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A framework for robust scheduling under stochastic perturbations

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Abstract: Industry 4.0 reflects a new area for production workshops. This new concept aims to bring more flexibility and agility to the production shopfloor. In this context, the scheduling problem is an important issue. In fact, a proposed schedule has to guarantee a high performance level able to take into consideration the several changes and perturbations occurring in the workshop. The proposed approaches usually aims to find a robust schedule capable of optimizing some criteria with considering a perturbation. With the new requirements of the workshop and the importance of decision making when implementing the schedule, it is essential to extend the robust scheduling problem to be adaptable to the needs of the decision maker in evaluating several properties. We propose, in this paper, a robust scheduling framework based on a robustness specification. The paper gives also the using of this framework in a decision making context.

Keywords: Robust scheduling, Robustness Framework, Industry 4.0,

1. INTRODUCTION

The evolution of the manufacturing towards Industry 4.0 is impacting the production workshops that are undergoing a gradual transformation based on new information technologies and communication. It is linked to the evolution of cyber-physical systems (CPS) in general and in particular cyber-physical production systems (CPPS). According to (Monostori et al., 2016), a cyber-physical production system production is composed of autonomous and cooperative entities and subsystems that interconnect according to the context, within and through all levels of production, from the machine to the logistics networks. This type of systems is characterized by an increased degree of autonomy, flexibility and agility. the increasing of communications with the environment allows for product customization. Processes are allowing the collection of historical data related to the follow-up of the workshop and its performances. In this context, the scientific community relates many challenges. Among these challenges, (Monostori et al., 2016) identified six main research issues.

- Autonomous systems adaptable to changes that may occur in the environment ;
- Cooperative production systems: development of learning algorithms, of consensus and distributed detection ;
- Identification and prediction of dynamic systems ;
- Robust scheduling for the management of disturbances that may occur in the future produced during its execution;
- Merging real and virtual systems ;
- Human-Machine Interaction.

The scheduling of production workshops is an integral part of these challenges (Vaidya et al., 2018) with emphasis on the notion of perturbations induced by a greater

variability of demand and flexibility of the production environment. Thus, the fourth challenge introduces robust scheduling as a necessary condition for development of Workshops implementing the concept of the industry 4.0. The present article is focused on this challenge. Indeed, the implementation of workshops 4.0 or cyber-physical production systems is based in particular on a technological part related to data processing: big data and data science . Indeed, this part allows to obtain an important flow of data and thus of information to build models of production workshop behavior. The place of data in the implementation of Workshop 4.0 is a significant opportunity. In fact, the information collected can constitute an important support for decision making in the Workshop. Taking the perturbations into account, in the scheduling issue, is therefore important in order to consider the real environment of the production system. Scheduling under perturbations is, however, not a new research problem. Indeed, this question has been addressed in depth in the field of Operational research (Billaut et al., 2010). Existing literature proposes to build robust schedules that guarantee particular performances and this despite the occurrence of perturbations. In (Bidot et al., 2009), a classification of existing approaches is given to consider the stochastic environment of production. They cover two complementary issues: the problem of searching for an optimal solution and evaluating the performance of the scheduling solution in the presence of perturbations. The proposed resolution approaches are often dedicated to a specific scheduling problem because depending on the type of production workshop, specific perturbations considered and performance indicators applied. This paper focus on the notion of performance that may be evaluated in the case of scheduling under perturbations. In this context, we propose a specification of the robustness performance based on existing indicators. The specification will then

allow the presentation of several robustness problems corresponding to the decision maker requirements. Actually, the proposed specification is based on the use of perturbations data to evaluate the performance of a schedule in the aim of helping the decision maker to implement a resistant schedule to perturbations. To do so, this paper is organized as follows. First, the necessary background to define the problem of scheduling under perturbations is presented in Section 2. Then the performance of robustness is presented in Section 3 as a good candidate for evaluating the impact of perturbations on the schedule. Then, the notion of service level is presented as a metric for robustness evaluation. In section 4, a framework gathering several robustness problems is presented based on the specification adopted for robustness evaluation. The use of the framework defined is illustrated in Section 5 allowing the resolving of several robustness problems. This section will highlight the importance of the framework in decision making process. Some conclusions and perspectives are detailed in Section 6.

2. BACKGROUND

In general, the scheduling production problem is based on, first, the definition of a workshop and the constraints that should be considered.

The workshop is defined by a set J of jobs j that are processed by a set R of resources r (NbR). Each job j is defined by a set of operations o_{jk} to be executed for completing the job. An execution duration d_{jkr} is associated to the operation o_{jk} on the resource r . The manufacturing workshops have different characteristics that may lead to precedence constraints between operations of the same job. For instance, the Flow Shop and the Job Shop have some precedence constraints between the operations of each job (o_{jk} is thus the k^{th} operation to be executed). For the Open Shop, the operations of a job can be executed in any order. When generating the schedule, an optimization criterion is considered. In this paper, we will consider the total completion duration (named Makespan) C_{max} . A schedule s (a solution) is an allocation of the operations to the resources and a sequencing of the operations on each resource (defining a starting and a completion date). Regarding a particular solution schedule, we can know: (i) the sequencing of the operations on the resources, (ii) The reference Makespan C_{max}^{ref} that does not consider the perturbations.

In a deterministic context, the workshop data is considered stable and certain. In reality, some perturbations may affect the generated schedule when occurring in the workshop. Indeed, two types of perturbations are identified : i) Uncertainties and ii) Hazards. On one hand, the uncertainties are defined as the difference between planned and actual information available (as uncertainties on the demand, or durations). On the other hand, the hazard is defined as the occurrence of uncontrollable events (resource breakdown, urgent order, etc.).

In order to integrate the perturbations into the scheduling problem, various approaches can be used for their description (Li and Ierapetritou, 2008): scenario based method, fuzzy based method and stochastic method.

In this paper, we focus on the stochastic description of perturbations, where each perturbation is considered as

a random variable that follows some probability distribution. In the context of Industry 4.0, it can be assumed that historical data are available in the workshop such that relevant and sufficiently precise probabilistic models of perturbations can be recovered. How to build these models is out of scope of this paper. Methods coming from data science are good candidates for building these models. So, in the following of this paper, we will consider that these perturbation models are known.

Two complementary strategies can be used to take into account perturbations in a scheduling process (Billaut et al., 2010):

- The first scheduling approach is called proactive: the scheduling is calculated offline based on the a priori knowledge of the perturbations trying to give to the solution some desired quality against these predictive perturbations.
- The second scheduling approach is called reactive: the scheduling is computed online according to the current available information and regarding the occurrence of events.

In the context of this paper, we are interested in the first strategy. The performance of a given solution schedule faced to perturbations can be measured either by a performance of flexibility or by a performance of robustness (Billaut et al., 2010). Flexibility performance is defined as the degree of freedom the schedule has during its execution to respond to actual conditions. Robustness performance is defined as the ability of a schedule to maintain some performances despite the various perturbations.

As part of our work, we are interested in assessing the robustness of a solution schedule faced to perturbations.

3. ROBUSTNESS AS A PERFORMANCE FOR SCHEDULE UNDER PERTURBATIONS

Robustness performance has been integrated into production management over the last century. Its definition has not stopped evolving. In (V.J.Leon et al., 1994), a schedule is robust if being insensitive to unpredictable perturbations on the shopfloor while considering the deployed control policy. In (Sevaux and Sørensen, 2004), the authors argue that one way to take into account stochastic data of a scheduling problem is to find solutions that are robust. In (Billaut et al., 2010) robustness is presented as a qualifier that refers to the ability to tolerate approximations on assumptions, models or data. In (Davenport et al., 2014), the authors define a robust schedule as being able to absorb a certain level of unexpected events (hazards) without having to resort to re-scheduling. More recently, another definition is proposed by (Ivanov et al., 2016): *a schedule that is able to achieve the planned performance despite perturbations is said to be robust*. These different formulations converge towards the same idea of robustness: the performance, quality or capability that a schedule must maintain or guarantee despite the various perturbations and variations emanating from the production system or its environment. In the following, we will focus on the concept of robustness as performance assessment to identify and address a corpus of relevant robustness issues and to provide the appropriate response elements to contribute

to the identified robustness challenge, in particular by (Monostori et al., 2016) for the implementation of Industry 4.0. This paper aims to answer the following questions. First, how to specify robustness performance? Second, how to structure robustness problems from this specification?

3.1 A definition of robustness

To integrate the notion of robustness into the problem of scheduling under perturbations, it is important to specify the measure of this performance. In the literature, this measure depends on the context of the problem and the performance objective to be achieved. For instance, in (Goren and Sabuncuoglu, 2008), the expectation of the makespan is used as a measure of robustness. In (Goren and Sabuncuoglu, 2008), maximum regret is adopted as the measure. In (Beck and Wilson, 2004), robustness is quantified by the probability that a scheduling performance reaches a given level. As soon as the perturbations are modeled as random variables, it seems natural enough to associate robustness with a probability measure to evaluate the risk that the schedule performance is too degraded. For production scheduling, the measure of probability allows to quantify the capacity of a given solution to maintain performance in a perturbed context. It is up to the decision-maker to define the performance criteria of the scheduling, for example, the makespan, a cost or any other classic scheduling criteria (maximum delay, work in progress, etc.). In this context, (Dauzère-Pères et al., 2010) introduces the notion of service level for the measurement of scheduling robustness. This service level measures the probability that the performance of a schedule is lower (or higher) than a given value. The notion of service level can then be considered as a robustness specification. To assess the service level, the following elements are considered. The schedule s to be evaluated, the optimization criterion (here the total completion time (makespan) denoted as C_{max}), the set of perturbations to be considered $Pert$ and the deadline \tilde{d} to be satisfied by s despite the perturbations. Regarding these elements, the service level is defined as follows.

Definition 1. Considering a schedule s , a set of predicted perturbations $Pert$, and a deadline \tilde{d} to be satisfied, the service level $RL(s, Pert, \tilde{d})$ is defined as the probability Pr that the makespan C_{max} of s is less than or equal to the deadline \tilde{d} , despite the set of perturbations $Pert$.

This definition can be formally translated into the expression 1.

$$RL(s, Pert, \tilde{d}) = Pr(C_{max}(s, Pert) \leq \tilde{d}) \quad (1)$$

According to the service level, it is possible to qualify if a schedule is robust as follows.

Definition 2. A schedule s , that has to satisfy a deadline \tilde{d} despite some perturbations $Pert$, is qualified as robust if its robustness level $RL(s, Pert, \tilde{d})$ is greater than or equal to a service level threshold RL_{lim} .

This definition can be formally translated into the expression 2.

$$RL(s, Pert, \tilde{d}) \geq RL_{lim} \quad (2)$$

The threshold RL_{lim} allows to define the accepted risk of not meeting the deadline. In fact if $RL_{lim} = 95\%$ would mean that the decision maker would accept that the deadline would not be met in 5% of cases only.

4. A FRAMEWORK FOR ROBUSTNESS ANALYSIS

The definition of robustness highlights two complementary but competing aspects of the robustness: stability and sensitivity. They can be seen as two facets of the same issue (robustness). Stability refers to the set of perturbations $Pert$ that is supported by a given schedule without degrading too much its performance. This can be considered as the risk that is covered by the schedule. In this case, the tolerated performance degradation is fixed by the deadline \tilde{d} .

On the other hand, sensitivity refers to the deadline \tilde{d} itself, which allows to measure at what point my schedule is sensitive to perturbations defined by $Pert$: i.e. how much the makespan is deviated due to the perturbations fixed by $Pert$. The following definitions are then given for these two aspects. First, the stability measures the variations allowed at the inputs of the problem (measured by $Pert$) without causing too much deviation in the output of the problem (constrained by \tilde{d}). Second, the sensitivity measures the variations generated on the output of the problem (measured by \tilde{d} when the problem inputs vary (constrained by $Pert$)).

Intuitively, we understand that these two notions are concurrent. If we try to increase stability ($Pert$ contains “more” perturbations) then the risk is to increase also the sensitivity (\tilde{d} also increases). If we try to decrease the sensitivity (decrease \tilde{d}) then the risk is to degrade the stability ($Pert$ must contain “less” perturbations). Thus, the robustness definition is fundamental because it highlights several robustness issues depending on whether the decision-maker is more interested in stability or sensitivity, or even looking for a compromise between the two. The objective of this section is to highlight and formalize this set of issues defining a framework for robust scheduling.

Actually, when considering the specification of robustness given in equation (2), it is possible to define several robustness problems. These problems can relate to stability and/or sensitivity analysis. In fact, these problems are defined according to the knowledge of the various input parameters of the problem: s , $Pert$, \tilde{d} and RL_{lim} .

Each input may or may not be known by the decision maker defining a relevant robustness problem.

The identified robustness problems can be classified into two categories:

- the evaluation problems, which assess the robustness of a known schedule s according to the different parameters of the problem.
- the optimization problems, which aim to compute the schedule s^* that optimizes one or more parameters of the defined problem.

Only the evaluation problems are presented in this paper with considering that an initial schedule s is known and needs to be evaluated. In fact, for each evaluation problem, an optimization problem can be associated that searches

ID	Input parameters	Output parameters	Type of problem	Specification
EV_1	$s, Pert, \tilde{d}, RL_{lim}$	Booleen : True or False	Robustness qualification	Is s robust? $RL(s, Pert, \tilde{d}) \geq RL_{lim}$?
EV_2	$s, Pert, \tilde{d}$	$RL(s, Pert, \tilde{d})$	Service level analysis	What is the value of $RL(s, Pert, \tilde{d})$?
EV_3	$s, Pert, RL_{lim}$	\tilde{d}	Sensitivity analysis	What is the minimal value of \tilde{d} denoted as $\underline{\tilde{d}}$ such that: $RL(s, Pert, \underline{\tilde{d}}) \geq RL_{lim}$?
EV_4	s, \tilde{d}, RL_{lim}	\overline{Pert}	Stability analysis	What is the maximum set $Pert$ denoted as \overline{Pert} such that: $RL(s, \overline{Pert}, \tilde{d}) \geq RL_{lim}$?
EV_5	$s, Pert$	$\overline{RL_{lim}}, \tilde{d}$	Compromise analysis sensitivity/service level	What is the couple $(\overline{RL_{lim}}, \tilde{d})$, such that: $RL(s, Pert, \tilde{d}) \geq \overline{RL_{lim}}$?
EV_6	s, \tilde{d}	$\overline{RL_{lim}}, \overline{Pert}$	Compromise analysis stability/ Service level	What is the couple $(\overline{RL_{lim}}, \overline{Pert})$, such that: $RL(s, \overline{Pert}, \tilde{d}) \geq \overline{RL_{lim}}$?
EV_7	s, RL_{lim}	$\underline{\tilde{d}}, \overline{Pert}$	Compromise analysis sensitivity/stability	What is the couple $(\underline{\tilde{d}}, \overline{Pert})$, such that: $RL(s, \overline{Pert}, \underline{\tilde{d}}) \geq RL_{lim}$?
EV_8	s	$\underline{\tilde{d}}, \overline{Pert}, \overline{RL_{lim}}$	Compromise analysis sensitivity/stability/Service level	What are $(\underline{\tilde{d}}, \overline{Pert}, \overline{RL_{lim}})$, such that: $RL(s, \overline{Pert}, \underline{\tilde{d}}) \geq \overline{RL_{lim}}$?

Table 1. Robustness problems framework

the solution s^* that optimizes the criterion defined in the evaluation problem.

Evaluation problems enable the expression of different characteristics that can be satisfied by the schedule. Based on the various parameters, the specification of the robustness is adapted to express the different problems (Table 1). Actually, by changing all parameters, eight robustness problems can be identified and then formalized. For each problem, we define the known parameters (input) and the searched parameters (output). Problems are sorted according to the number of characteristics to be evaluated.

For the first evaluation problem (EV_1), the aim is to know if a given solution s can be qualified as robust regarding the definition in equation (2).

The second problem EV_2 aims to evaluate the service level.

The next two defined problems focus on the properties of sensitivity and stability. The sensitivity analysis (EV_3) aims to assess the minimal deadline that the schedule can satisfy with considering the perturbations and the defined robustness threshold. The expected answer is here the value of the minimal deadline obtained $\underline{\tilde{d}}$. The stability analysis (EV_4) aims to assess the maximum set of perturbations that can be handled by the schedule s with satisfying a known deadline and a defined robustness threshold. The expected answer is here the maximal set of perturbations \overline{Pert} .

The last defined problems are concerned by the compromise between two or more characteristics. In fact, the problem defined in EV_5 expresses the compromise between the sensitivity property and the service level. It means that the specification will look for the minimal deadline $\underline{\tilde{d}}$ satisfied by s with the maximal service level that can be reached \overline{RL} . The second compromise expressed is between the stability and the service level (EV_6). This compromise aims to find the set of maximal perturbations \overline{Pert} and the maximal perturbations \overline{RL} . The problem EV_7 express the compromise between the sensitivity and the stability. It actually allows to obtain a kind of balance between

the minimal deadline reached $\underline{\tilde{d}}$ when the maximal perturbations are considered \overline{Pert} . The last defined problem EV_8 analyses the global compromise between the three properties: sensitivity, stability and the service level.

The defined framework is based on the service level expression. Therefore, the resolution of each problem can be based on the assessment of the service level $RL(s, Pert, \tilde{d})$ (EV_2). Thus, to solve the other problems, a first step would be to assess RL and a second step to compare it to the threshold RL_{lim} .

The goal of the next section is to show how this framework can be applied to a representative use case.

5. APPLICATION

The purpose of this application is to explore the use of the framework defined in an industrial scenario. The scenario presented allows to illustrate decision situations that may occur in a production workshop. The presented scenario is based on a workshop with a production unit in charge of product assembly and a packaging unit in charge of finalizing the order of the customer (Figure 1).

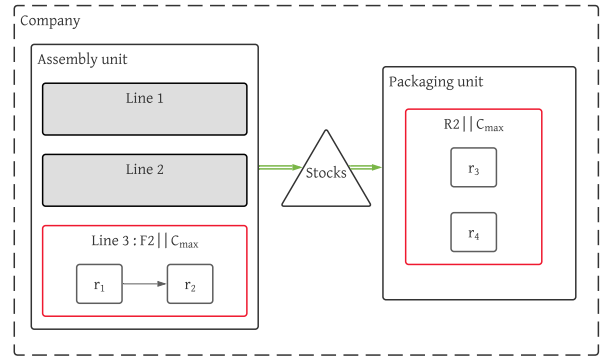


Fig. 1. Application scenario

In the assembly shop two pre-existing production lines ensure the manufacturing of products. In order to expand

its market, the company decides to open a third assembly line to support new customer needs. The production line is a Flow Shop type with two resources and 3 new jobs (representing 3 new products). The scheduling problem related to this application is denoted in the literature as $F2||C_{max}$ (F for flow shop, 2 for the number of resources and C_{max} for the makespan to be minimized). This Flow Shop line integrates two resources r_1 and r_2 . 3 jobs has to be completed on this line. Each job is defined by a pair of operations o_{jk} . Each operation must be executed on a resource respecting a reference execution duration d_{jkr}^{ref} established by the product design department. The reference execution times are listed in Table 2.

Job	Operation	d_{jkr}^{ref} (hour)
1	o_{11}	12
1	o_{12}	12
2	o_{21}	4
2	o_{22}	16
3	o_{31}	20
3	o_{32}	8

Table 2. Flow Shop conception data

From these problem data, six deterministic schedules (corresponding to the 6 possible permutations in the set of 3 jobs) are determined (Figure 2). Among these schedules, the optimal one for the deterministic problem corresponds to the schedule s_3 with a makespan of 44 hours.

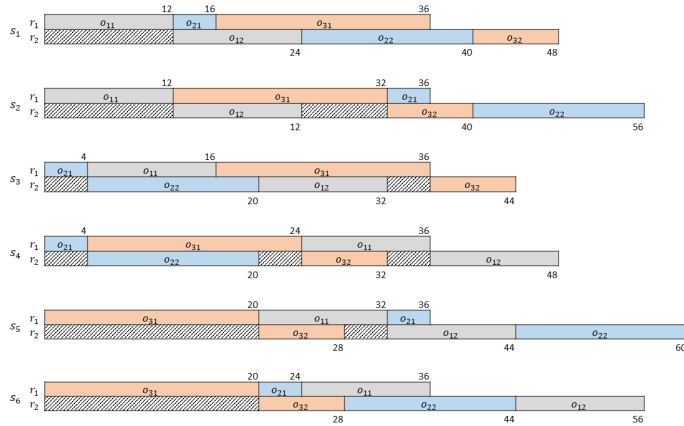


Fig. 2. Deterministic schedules for the problem $F2||C_{max}$

Three scenarios are described to exploit the proposed robustness framework. We will show how the appropriate use of the framework provides relevant information to the decision-maker to help him make the right choice in its workshop. The scenarios are described as follows:

- (1) When the new flowshop line is implemented, the decision-maker does not have an historical data of the perturbation such it is not possible to have a relevant model of the uncertainties on execution durations. The decision-maker want to choose the schedule that allows to absorb the largest deviation on these durations.
- (2) After six months of production, the production data history now enables to have information on the realised execution durations. The decision-maker needs

now to choose the schedule having the best behavior faced to the uncertainties on execution durations.

- (3) The products manufactured on the production line are sent to the the packaging unit. The decision maker would like to provide to the packaging workshop manager a realistic delivery date of these products despite the uncertainties on the execution duration.

To solve these scenarios, we make the assumption that the problems presented in the framework have been implemented in a decision making process allowing the assessment of the service level $RL(s, Pert, \tilde{d})$.

5.1 Scenario 1: Maximum deviation supported

The decision-maker is interested here in the uncertainties that may impact the execution durations of operations. The objective is to identify and implement the scheduling that will allow the absorption of a maximum set of perturbations $Pert$ while satisfying a defined robustness threshold RL_{lim} and a deadline \tilde{d} . Thus, obtaining this maximum set of perturbations means performing a stability analysis (EV_4). We assume that each execution duration can be defined as $d_{jkr} = d_{jkr}^{ref} + \Delta d_{jkr}$ where $\Delta d_{jkr} \in [-\delta \times d_{jkr}^{ref}; +\delta \times d_{jkr}^{ref}]$. Here, Δ is the fluctuation generated by the perturbation on the reference execution duration of operation d_{jkr}^{ref} and δ is the percentage of this variation. Thus, solving (EV_4) means finding $\overline{Pert} = \max\{\delta\}$ such that $RL(s, \overline{Pert}, \tilde{d}) \geq RL_{lim}$. We consider that the service level threshold is fixed to $RL_{lim} = 95\%$ and the deadline is fixed at $\tilde{d} = 51$ hours which means that the decision maker authorize 7 hours (one day) more than the shortest makespan (44 hours). Results, for several schedules s_i whose makespan is initially under \tilde{d} , are given in table 3.

\tilde{d}	Schedule	\overline{Pert}
$\tilde{d} = 51$	s_1	12%
	s_3	37%
	s_4	12%

Table 3. Stability analysis

The schedule s_3 is able to absorb a deviation of 37% while the two other schedules absorb only 12%. The decision-maker will obviously takes the decision to implement the schedule s_3 for more safety.

5.2 Scenario 2: Choosing the most robust schedule

After retrieving historical data, the decision-maker may wish to reconsider the choice of s_3 in order to execute the most robust scheduling when facing actual perturbations. The six deterministic schedules (Figure 2) are then reevaluated taking into consideration the available information on the realized execution durations. We consider again that each execution duration can be defined as $d_{jkr} = d_{jkr}^{ref} + \Delta d_{jkr}$ where $\Delta d_{jkr} \in [-\delta \times d_{jkr}^{ref}; +\delta \times d_{jkr}^{ref}]$. The historical date allow to evaluate $\delta = 20\%$. Moreover, the decision maker accept a deviation of the reference makespan such that the accepted deadline is fixed to

$\tilde{d} = 110\%C_{max}^{ref}$. The goal is to identify, among the six deterministic schedules, the most robust one. So we evaluate for each of them, its service level (EV_2). The results are given in table 4.

Schedule	C_{max}^{ref}	\tilde{d}	RL
s_1	48	53	97%
s_2	56	61	95%
s_3	44	48	93%
s_4	48	53	97%
s_5	60	66	97%
s_6	56	61	94%

Table 4. Robustness evaluation for 6 schedules

Three schedules (s_1, s_4, s_5) have the best and same service level (97%). The decision-maker can decide to choose the one whose Makespan C_{max}^{ref} is the lowest making a compromise between optimality (makespan) and robustness (service level). Here s_1 and s_4 have the same compromise. We assume that the decision-maker decides to implement s_4 .

5.3 Scenario 3: Determination of the delivery date

Following the determination of robust scheduling (s_4), the decision-maker must inform the packaging unit of the delivery date of the products despite the uncertainties. This delivery date must be the most accurate possible to avoid creating stock upstream of the packaging workshop or conversely to create a lack of jobs in this one. For the schedule s_4 , the decision-maker wants to know which deadline \tilde{d} he can promise to the person in charge of the packaging workshop despite the perturbations (with the same conditions as in scenario 2). In order to determine this deadline, it is sufficient to carry out a sensitivity analysis (EV_3). The input parameters of the problem are therefore, the schedule s_4 , the perturbation of uncertainty on execution durations with the same parameters as previously and a service level threshold equal to RL_{lim} . When applying the EV_3 problem, we can find the minimal deadline reached is $\tilde{d} = 53$ hours for s_4 . This represents the deadline that the decision maker can propose.

6. CONCLUSION AND PERSPECTIVES

This paper proposes a formalization of robustness specification for evaluating the schedule facing perturbations. The robustness measure is then based on service level as robustness metric. From this specification, this paper define a framework gathering several relevant problems of robustness. In fact, instead of simply with trying to evaluate and then maximize a single performance of robustness, we have shown in this paper that the robust scheduling problem can be enriched. Indeed, robust scheduling is a multi-faceted issue that can be approached considering different points of view (stability, sensitivity, service level). It seems important to us, since the final objective is to help the decision maker, to be able to preserve these different points of view in a robust scheduling framework. This is the goal of the presented framework.

We then illustrated how these problems can effectively be useful to the decision maker's concerns in a real-world context.

The proposed framework allows to contribute to the concept of industry 4.0 and specially to the robust scheduling challenge. When implementing such framework in a decision process, it can give to the decision maker a constant information on the schedule to be implemented in the workshop. When using the data recovered from the data science unit in the workshop. The decision process can be continuously adapted to the upcoming changing in the perturbations considered. A perspective of this work is therefore to implement this framework in an industrial context in order to create a complete decision making process. This perspective opens the doors for several research questions going from data processing to the implementation of the process in a flexible and agile environment. Furthermore, the proposed framework has been defined in the context of scheduling, but this framework can be more general. Indeed, it would be interesting to generalize this framework whatever the problem, the criterion and the perturbation taken into account.

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