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► **To cite this version:**

Zakaria Yahouni, Nasser Mebarki. A new HMI scheduling model implemented on a real manufacturing scheduling system. 7th workshop on Service-Oriented in Holonic and Multi agent manufacturing (SOHOMA'2017) , Oct 2017, nantes, France. 10.1007/978-3-319-73751-5_25 . hal-01710260

HAL Id: hal-01710260

<https://hal.science/hal-01710260v1>

Submitted on 15 Feb 2018

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A new HMI scheduling model implemented on a real manufacturing scheduling system

Zakaria YAHOUNI and Nasser MEBARKI

Abstract Manufacturing scheduling systems operate in a highly dynamic environment where several perturbations occur during the execution of a schedule. These perturbations prevent the execution of the planned schedule exactly as it was supposed to. To cope with this drawback, some techniques propose several scheduling solutions instead of a unique one, allowing during the execution phase to select the appropriate schedule that hedges against the perturbations. This selection is effectively done by a human operator who plays a key role in decision-making because of his knowledge and expertise. But, because of the limited complexity that he can handle, he needs to cooperate with the machine to take efficient decisions. In this context, the Human-Machine-Interface (HMI) literature research in planning and scheduling is rather theoretical. This paper addresses this relation from a practical-oriented perspective by proposing a new HMI model adapted to the *groups of permutable jobs* method, which is one of the most used literature methods to cope with shop perturbations. A practical experiment using the proposed HMI is then conducted. The results stress the usability and the limits of the proposed model.

1 Introduction

In an industrial production context, planning designates generally the *offline production phase*, where tools such as Gantt chart are used to model and plan the production activities. Whereas scheduling generally refers to the *online produc-*

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tion phase where production activities are executed in real-time on the available resources based on the offline planned schedule [3].

During the online phase, a simple perturbation such as *machine breakdown*, prevents the execution of the offline schedule exactly as it was planned and therefore deteriorates its expected performances. To cope with this drawback, several techniques seek to incorporate models of disturbances into the offline schedule in order to absorb shop uncertainties [13, 16]. These techniques usually construct a flexible offline schedule that encapsulates a family of schedules instead of a unique one, such that during the online phase, the schedule that copes appropriately with the current perturbation is selected in real-time. This selection is usually done either using a reactive-scheduling-algorithm policy or by a decision-maker: *human operator* who is more capable for adapting to the shop volatility [11].

In this context, the human appears to be crucial for taking the large set of scheduling constraints into account and adapting to changes [2, 10], but a human operator is limited by the complexity of large calculations that are usually handled easily by machine algorithms. Therefore, a human-machine cooperation is critical for the scheduling decision process.

To our knowledge, most of the literature work on human-machine cooperation in manufacturing scheduling are rather theoretical. In this paper, we investigate this cooperation from a practical-oriented perspective by conducting a case study using a real manufacturing system. The proposed contribution consists of a new HMI that identifies the relation and control between the human and the machine.

The proposed HMI is driven by a *decision support system* (DSS) that incorporates three decision-aid criteria. This DSS should favor the activity of the operator and therefore the scheduling performance.

In section 2, a literature review on the human-machine cooperation in scheduling is given. Section 3 is devoted to the proposed HMI and its application to the groups of permutable jobs. Then, a case study is presented in section 4. This section contains also the experimental protocol and results concerning the usability of the proposed HMI. Final conclusions are summarized in the last section.

2 Literature review

The human intervention in planning and scheduling has been a conflicted issue between operation research researchers and artificial intelligence researchers since the fifties. Observations of the human decision behavior in scheduling were first formulated by [2]. Artificial intelligent researchers claim that such behavior is algorithmic and can be replaced by an expert system [5, 6]. However, the work of decision-support researchers revealed that the human decision behavior is non-algorithmic and differs somewhat from rational theories; because of certain factors that occur in real-time and can not be taken in advance by an algorithm [7, 10, 20].

In this context, various studies have been made on the basis of observation analyses of the human behavior [10, 15]. These studies had the aim of investigating the

factors affecting the human behavior in a real scheduling environment. Three main factors were identified:

- Factors related to the human natural brain, including the social environment, biological formation, cognitive, psychological mindset and intuitive judgment.
- Organizational factors such as the organization and management of the different activities interfering with its primary scheduling activity.
- Technological factors such as interfaces and software used during the decision-making scheduling process.

The work presented in this paper focuses on the technological factors affecting the human scheduling decisions. In this context, some preliminary questions about the organizational context need to be addressed. These questions focus primarily on the amount of scheduling control and role given to each entity: the human and the machine. The work of [21] characterizes various control levels:

- Manual control: all the decisions are made by the human and the machine has no control at all.
- Advisory control: all the decisions are made by the human, but the machine checks the feasibility of each decision.
- Interactive control: the decisions are shared between the human and the machine.
- Supervisory control: in this mode, the machine is playing the role of a supervisory control for taking decisions, but the human validates them.
- Automatic or algorithmic control: contrarily to the manual control, all the decisions are made by the machine algorithms which replace the human.

These control modes allow determining the decision task of the two entities: the human and the machine. In a manufacturing context, the aim is not to exclude any entity such as in manual and automatic control, but to exploit the cooperation between the human thinking and the machine high computation complexity in order to achieve maximum scheduling efficiency.

The identification of the control mode leads to the definition of the HMI. However, designing an HMI model can follow general theoretical principles based on theories of cognitive processing, ergonomics and technological interfaces [23, 8, 9, 19, 23]. The work of [23] addresses the human decision process for the time-table problematic. The authors stress the lack of ergonomic and ecological HMI software in order to take advantage of the human-machine cooperation.

Furthermore, the research perspectives on HMIs have a particular interest in scheduling. Most of the proposed literature HMI are based on observational analysis in real or simulated situations using realistic scenarios. The resulted HMIs emphasize the usefulness of a DSS in order to assist the human decisions.

A DSS has been proposed in [22] in order to optimize and manage the transportation scheduling problem. A set of scheduler-oriented algorithms taking into account operational and cognitive research aspects, has been integrated into the proposed HMI. These algorithms are developed based on a 3-phase approach and uses the three cooperation control modes in order to favor the human-machine cooperation

for the transportation scheduling problem. The effectiveness of the proposed DSS is illustrated on small size benchmark instances.

Furthermore, another recent study presented in [24] has led to the definition of a new industrial HMI model called i-DESM. This model permits the creation of decision support software to assist the decision scheduling process in micro/small companies. The advantage of the proposed model is that it considers multidisciplinary characteristics of the HMI related to the human behavior factors, such as ergonomics and cognitive aspect. The proposed model has identified several oriented decision algorithms that provide support to the human scheduler during the online phase of the scheduling process.

3 A proposed HMI using Groups of Permutable Jobs

In this section, we propose a new HMI for scheduling under uncertainties using the *groups of permutable jobs* method which is one of the most studied proactive-reactive approaches to cope with uncertainties. The following section gives a brief theoretical background about this method.

3.1 Groups of permutable jobs

It was first introduced in [1] and it has been implemented in an industrial software called *ORDO* [4, 18], which has been used by more than 70 make-to-order manufacturing companies in France.

This method provides a flexible solution to the scheduling problem, that encapsulates a set of schedules during the planning phase. The groups of permutable jobs are used according to two stages:

- The first stage consists of proposing an offline flexible schedule that represent a family of schedules instead of unique one; the technique used merges activities (jobs) executed successively on the same resources (machines), such that any order of jobs inside each group leads to a feasible schedule that can be executed in the shop.
- The second stage is a decision stage. It consists of executing in real-time one of the schedules characterized by the groups of permutable jobs, and therefore choosing the next job to proceed within each group.

This two stages are illustrated on a flow shop scheduling example. In a flow shop problem, we have a set of jobs J_1, J_2, \dots, J_n executed on the same set of machines M_1, M_2, \dots, M_m . A scheduling solution to this problem consists of ordering the jobs in each machine. The performance of this solution is usually measured through a regular objective function. In this paper, the performance is measured using the makespan performance which refers to the maximum completion time of all jobs

(C_j is the completion time of J_j and C_{\max} is the maximum completion time of all jobs).

A group of permutable jobs in a given machine represents a group of at least two jobs that can be executed in an arbitrary order during the second stage. Fig. 1.a and fig. 1.b illustrates respectively a solution of a four-jobs/two-machines flow shop and a flexible schedule represented by groups of permutable jobs.

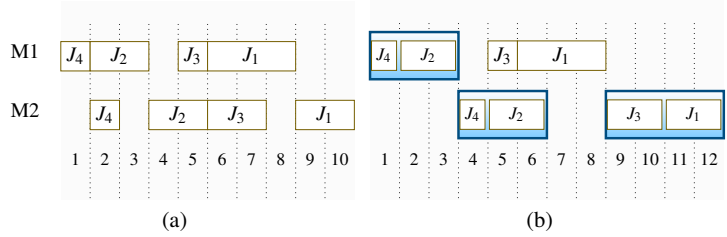


Fig. 1 Example of groups of permutable jobs

The flexible schedule constructed in stage 1 contains three groups of permutable jobs. These groups characterizes eight different schedules ¹. The decision phase consists of selecting the order of jobs in each group of permutable jobs. At the end, one of the eight possible schedules is established in the shop.

3.2 Decision stage of the groups of permutable jobs

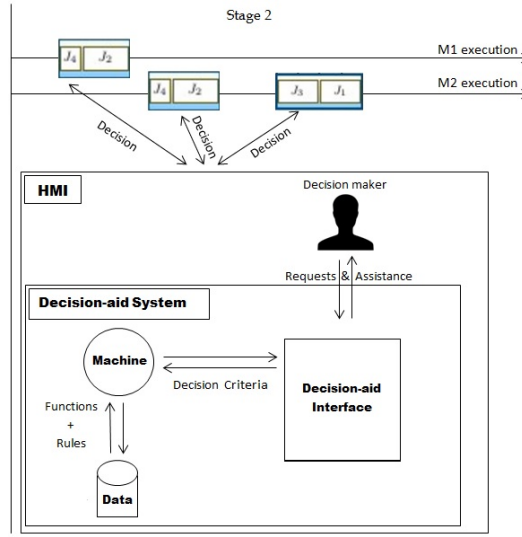
To allow the human-machine cooperation, we present in fig. 2 the overall model for the decision stage of the groups of permutable jobs. The operational concept of this model requires that the human interacts with the machine using a DSS (called Decision-aid System in the figure) and that during the online phase of the groups of permutable jobs.

The DSS represents the core of the proposed HMI and is supposed to assist the operator with all the information needed during the decision phase. This DSS is composed of three modules:

- The *decision-aid interface*, which represents the interlocutory module between the human requests and the machine assistance. It allows to provide the operator with the information needed and also allow to trigger the jobs' execution according to the order selected by the operator.
- **Data storage**: this module stores all the variables of the planned offline schedule such as the jobs starting time, completion time, etc.

¹ The number of schedules is the factorial multiplication of the number of jobs in the groups: (2! x 2! x 2!)

Fig. 2 Proposed HMI model



- The machine uses the information stored in the data module in order to compute and assist the requests of the decision-maker.

In this proposed HMI, we assume that the human has the control over all decisions, and the machine evaluates, validates and assists his decisions; because it is more useful to calculate the consequences of the human decisions by the machine rather than the human itself. In addition, as stated by [11], the human scheduler remains efficient for taking decisions, although not optimal, contrarily to the machine, optimal in computation, but with relatively poor performance in realistic situations.

However, the requests/answers transferred between the decision-maker and the decision-aid system are carried out using a simple decision-aid interface. In this interface, the decision-maker finds all the information concerning each job of a group so that he can make correct/optimal decisions. According to the information provided, the decision-maker may or may not take advantage of the decision-aid interface, which can significantly increase or reduce its activity and therefore affects the scheduling performance as stated by [14] who studied the activity of manual rescheduling. In order to avoid this lack of interaction, we propose to use three decision-aid criteria in order to anticipate the consequences of a decision before taking it:

- *Best-case schedule*: it provides the best possible performance if the selected job is chosen first in its group. However, computing the best-case schedule is NP-hard and a branch and bound method would be too much time consuming. For this reason, we use the lower bound presented in [25, 26] for estimating the optimal value of this criterion.

- *Worst-case schedule*: it provides the worst possible scheduling performance if the selected job is chosen first in its group. This value is computed in polynomial time using the algorithm of [12].
- *Best starting time*: unlike the previous criteria, this one gives direct information about the best possible starting time of jobs. A job can start after the completion time of all its predecessors. This problem is NP-hard and the lower bound presented in [25] is used.

4 Case study

In this section, we implement the proposed HMI in a real flow shop manufacturing system (Fig. 3). This system called MPS500 from FESTO Company is used for constructing short stroke cylinders. It is composed of six workstations, eight pallets and a conveyor transferring pallets (products) from one station to another one.



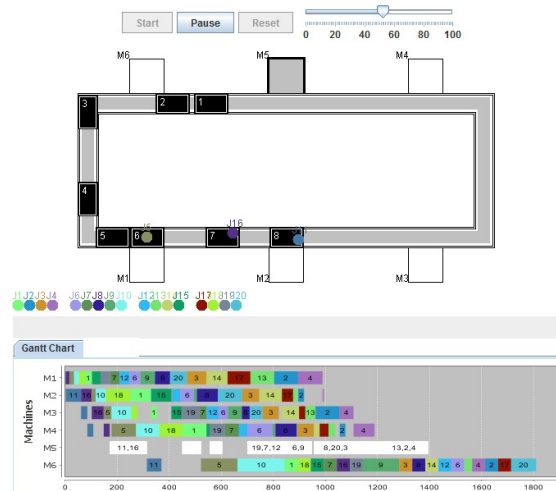
Fig. 3 MPS500: system under study

4.1 Experimental protocol

An emulation home-made driven-even program of MPS500 has been built (using JAVA) in order to speed up the manufacturing process and facilitate the experiment conditions. For each machine, a virtual queue is created in order to store the products. Once the product arrives at the machine, it will be automatically transferred to the queue. If all its predecessors products are already executed on this machine, the product will be then handled by the machine as planned to.

The overall configuration of the setup is presented on fig. 4. As shown from this figure, a Gantt chart representing the real-time schedule is printed along with the simulation interface. The transportation times on the Gantt chart are considered null.

Fig. 4 Simulation program of MPS500



The input (schedule) of the data module used for the experiment is a flow shop schedule containing 20 products (jobs). We assume that the scheduling decisions can be made only on the fifth workstation, therefore several groups have been constructed on this workstation. The overall decisions are twelve.

The decision-makers of the experiment are 35 students from manufacturing knowledge background and are familiar with MPS500. Despite the fact that conducting the experiment with students is easier than with professional employees, [2, 17] have shown that, in the field of scheduling, experiments done on students may drawn general conclusions applicable to professional situations.

Each time a job of a group arrives at the fifth workstation, it will be stored in the virtual queue of this workstation. Once all jobs belonging to the same group arrive at this queue, the decision-aid interface interrupt the simulation process. The student makes his decision by selecting each time the job that he wants to execute first until the last job of the group. This decision process is repeated until no group of permutable jobs remaining.

However, before taking any decision, the student can use the three proposed criteria in order to make his decision. The criteria are computed in the background by the machine module and the transportation time of products is considered null for computing these criteria as well.

To be more realistic, we introduce two perturbations in the schedule. We assume that the first one occurs on decision five and the second, on decision eleven. These perturbations are caused by the fact that two jobs took longer time execution than expected. However, the machine module does not consider these perturbations for the computation of the three criteria, and therefore the results may not be correct; it is up to the decision-maker to detect these changes and adapt the results of the decision-aid criteria.

To study the effect of the perturbations on the scheduling performance, we introduce two scenarios:

- In the first scenario, the perturbation can be detected from the HMI interface by checking the planned/executed starting/completion time of jobs. In this case, the student has to calculate by himself the consequences and impact of the perturbation on the current schedule.
- In the second scenario, additionally to the previous one, the perturbations are showed on the Gantt chart from the simulation interface as shown in fig. 5. However, the machine module still does not consider these perturbations for the computation of the criteria. Therefore, the student has still to verify and correct the results provided by each criterion.

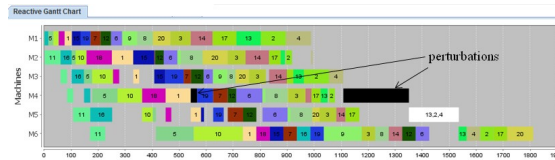


Fig. 5 Representation of the perturbations in the second scenario

The students were divided into two groups. *G1* (of 10 students) and *G2* refer respectively to the first group with the first scenario and the second group with the second scenario. The experiment has been conducted only once for every student.

4.2 results

The performance of the HMI system has been measured through the makespan objective; once all the decisions are taken, the HMI measures the scheduling performance obtained by each student (referred to as C_{max}). The optimal schedule that can be achieved is referred to as C_{max}^* and is equal to 1607.

Furthermore, during each decision, the HMI verifies if the current decision is optimal or not (compared to the schedule represented by C_{max}^*). This measurement is called a *local performance* and is represented by a binary variable indicating if a decision is optimal or not. In this way, we can compare the local performance of students before and after the perturbations and its effect on the C_{max} .

Table 1 represents the local performance of *G1* and *G2*. For each decision, is given the percentage of good decisions and the anticipated C_{max} if the remaining decisions will be optimal. The index 1 and 2 in the columns' labels refer respectively to *G1* and *G2*. The last column of the table indicates the optimal makespan that can be achieved at the end of each phase regarding the perturbations (the first perturbation occurs at the fifth decision and the second at the eleventh decision).

It can be shown that *G2* took better decisions than *G1* for almost 67% of the decisions². Furthermore, all students of *G2* were able to take optimal decisions on more than 30% of the decisions. *G1* was able to slightly outperform *G2* on decision

² This result is significant with an error level of 10% using the statistical T-test

Table 1 Performance on each decision

Decision number	Local perf. 1	$C_{\max 1}$	Local perf. 2	$C_{\max 2}$	C_{\max}^*
1	92%	1578	100%	1571	1571
2	92%	1585	100%	1571	1571
3	75%	1606	82%	1587	1571
4	71%	1613	82%	1595	1571
5	58%	1611	55%	1593	1571
6	96%	1613	100%	1593	1571
7	83%	1612	100%	1593	1571
8	88%	1615	91%	1593	1571
9	88%	1625	82%	1603	1571
10	83%	1629	82%	1609	1571
11	92%	1642	91%	1626	1607
12	54%	1654	73%	1630	1607

5, 9, 10 and 11. However, the gap difference on these decisions does not exceed 6%. Overall, $C_{\max 2}$ was better than $C_{\max 1}$.

The worst decisions of $G1$ were taken on decision 5 and decision 12, while the worst decision of $G2$ were taken on decision 5. This is due to the perturbations; at the first perturbation, 50% of the students were misled by the decision-aid interface and were not able to correct the values provided by the decision-aid criteria, even that this perturbation did not have a big impact on the planned schedule. This may be due to the inaccuracy of the lower bound used for computing the best-case schedule.

However, after the fifth decision, the students were able to take better decisions. All the students of $G2$ were successful in taking optimal decisions during decision 6 and 7. At the last decision, 73% of these students were able to take an optimal decision even that the last perturbation introduced had a significant impact on the planned schedule. In fact, the criteria were supposed to mislead the student by implicitly suggesting the wrong decision as optimal for decision 11 and 12. This was the case for the students of the first group. But overall, the final C_{\max} of both groups is acceptable and represents 2.94% and 1.45% gap distance from C_{\max}^* for $G1$ and $G2$ respectively.

Furthermore, these results suggest that the representation of the perturbations in a real-time Gantt chart affects the decisions of the decision-maker, and therefore $G2$ was able to have a farsighted overview about the perturbations impact on the remaining jobs.

Finally, these first results confirm the usability of the proposed HMI in a practical environment and showed the limits of the control mode used as most of the students were not able to take optimal decisions before the first perturbation. To cope with this drawback, we suggest using different control mode on each decision based on the state of the system. This could significantly improve the local-performance/global-performance of the schedule.

5 Conclusion

In this paper, we proposed a new HMI system for manufacturing scheduling under uncertainties. The aim of the proposed HMI is to improve the cooperation between the human decision-maker and the machine in a context of manufacturing control based on *groups of permutable jobs* method. This method proposes a set of solutions to the scheduling problem, leaving to the decision-maker the decision of executing one of these solutions in order to cope in real-time with the perturbations of the shop floor.

For investigating the usefulness of the proposed HMI, we conducted a practical experiment on a real manufacturing system, with students from manufacturing engineering background. The students were divided into two groups, and to each group was affected one scenario. The particularity of the second scenario relies on the perturbations representations on the HMI model in order to help the decision-maker having a farsighted overview on the perturbation impact and therefore taking better decisions.

The experiments conducted on an emulation program using three decision-aid criteria showed the usability of the proposed HMI. However, the students were not able to take optimal decisions all the time, surprisingly even when the shop is stable. In this case, it may be better to switch the control mode to the machine. This research is still in its early stage and should open new questions about the best practice of scheduling under uncertainties using other objective functions.

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