against rare but very extreme scenarios, as discussed in (Alfieri *et al.* 2012) and (Manzini and Urgo 2015) for *Make-to-Order* processes. To this aim, we propose a *proactive-reactive* approach providing a *baseline schedule* and looking for the optimal sequence of the robot considering the actual duration of operations during the execution of the assembly process. Differently from other approaches of this class, e.g., (Davari and Demeulemeester 2016), the proposed approach identifies *disjunctive constraints* without explicitly deciding the starting times of operations.

2 Solution approach

Consider an *Activity-on-Node* (AoN) representation of a flow-shop where $V = \{0, 1, ..., n\}$ is the set of nodes representing operations and $E = (i, j),\ i, j \in V$ the set of arcs modeling precedence constraints. Operation durations are modeled through general and independent random distributions $\tilde{\mathbf{p}} = \tilde{p}_0, \ldots, \tilde{p}_n,\ p_i$ being a realization of distribution $\tilde{p}_i$ and $\mathbf{p} = p_0, \ldots, p_n$ a realization of the entire set $\tilde{\mathbf{p}}$. Notice that, if an operation is deterministic, the described formulation still applies with a single value as support. The flow-shop under study has a limited availability of the transporter and hence we consider a single resource with unary availability. We address the scheduling of shared transporter's misisons through the decisions over a set of *disjunctive constraints* named E_{DC} (additional to the ones in E), resolving resource utilization conflicts.The uncertainty embedded in the problem is addressed by adopting a *proactive-reactive* approach made up of two steps. The first step provides the *baseline schedule* as the optimal sequence of the robot considering a given duration of the uncertain operations (e.g., a quantile can be used). The second one is supposed to operate while the *baseline schedule* is being operated, every time an incongruity between the fixed operation duration and the one experienced in the execution of the schedule occurs. It checks whether the *baseline schedule* is supposed to remain optimal and, if needed, reacts by inverting some of the *disjunctive constraints* previously selected. The two steps are described in detail in the following.

2.1 Proactive step

The *proactive* step hypothesizes that the duration of operations is fixed. In case of uncertain durations this value can be decided by fixing a quantile q obtaining $\mathbf{p^q} = p_0^q, \ldots, p_n^q$, without considering any anticipation of associated uncertainty. The scheduling problem is solved using the deterministic approach presented in (Demeulemeester and Herroelen 1992). The *baseline schedule* obtained provides the set of additional constraints E_{DC}. In addition to this, a sensitivity analysis on the solution is also executed. For each precedence constraint in E_{DC}, the range of variability of operation durations is calculated such that, if the durations go outside this range, then the decision taken for the considered *disjunctive constraint* is not optimal anymore, and thus the opposite constraint should be considered. Consider the constraint $(i, j) \in E_{DC}$ assuming durations $\mathbf{p^q}$, and the eligible times of operations i and j, $Q_i^{\mathbf{p^q}}$ and $Q_j^{\mathbf{p^q}}$, defined as the instants on which each operation can start in terms of all the precedence constraints in E, without considering any of those in E_{DC}. Define $\varDelta_{i,j}^{\mathbf{p^q}} = Q_i^{\mathbf{p^q}} - Q_j^{\mathbf{p^q}}$ as the difference between the eligible times of two operations linked with a *disjunctive constraint* (i, j). If the decision on this *disjunctive constraint* is optimal, the associated makespan is shorter than the one considering the opposite direction, i.e., $S_n^{(i,j)} \leq S_n^{(j,i)}$, where $S_n^{(i,j)}$ is the starting time of operation n, considering *disjunctive constraint* (i, j). Clearly, this depends on the duration of the operations in $\mathbf{p^q}$. The makespan takes advantage of an inversion of the *disjunctive constraint* if and only if the lateness of i, compared to $Q_i^{\mathbf{p^q}}$, is enough to cause a delay of the makespan that is longer than the delay caused by an inversion without any lateness of i. More formally, the inversion is effective if there is a difference between the eligible times that is greater than $\varDelta_{i,j}^T = \varDelta_{i,j}^{\mathbf{p^q}} - (S_n^{(i,j)} - S_n^{(j,i)})$. The threshold $\varDelta_{i,j}^T$ will be used in the *reactive* step for evaluating the optimality of the *disjunctive constraint* (i, j) during the process execution.

2.2 Reactive step

The *reactive* step considers a vector of realizations $\mathbf{p}$ for the durations of the operation and grounds on the definition of a state space $\varOmega$ modeling the execution of the operations in the flow-shop. The execution of the operations can be modeled through a sequence of states over time t, $\omega(\mathbf{p}, t) = (O, F, S, d_O) \in \varOmega$. Each state is fully described by the set of operations in execution O, their starting times S and their durations $d_O(i), \forall i \in O$, as well as the set of completed ones F. Algorithm 1 models the execution of operations starting from $t = 0$ with initial state $\omega(\mathbf{p}, 0) = (0, \emptyset, 0, 0)$ and finishes when all the operations are completed, i.e., $F = V$ (steps 1-2). Every time an operation is completed, the set F is updated (step 4) and, if there is an operation i that can start because all its predecessors are completed (step 6), it is put into execution and added to the set of ongoing operations O (step 11). On the contrary, if its execution is constrained by the completion of another operation k through a decision on one *disjunctive constraint* $(k, i) \in E_{DC}$ (step 7), then the algorithm checks whether (k, i) remains optimal in relation to the realizations in $\mathbf{p}$. This evaluation is done through the estimation of the probability that the actual difference between the eligible

Reactive-Procedure

1 $\omega(\mathbf{p}, 0) = (0, \emptyset, 0, 0)$
2 **While** $F \mathrel{!}= V$
3 $\quad t = t + 1$
4 $\quad$ **If** $d_O(i) - S(i) = p_i, \forall i \in O \rightarrow F = F + i$
5 $\quad$ **Else** $d_O(i) = d_O(i) + 1$
6 $\quad$ **If** $i \notin O, i \notin F$ and $j \in F, \forall j \in (j, i)$
7 $\quad\quad$ **If** $(k, i) \in E_{DC}$ and $\mathbb{P}(\Delta^{\mathbf{P}}_{k,i}(t) > \Delta^{T}_{k,i}) > T$
8 $\quad\quad\quad E_{DC} = E_{DC} - (k, i) + (i, k)$
9 $\quad\quad\quad O = O + i,\ S(i) = t$
10 $\quad$ **Else**
11 $\quad\quad O = O + i\ ,\ S(i) = t$

Algorithm 1: Reactive step algorithm.

Operation	Mode	Min	Max
I	6	5	29
T_1	13	–	–
A	10	–	–
T_2	9	–	–
O	5	4	21

Table 1: Operation duration in seconds.

times exceeds the threshold previously identified: $\mathbb{P}[\Delta^{\mathbf{P}}_{k,i}(t) > \Delta^{T}_{k,i}]$. If this probability exceeds a threshold T, the reaction is applied by inverting the constraint (k, i) (steps 8-9). The $\mathbb{P}[\Delta^{\mathbf{P}}_{k,i}(t) > \Delta^{T}_{k,i}]$ is estimated considering the duration of the operations in O preceding k and their distributions $\tilde{p}$. The probability that $\Delta^{\mathbf{P}}_{k,i}(t)$ is greater than $\Delta^{T}_{k,i}$ is equal to the probability that the difference between the finish time of the last preceding operation of k and the eligible time of i is greater than $\Delta^{T}_{k,i}$, conditioned on the ongoing durations in d_O. We are looking at the residual duration probability of the operations preceding k: $\mathbb{P}[\Delta^{\mathbf{P}}_{k,i}(t) > \Delta^{T}_{k,i}] = \mathbb{P}[max_{l \in prec(k)}(d_F(l)) - Q_i > \Delta^{T}_{k,i} \mid d_O(l)] = \mathbb{P}[max_{l \in prec(k)}(d_F(l) - d_O(l)) > \Delta^{T}_{k,i} - Q_i]$, where $prec(k)$ indicates an operation preceding k.

3 Application

The proposed approach is applied on a single product flow-shop assembling a hood bodywork. The execution of the process is modeled using the *AoN* representation in Figure 1. The process consists of five operations, the first and the last ones model the loading (I) and unloading (O) of the parts, executed manually. In the third operation (A), a reinforcement bar is added through a spot welding process, while the second and fourth operations are handling tasks (T_1 and T_2 respectively) operated by the *7-axis* robot moving the hood in the line. The two manual operations follow a triangular distribution, while the others are deterministic (Table 1). The triangular distributions consider an average execution duration as the *mode*, very close to the minimum value, and a worst-case duration as the maximum value, modeling the occurrence of a problem or a delay. The approach addresses the conflicts between transport operations in the production of a whole batch. These conflicts are depicted with dotted arcs in Figure 1 for a single transport of the first job, only (T_{21}), but are repeated for the whole batch. In addition, we set the threshold T to 0.5, but let the quantile q, used for fixing the duration in the *proactive* step, vary between 0.1 and 0.9. We evaluate the performances of the approach in terms of the *mean square error* compared to the minimum makespan solution obtained with complete knowledge of the durations of operations using 10000 runs. In addition, we estimate the approach's performances without the *reactive* step and compare the results. Aggregated performances for different lengths of the batch (from 5 to 50 jobs) are included in Table 2. Grounding on these results, the *proactive-reactive* approach always performs as good or better than the *proactive* schedule without reaction (*PR* and *P-only* in Table 2). Indeed, if the *reactive* step

		P-only			*PR*		
Quantile		0.1	0.5	0.9	0.1	0.5	0.9
	5	5.473	5.473	0.917	0.917	0.917	0.917
# jobs	10	4.963	4.963	0.980	0.980	0.980	0.980
	20	7.445	7.445	1.347	1.347	1.347	1.347
	50	8.456	8.456	1.865	1.865	1.865	1.865

Table 2: Aggregated results of the application.

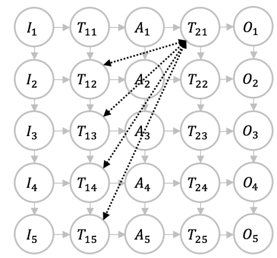

Fig. 1: *AoN* process representation.

does not apply any modification, the *baseline solution* is automatically applied, as depicted for the 5 jobs and 90*th* percentile case. The impact of the number of jobs and the percentile is also analyzed: the percentile impacts on results of the *only-P* approach, with better performances for high values. On the other hand, this parameter does not affect the reaction's performance due to the uncertainty source being limited to the first and last operations. The performances get worse as the number of jobs increases for both approaches. As a conclusion, the *proactive* approach provides a good *baseline schedule*, nevertheless, the *reaction* step improves the performances when used to manage the occurrence of unexpected events, providing a good support in the line's real-time management.

4 Conclusions

In this article we propose a *proactive-reactive* approach to schedule a semi-automatic assembly system, with a specific focus on the definition of the reaction policy. The approach has been tested on a five-operation process with good results, demonstrating that the application of the *reactive* step significantly improves the performances of the *baseline* one. Future developments will address the investigation of (i) completely manual processes or (ii) tuning the threshold for the reactive step to match user's aversion to risk and (iii) the application of additional *disjunctive constraints* modeling the schedule of machines besides handling operations.

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