Human-centered interactions for project scheduling decision-aid in space industry

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Introduction

As modern production environments tend to be increasingly complex and stressful for production process supervisors (Khademi K. 2016), providing interactive decision support tools (DSTs) is seen as a relevant way to help humans better organize and monitor operations, in the face of production uncertainties. This organization is mainly related to task planning and scheduling, which are very complex functions involving many decision variables, a lot of non-trivial time and resource constraints, and a highly combinatorial search space (Lopez P. and Roubellat F. 2013). Beyond the management of this complexity, DSTs must help supervisors to cope with the occurrence of the (numerous) hazards that appear during the execution of the production plan (quality defects, supply disruptions, delays, breakdowns, etc.). Indeed, the real-time management of hazards is a major source of cognitive and emotional load for a supervisor (Robin Morris GW. 2004) as it implies adapting the schedule by frequently scheduling and re-scheduling production tasks so that the production plan remains consistent with the new constraints (Mailliez M. *et. al.* 2021). This is usually done in a hurry, under pressure from the hierarchy, also taking into account the stress of the operators who undergo the changes on the production floor.

The development of efficient DSTs is a major issue in the production field, the "Human-Machine" performances having to be taken into account in a global way. In (Peissner U. and Parasuraman R. 2013), the authors highlight the potential of DSTs and describe the requirements they should met. In the field of air traffic control, it is shown in (Metzger U. and Parasuraman R. 2005) that DSTs can allow a reduction of the mental load and an increase in the performance of the resolution of air conflicts, provided that they are reliable and easy to use. Several authors, see e.g. (Trentesaux D., P. Millot 2016), have alarmed that most DSTs for production supervision suffer from technocentrism: when a hazard occurs, the algorithms propose (and sometimes even impose) a solution to the problems faced by the decision makers, assuming that supervisors will be able to implement perfectly the solution, whatever the situation, respecting the expected response times. Consideration of the actual needs and capabilities of supervisors in the DST development process thus seems to be a prerequisite for the development of usable, accepted and effective tools.

The results presented in this paper synthesize the findings of an ongoing multidisciplinary project taking interest in human-centered design of DSTs related to production supervision. This work was conducted in partnership with a major French company specialized in space technologies, which provided our case study. The activity of this company consists in assembling high-tech systems, each system being produced in a single unit. Interviews and observation campaigns with the supervisors of this company helped to understand the different decision-making processes and to extract the requirements that a DST should meet. Section 1 details the major requirements and specifies the key features that a DST should incorporate. Section 2 focuses on the decision aspects and the benefits that a constraint-programming (CP) approach could bring in the context of DSTs-supervisors interaction. Conclusions and future directions are drawn in the last Section.

1 Supervisor requirements and main DST features

The observed company is specialized in high-tech product assembly in space industry. Each system built is composed of hundreds of high-tech components that fit together and connect to each other. Each system is specifically designed for one customer. Its assembly generates thousands of activities, the quality of each of which must be carefully controlled (because the system cannot be maintained once in service). The assembly activities are all performed manually and we distinguish between several operator skills depending on the nature of the activity. The accessibility of a specific part of the system depends on both its physical orientation (pan/tilt) and the number of operators already working on it. The length of the project horizon commonly varies from 6 to 18 months. Expensive penalties have to be paid in case of tardiness. The schedule results from a cooperation between several supervisors, who play the roles of both project manager and chief-operator. Each one is in charge of the detailed schedule of a category of operators (e.g., mechanics, controllers, electricians) for each 8-hour shift, this schedule being dynamically changed to react to the numerous unpredictable events that occur during the process. There are also classical project managers having a long-term vision of the project portfolio, from both the delay and cost viewpoints. They allocate operators to projects along the time periods, according to the requirements of the supervisors, set-up milestones to be met, and manage the orders passed to the suppliers. Each category of project manager works with their own heterogeneous DSTs and (surprisingly) they are not numerically integrated together. Hence, the need for an integrated DST is strong so that the global consistency of the decisions can be checked easily all along the project. Project managers are more interested in finding one feasible solution than an optimal one. They clearly formulate the desire to keep the hand on the design of the schedule so that they can enforced decisions at any moment (e.g., to take non-modeled knowledge into account). The decision processes must therefore include humans in the loop and be consistent with their way of working. Hence, a DST should be kept focus on helping decision-makers to manage the problem complexity, quickly helping her/him to evaluate the consistency, the quality, and the consequences of her/his decisions. Autonomous decision making is only desired if the decision maker explicitly requests it (e.g., to automatically complete the construction of a schedule or to react quickly to unexpected disturbances).

Another major consequence of the human-in-the-loop requirement is to give support to help decision-makers in negotiating the constraints and finding a fair/efficient trade-off between their possibly conflicting objectives (Briand C. *et. al.* 2017). It should also support the whole project life cycle such that the various decision levels and horizons are integrated, which means that activity/resource/time decision variables can be disaggregated/aggregated into smaller/higher abstraction elements.

Another requirement is the management of disruptions that impact short-term scheduling decisions. DSTs obviously need to offer features that help supervisors to both prevent and react to disruptions. The trace and causes of the various decision changes should be saved so that decision-makers can explain to their hierarchy the path followed by the project and capitalize experience.

2 A CP-based approach

The wide variety of performance indicators, situations and decision-makers, as well as the multi-faceted nature of the production process, make the search for an optimal solution unnecessary. As mentioned before, the main objective is to provide decision makers with relevant information, presented in an understandable way, in order to facilitate the coordination and negotiation of decisions. The satisfiability of constraints is obviously a relevant property to be checked in real time. The ability to quickly compute good lower/upper bounds on well-targeted performance indicators is also of major interest to supervisors. In case of inconsistent constraints, providing explanations to decision makers and helping them to recover the desired satisfiability can also be of great help. Finally, the ability to quickly generate detailed feasible solutions is also useful.

The above features can be met in the constraint programming paradigm in which many researchers precisely focused for decades on designing algorithms able to efficiently prove constraint satisfiability, propagate time/resource constraints to refine variable domains, or provide minimal inconsistent constraint sets (see e.g. (Ceberio M. and Kreinovich V. 2014) for a survey). Constraint propagation solvers now even advantageously rival against best top-ranking MILP solvers to quickly find good-quality schedules. Eventually, distributed constraint satisfaction techniques (Fioretto, F. *et. al.* 2018) can be used to negotiate constraints among a set of decision makers. The remainder of this section discusses a CP model for our company's project planning environment, specifically addressing how work, and resources can be disaggregated, i.e., how constraints can be settled to link the disaggregated/aggregated decision variables all together. It shows how the specific *bin_packing* global constraint can be advantageously used. Such constraint links the placement of sized/weighted items into bins and the capacity of the bins (Régin, J.C. and Rezgui, M. 2011).

The time horizon is assumed to be modeled as a set of period T of identical length, each period being indexed from 1 to $|T|$ (a period corresponds to a shift in our case study). Cumulative resources, each of them representing a set of disjunctive resources, are distinguished. K^* refers to as the set of all the disjunctive resources (i.e., the set of all operators or system states in our case study). $\mathcal{K}$ is the set of all the possible subsets of resources (e.g., a subset represents a category of operators or a specific state of the system). A subset K in $\mathcal{K}$ can be modeled as a cumulative resource, Q_K being its capacity. The project is defined by a set of tasks J. We refer to $\mathcal{A}$ as the set of precedence constraints, i.e., $(j \prec j') \Leftrightarrow (j, j') \in \mathcal{A}$. Each task $j \in J$ can be decomposed into p_j subtasks of duration equals to one period. A task has to be allocated to a set of periods (Dom_j is the index of periods where subtasks of j can be carried out) and a *set* of cumulative resources $\mathcal{K}_j \in \mathcal{K}$. Furthermore, each subtask of j must be assigned to a disjunctive resource belonging to K, for each $K \in \mathcal{K}_j$ and to a specific period of Dom_j.

The decision variable $x_{j,i}$ models the index of the period assigned to subtask i of task j ($j \in J$, $i \in [1, \ldots, p_j]$). The domain $Dom(x_{j,i})$ of $x_{j,i}$ is initialized to Dom_j. The value of variable $y_{k,t}$ is t ($t \in T$) if resource k ($k \in K^*$) is made available at period t, else 0 ($Dom(y_{k,t}) = \{0, t\}$). $w_{K,t}$ is the intensity of set of resources $K \in \mathcal{K}$) required at period t ($Dom(w_{K,t}) = [0, \ldots, Q_K]$). $w'_{K,t}$ is the capacity of resource K made available at period t ($Dom(w'_{K,t}) = [0, \ldots, Q_K]$). A dummy variable $w'_{K,0}$ is defined for unused resource units in order to keep the available capacity and the assigned capacity balanced for each K.

For all $K \in \mathcal{K}$, X^K is the array of all variables $x_{j,i}$ with $j \in J$, $K \in \mathcal{K}_j$, $i \in [1, \ldots, p_j]$. For all $K \in \mathcal{K}$, Y^K is the array of all variables $y_{k,t}$ with $k \in K, t \in T$. Finally, for all $K \in \mathcal{K}$, W_K (resp. W'_K) is the array of all variables $w_{K,t}$ (resp. $w'_{K,t}$), such t is in $\{0\} \cup T$. The CP model is presented below. Constraints (1) guarantee that two subtasks belonging to the same task are not executed in the same period. Constraints (2) model the precedence constraints. Bin-packing constraints (3) models the link between x and w variables: x are the items to be assigned to bins w, where each w is associated with a set of resources and a specific period. Similarly, the link between y and w' variables is modeled by bin-packing constraints (4) : y are the items to be assigned to bins w', where each item $y_{k,t}$ with $k \in K$ has to be assigned either to bin $w'_{K,0}$ or $w'_{K,t}$. Constraints (5) ensure that, for each period, the number of assigned resources is higher than the resource consumption. All the above constraints are available in modern CP solvers with their specific propagators, which can be used together with the other solver features to check consistency, explain inconsistency, and find efficient bounds.

$$x_{j,i} < x_{j,i+1} \qquad \forall j \in J,\ \forall i \in [1, \ldots, p_j - 1] \tag{1}$$

$$x_{j,p_j} < x_{j',1} \qquad \forall (j, j') \in \mathcal{A} \tag{2}$$

$$bin\_packing(W_K, X_K) \qquad \forall K \in \mathcal{K} \tag{3}$$

$$bin\_packing(W'_K, Y_K) \qquad \forall K \in \mathcal{K} \tag{4}$$

$$w_{K,t} \leq w'_{K,t} \qquad \forall K \in \mathcal{K},\ \forall t \in T \tag{5}$$

In the state of this work, a first high-fidelity prototype has been developed, using this model and addressing some requirements presented above. The resolution, constraints propagation and constraint inconsistency features of CP solver are included in an interaction with the decision maker. The goal of this interaction is to help him to build and refine a planning corresponding to his preferences in an efficient way.

Conclusion and perspectives

The major features that a DST should include in the context of project scheduling in space industry have been presented. A preliminary CP model has been provided in order to support the various human-in-the-loop decision processes. It integrates resource and task aggregation and will be updated soon to also deal with time abstraction. Concerning the interaction scenarios, the various way of using the algorithms that check consistency on this model, provide lower/upper bounds on performance indicators or recover consistency are currently under study. They will be implemented to assess the real usability, acceptability and efficiency of the proposed approach. Future research works will address the multi-agent nature of the decision problems, as well as the negotiation mechanisms they involved.

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