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A new human-machine system for group sequencing [*]

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Abstract

The group sequencing method is a proactive reactive scheduling method which aims at bringing flexibility as well as quality. This method is based on a human-machine system allowing to choose in real-time the next operation to perform in a group of permutable operations. In this paper, we propose a new method to improve the cooperation between the human operator and the machine for group sequencing. This new method intends to favor the activity of the operator. To evaluate the pertinence of this new method, an experiment is planned. The factors and the expected results of this experiment are discussed in this paper. Depending on the results of this experiment, changes in the reactive phase of the group sequencing will be done in order to improve the cooperation between the operator and the machine.

Key words: Scheduling, Human-machine cooperation, Group sequencing, Human factors

1 Introduction

The job shop problem is an optimization problem composed of resources, jobs, operations, and constraints. A job i has a set of operations ($O_{i,j}$), each operation $O_{i,j}$ is executed on at least one resource during a processing time $p_{i,j}$ with precedence constraints: the operation $O_{i,j+1}$ cannot be executed before operation $O_{i,j}$ is completed.. A resource, also named machine, can execute only one operation at a time. An operation $O_{i,j}$ has a starting time denoted $t_{i,j}$ and a completion time denoted $C_{i,j}$ with $C_{i,j}= t_{i,j}+ p_{i,j}$. A job i has a completion time C_i which corresponds to the completion time of the last operation of the job. A job i has also a release date r_i before which the job cannot be executed and a due date d_i used to compute the lateness L_i of the job: $L_i = C_i-d_i$. If L_i is positive, the job is late. Generally, the job shop problem uses a regular objective function f that is an increasing function of the C_i. The goal is to minimize this objective function. The makespan, denoted by C_{max}, calculated $max_i C_i$, which corresponds to the total time of execution of the schedule, is a classical regular objective. Another classical regular objective is the maximum lateness noted L_{max}, calculated $max_i L_i$.

Actually, manufacturing problems are not so deterministic. Most of times they present uncertainties, which are due to the lack of precision of the model or to hazardous phenomenon very frequent in manufacturing systems (e.g., machine breakdown, new operations to be done urgently, etc...). To cope with these uncertainties, systems which favor cooperation between human and machine are appropriate ([2], [3]).
This is why group sequencing was created by [4]. This method aims at describing a set of feasible schedules in order to delay decisions to take into account uncertainties. Group sequencing is used according to two stages: a predictive phase and a reactive phase.

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The predictive phase is done offline. It aims at introducing flexibility in the sequence of operations by creating groups of permutable operations which enable to describe a set of schedules without enumerating them. Group sequencing evaluates a group sequence according to the worst case quality in the set of feasible schedules.

The reactive phase is done online on the floor. It needs the intervention of a human, named the operator, who chooses during the execution of the group schedule the operation to be executed in each group of permutable operations. Thus, this method brings flexibility and enables to choose in real-time the operation (among a group of permutable operations) that fits best to the real state of the system.

But this method has some drawbacks. During the predictive phase, the group sequencing is done by the machine with a model of the shop which is always a simplified representation of the real system. Moreover, during the reactive phase, the operator has to make decisions with very few information. This lack of information does not favor the activity of the human during the decision-making phase and thus does not permit to use optimally the group sequencing method.

In this paper, we present an extension of the group sequencing method which aims at favoring the activity of the human during the reactive phase of the method. Thus, this extension should permit to improve the cooperation between the human and the machine and consequently to improve the performance of the scheduling especially in presence of uncertainties.

The paper is organized as follows: first we present the group sequencing method, then a new approach which enables to facilitate and to enhance the cooperation between the human and the machine during the reactive phase is presented. The last section describes the experimental protocol used to evaluate this new approach.

2. Groups of Permutable Operations

Group of permutable operations was first introduced in [4]. The goal of this method is to have a sequential flexibility during the execution of the schedule and to guarantee a minimal quality corresponding to the worst case. This method has been widely studied in the last twenty years, in particular in [4], [5], [6], [7]. For a theoretical description of the method, see [7].

This method is a predictive-reactive method, composed of two phases:

- A predictive phase which aims at computing a solution offline. This solution is a set of schedules.
- A reactive phase in which a schedule is realized online in the shop. This phase relies on the solution proposed during the predictive phase and takes into account the real state of the shop. Thus, the schedule which is realized takes into account the uncertainties which occur in the shop.

This method has two main advantages: it combines an optimization method during the predictive phase which enables to give a good quality schedule and a real-time method during the reactive phase which enables to adapt the schedule to the uncertainties.

2.1 Definition

A group of permutable operations is a set of operations to be performed on a given resource M_l in an arbitrary order. It is named $g_{l,k}$. The group containing the operation O_i is denoted by $g(i)$.

A group sequence is defined as a sequence of groups (of permutable operations) on each machine M_l: $g_{l,1};......;g_{l,\nu l}$, performed in this particular order. On a given machine, the group after (resp. before) $g(i)$ is denoted by $g^+(i)$ (resp. $g^-(i)$). A group sequence is feasible if for each group, all the permutation among all the operations of the same group gives a feasible schedule (i.e. a schedule which satisfies all the constraints of the problem). As a matter of fact, a group sequence describes a set of valid schedules, without enumerating them.

The quality of a group sequence is expressed in the same way as of a classical schedule. However, it is measured as the quality of the worst semi-active schedule[1] found in the group sequence, as defined in [7].

2.2 Example

1 A semi-active schedule is a feasible schedule in which no local left-shift of an operation leads to another feasible schedule.

To illustrate these definitions, let us study an example. Tab. 1 presents a job shop problem with three machines and three jobs, while Fig. 1 presents a feasible group sequence solving this problem. This group sequence is made of seven groups: two groups of two operations and five groups of one operation. This group sequence describes four different semi-active schedules shown in Fig. 2. Note that these schedules do not always have the same makespan: the best case quality is with $C_{max} = 10$ and the worst case quality is with $C_{max} = 17$.

Table 1
A job-shop problem.

Job i	*Sequence j*	$M_{i,j}$	$p_{i,j}$	*Operation*
1	1	1	3	1
1	2	2	3	2
1	3	3	3	3
2	1	2	4	4
2	2	3	3	5
2	3	1	1	6
3	1	3	2	7
3	2	1	2	8
3	3	2	2	9

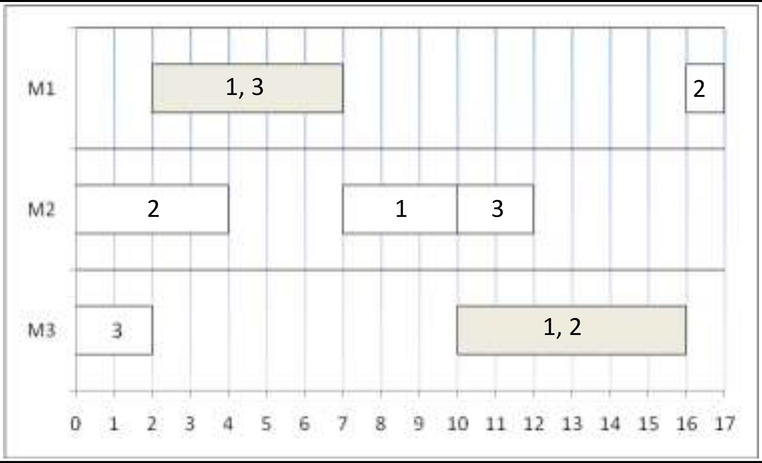
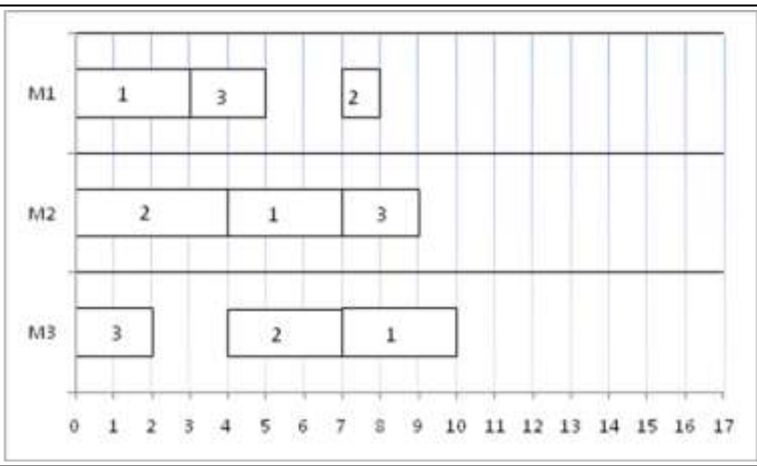


Fig. 1. A group sequence solution of the job-shop problem described in Table 1.



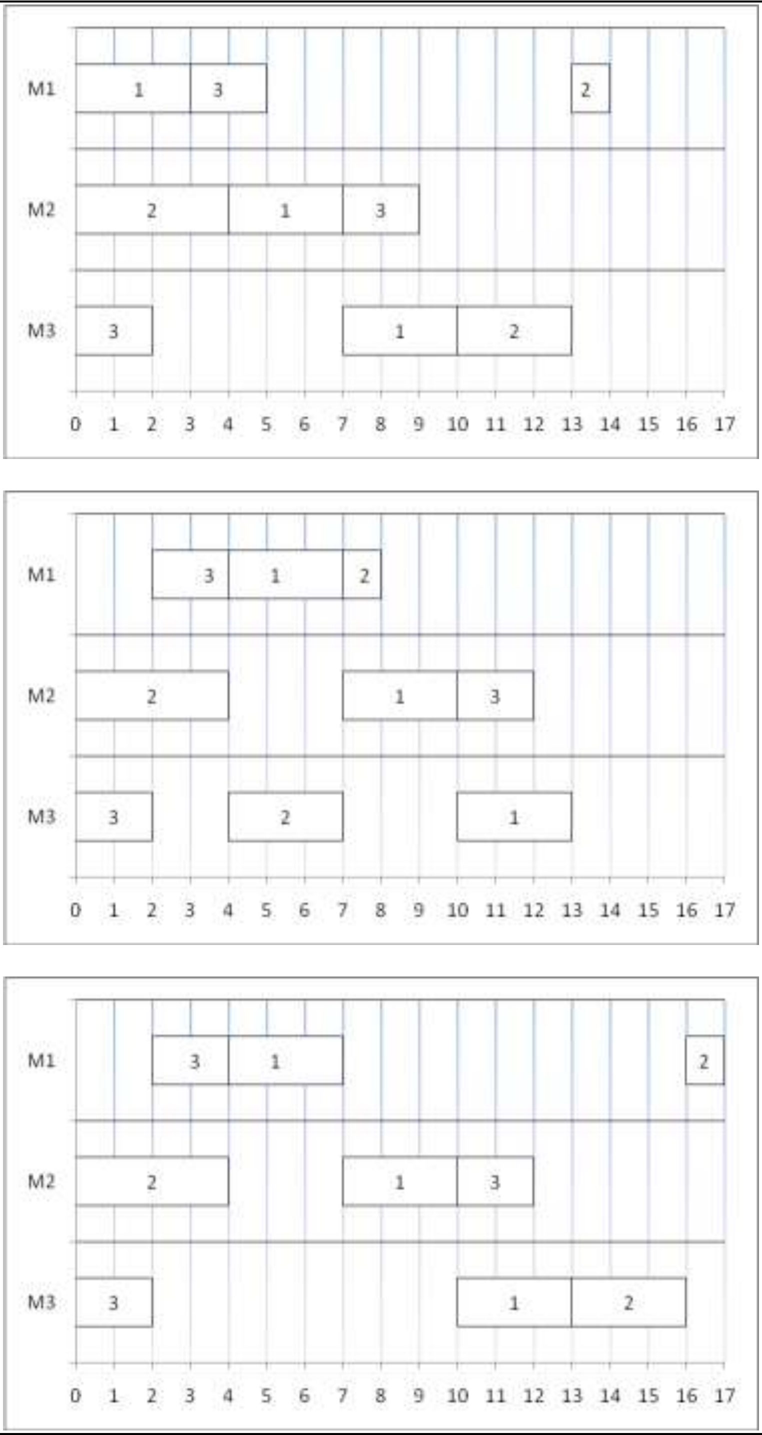


Fig. 2. Semi-active schedules described by the group sequence in Fig. 1

The execution of a group sequence consists in choosing a schedule described by the group sequence. It can be viewed as a sequence of decisions: each decision consists in choosing an operation to execute in a group when this group is composed of two or more operations and that the previous group is executed. For instance, for the group sequence described on Fig. 1, there are two decisions: on M_1, at the beginning of the scheduling, operation O_1 or O_8 have to be executed. Let us suppose the decision taken is to schedule O_1 first. On M_3, after O_7 is executed, there is another decision: scheduling operation O_3 or O_5 first. If the decision is to execute O_5 first, the first schedule of Fig. 2 is realized.

2.3 Evaluation

Group sequencing has an interesting property: the quality of a group sequence in the worst case can be computed in polynomial time for minmax regular objective functions like makespan and maximum lateness (see [7] for the description of the algorithm). Thus, it is possible to compute the worst case quality for large scheduling problems. Consequently, this method may be used to compute the worst case quality in real time during the execution of the schedule. Due to this real-time property, it is possible to use it in a decision support system dynamically.

[8] proposes an adaptation of the free margin to group scheduling: the free sequential margin for each operation. This measure computes for an operation according to its earliest execution the maximum lateness which ensures that all schedules enumerated in the group scheduling will present no tardiness. Moreover, choosing the operation with the highest free sequential margin in a group will permit to increase the margins of the other operations of the group, and thus enable to preserve the flexibility of the schedule.

During the reactive phase, several situations may occur:

- All the free sequential margins of the current group are positive, in that case whatever the chosen operation, the schedules will present no tardiness.
- There is one or several (but not all) operations in the group which present negative free sequential margin. In that case, there may be schedules with tardiness, especially those beginning with an operation with a negative free sequential margin and [8] recommends executing operations with large free sequential margins in order to increase the negative margins, trying to make them become positive.
- All the operations of the group have negative free sequential margins. In that case, there will be schedules with tardiness whatever the chosen operation, but it is also possible to have schedules with no tardiness.

Thus, the free sequential margin is a precious tool to choose in real-time an operation during the reactive phase. But it does not permit to know if there is a schedule with no tardiness in case of one or several (but not all) negative free sequential margin(s) in a group.

To cope with this drawback [11] propose a method enabling to compute the best-case quality for group sequencing.

2.4 Flexibility and robustness

Group sequencing is a method which enables to describe a set of schedules in an implicit manner (i.e. without enumerating the schedules) and guarantees a minimal performance. Actually, as it proposes a group of permutable operations, one can choose inside a group the operation that best fits the real state of the system. Furthermore, the flexibility added to the schedule should be able to absorb uncertainties. Only three studies have tried to verify this property. [6] studies the impact of disturbed processing times on the objective of weighted sum of tardiness in comparison with static and dynamic heuristics. When processing times are not greatly disturbed, they observe that group sequencing obtain better performances. [9] studies the impact of disturbed processing times, due dates and release dates on a one machine problem and compares its results with a static heuristic method. On average, performances are better with group sequencing than with the static method. [10] studies the impact of non-modeled transportation time between two operations. The method exhibits good performances, even when transportation times and processing times are comparable.

3. ORABAID: the current reactive phase

ORABAID (ORdonnancement d'Atelier Basé sur l'Aide à la Décision) is a scheduling method based on group sequencing. This method is currently implemented in the software ORDO from ORDOSOFTWARE. ORABAID's reactive phase relies on the free sequential margin described in the previous section. During the reactive phase, the method provides for each operation to be performed its free sequential margin. The operator is suggested to choose the operation with the largest margin. The operator can choose another operation to be realized, even from another group than the one which is currently performed. If the operator chooses an operation different than the one proposed by the machine, the software computes the new margins (according to the choice of the operator) and finally the operator validates the sequence. This method enables the operator to monitor the execution of the schedule while it guarantees a minimal quality. Moreover, a possible tardiness can be detected before it really occurs, which enables to anticipate the problem.

But a major drawback of this method is that it leaves the operator with very few information to take a new decision. If the operator doesn't choose the operation with the largest free sequential margin (as proposed by the method) he must evaluate the other solutions one by one with the free sequential margin only as an indicator.
The main risk of such a procedure is that the system may be under-utilized: a decision change by the operator is so costly (from a cognitive point of view) that the operator will prefer to follow the software's propositions as indicated in [3]. In that case, the system is no more flexible and the operator doesn't really participate to the scheduling process.

4. A new reactive phase

Experimentations ([2], [3]) indicate that the performance is better when human and machine cooperate together. Our goal is then to favor this cooperation in order to improve the performance of the scheduling especially in case of uncertainties.

For this, we propose a new multi-criteria approach for the use of the group sequencing approach during the reactive phase. We intend to propose not one indicator (i.e., the free sequential margin) but several indicators to help the operator in his choice. Moreover, [9] indicates that a multi-criteria approach in the reactive phase of ORABAID should permit to improve its performance.
As in a manufacturing system, decisions to be taken involve different criteria such as flexibility and performance, in this context, a multi-criteria approach seems adapted. The weight of each criterion depends on the context of the decision. For example, if there are a lot of uncertainties to deal with, it will be more judicious to maximize the flexibility. However, if the system is less hazardous it will be preferable to focus on the performance of the system.
The new human-machine system for group sequencing we propose will rely on several measures. These measures will represent the machine's knowledge, especially for what the machine is adapted: computations. Each measure will represent either a decision criterion (i.e., an information that has been computed) or it can show more information on the operations to be performed. So, the operator will access information that he cannot get by himself and thus, he will be able to combine these informations with his own competencies and knowledge. The operator can do his own choice with the help of the machine and not under the guidance of the machine. He will be more involved in the decision process and then the cooperation with the machine should be more efficient.
We propose the following new measures:

- The free sequential margin, already proposed in ORABAID
- The worst-case quality for an operation, which gives the worst predictable quality of the schedule if this operation is chosen
- The best-case quality for an operation, which gives the best predictable quality of the schedule if this operation is chosen.

Several regular objectives can be used for the worst and the best case quality, especially the makespan or the maximum lateness. All these measures are directly related to manufacturing criteria such as the flexibility for the free sequential margin, meeting the due dates for the maximum lateness in the worst and the best case.
Other measures more simple will also be proposed to the operator:

- Processing times of the operations ;
- Earliest starting times of the operations;
- Remaining operating times;
- Remaining number of operations;
- Due dates.

These measures will give complementary informations directly related to the operations, allowing the operator to better anticipate the effects of his decision.
We think that this new formulation of the reactive phase of the group sequencing should favor the activity of the human, thus the cooperation between the human and the machine and consequently the performance of the schedule.
We intend to experimentally verify our hypotheses. In the next section we propose a protocol to conduct this experiment.

5. The Experiment

5.1. Goal

No theoretical proof can validate a human-machine interaction. So, it is necessary to use an empirical approach to validate or to infirm our hypotheses. This is why we propose to conduct an experiment for that purpose.

The main goal of this experiment is to compare ORABAID's reactive phase with our new reactive phase presented in the previous section. As the difference between the two approaches relies essentially on the measures proposed to the operator, the experiment will study the impact of these measures on the cooperation and the performance.

Our hypothesis is that the new approach we propose should lead to a higher activity of the operator in the decision process. It means that the operator should participate directly in the making of the schedule with the help of the machine and not under its guidance; otherwise the operator should be passive. Actually, it is likely that the operator will be more or less active, so it is preferable to define a level of activity. A higher activity of the operator should lead to a more efficient human-machine system, improving the performance of the schedule. A higher activity of the operator should also allow the operator being more aware of the shop floor, thus the operator should better assume his responsibilities on the shop.

5.2. Experiment's plan

In the following, we will present the experiment's factors, which are our control data, and the dependant variables which are the experiment's results.

The first factor will be the operator's level of activity. As a factor it will be controlled during the experiment.

The performance of the schedule, such as the makespan and the maximum lateness, will be used as dependant variables. Another dependant variable will be the way the operator uses the different measures provided by our new approach. This particular variable will permit to identify the most used measures and thus the most pertinent.

5.3. Experiment's protocol

For our experiment, a framework composed of two computer programs is built. The first program, named the simulator, will simulate the dynamic behavior of the shop. The second one is a control program supervising the simulator and computing the different measures, it is named the supervisor. The supervisor will present the different measures to the operator. Contrarily to the simulator, the supervisor is part of the human-machine system under study. The simulator is built only to facilitate the conditions of the experiment. The simulation is driven-event: it means that is doesn't simulate in real time the shop, it goes directly to the next event which necessitates an operator's decision, then it stops waiting for the operator's decision. The operator can ask the supervisor, and observe the shop state on the simulator to choose the next operation to perform. Once the choice is done, the operator gives the simulator his decision. This procedure is repeated until the end of the scheduling where the schedule's performances are collected.

To be more realistic, the simulator will simulate uncertainties. It means that data from the simulator (operating times, transfer times from an operation to another, etc...) can be different (more or less) from data given by the control program. Thus, we will be able to test different scenarios such as:

- There are no uncertainties. Data from the simulator and data from the supervisor are the same. In this case, the control program will always give exact predictions.
- Slight uncertainties will occur during the scheduling. For example, operating times are slightly different between the simulator and the supervisor or there are transfer times in the simulation whereas they are not present in the supervisor. In this case, the supervisor will make approximate predictions.
- A very local but very large uncertainty will occur. For example, a single operating time is 20 times bigger in the simulation than in the supervisor. In such a case, there will be a lateness caused by an isolated event. The supervisor would not predict this lateness but would adapt its predictions to the observed state, i.e., the state given by the simulator. After this occurrence, there will be no more uncertainties but the performance should be degraded from the predictions.

During the experiments numerous data will be recorded to be analyzed later:

- For each decision, a beginning time and an end time will be recorded. It will allow computing the amount of time taken for each decision. Moreover, for a given decision all taken actions will be positioned during the time.
- In order to understand how the operator uses the different measures provided by our system, the supervisor will not show immediately these measures. For each operation, the operator will have to ask the supervisor for the measure he wants to see. Thus, the access times of the different measures will be recorded. So, we will be able to know which measures are used for a given decision and when they are used in the decision process.
- To evaluate the cooperation between the human and the machine, a sonorous recording of the operator will be made during the experiment. The operator will be asked to verbalize his actions, i.e., he will speak loudly to explicit what he is doing. Thanks to these records, we will be able to follow precisely the cooperation process between the human and the machine.

As it has been exposed in the previous section, the activity level of the operator is a factor that will be controlled. This control will allow identifying the relation between the activity level of the operator and the performance of our human-machine system and then to determine whether the operator's activity has to be favored or not.

To make a passive operator being more active, the machine will suggest another solution after the operator has taken his decision. Thus, the operator will have to think about his choice versus the machine's choice and then it will make the operator more active in the decision process.

We have chosen to conduct this experiment with students preparing a Bachelor degree in Production Management. They are not yet experimented in the practice of scheduling but they have studied largely production management, scheduling and manufacturing systems. We intend to conduct a first experiment with a sample of ten students. If the results are not reliable, other experiments with more students will be conducted. Statistical analyses will also be done to obtain confident intervals on the results in order to validate the results obtained.

5.4. Results

The most important result expected is the influence of the activity level on the cooperation and then on the scheduling performance. Indeed, if we think that a higher activity of the operator allows improving the performance of the scheduling, it is essential to propose a method which aims at improving the cooperation between the operator and the machine.

We don't think that a higher activity of the operator can reduce the cooperation between the human and machine, nevertheless it is possible that a higher activity can reduce the performance. In that case, it means that the machine alone would be more efficient than a human-machine system for this scheduling problem. If so, a scheduling method without any cooperation with a human should be proposed. According to the state of the art in the field and our first experiments, this hypothesis seems not pertinent. There may be another hypothesis: a higher activity doesn't change significantly the performance. In that case, we think that a higher activity of the operator should yet be favored, simply to improve the implication of the operator in the schedule's execution and thus to ensure that he will better control the operations in the shop.

Another important result concerns the comparison to be done with the method ORABAID. We hope (and we think) that the cooperation and the performance should be better with our new method. Even if the results' experiment show the opposite, it will be interesting to analyze why our new method with more measures is not more efficient than ORABAID with only one measure.

The other expected results from the experiment are:

- What are the measures used by the operator in his decision process? This result will allow to choose the more appropriate measures and to make them more accessible. Moreover, depending on the information used in the measures (sign, magnitude order, etc…), graphical tools could be used to make the results more easily readable.
- The operator's confident level in the supervisor according to the uncertainties. This information will allow evaluating the algorithms' quality as it is felt by the operator, and eventually to focus on some algorithms to be improved.
- The operator's remarks on the supervisor. It will allow improving the way the supervisor works.

In all cases, the results expected from this experiment should let us better understand the human-machine system needed for group sequencing, whatever it is ORABAID or our new method. With this understanding, changes in the human-machine system used in the reactive phase of the group sequencing could be made in order to improve the performance of this phase.

6. Conclusion

In this paper, the group sequencing method, a proactive reactive scheduling method, has been presented. This method is composed of two phases: a predictive one which aims at proposing groups of permutable operations for scheduling rather than only one operation and a reactive phase. In this paper, we focus on this last phase which is used in real-time in the shop. The reactive phase is essentially a human-machine system allowing to choose in real-time the next operation to perform in each group of permutable operations. Actually, this choice is done with only one measure: the free sequential margin which is an adaptation of the free margin for group sequencing.

In this paper, we propose a new method to improve the cooperation between the human operator and the machine. This new method intends to favor the activity of the operator during the reactive phase. To evaluate the pertinence of this new method, an experiment is planned. The factors and the expected results of this experiment have been discussed in this paper. Depending on the results of this experiment, changes in the reactive phase of the group sequencing will be done in order to improve the cooperation between the operator and the machine.

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