Process for joint scheduling based on health assessment of technical resources

G. Bencheikh, A. Letouzey, X. Desforges,

Ecole Nationale d'Ingénieurs de Tarbes, Laboratoire Génie de Production
(e-mail: {ghita.bencheikh, agnes.letouzey, xavier.desforges}@enit.fr)

Abstract: Production and maintenance services are usually in conflict since their activities are performed on the same resources, their operations are often considered as sources of disturbance to each other. The objective of this paper is to describe a process enabling to schedule simultaneously the production activities and maintenance operations. The proposed process is based on a multi-agents system that has shown its effectiveness in dealing with conflict situations. It consists in scheduling the production activities on the resources taking into consideration their health states. Thus, instead of waiting for the resource to fail or of planning in advance preventive maintenances where some would be unneeded, the health assesment functions provide information about the reliability of the production technical resources. Among this information, degradation measurements permit the prediction of the remaining durations of use also known as remaining useful lifetimes. Thus they enable prior planning for maintenance orders and scheduling the production activities, so that conflicts can be managed between maintenance and planning activities.

Keywords: condition-based maintenance, prognostics and health management, multi-agents systems, scheduling.

1. INTRODUCTION

In the industry sector, the scheduling problems are among its most significant activities for which the various resources, manpower or materials, can be unavailable for many reasons. However, most of the literature dealing with this field of research consider either the total availability of the resources or the deterministic case where the demands and the unavailability periods are priorly known. Even if periods during which some resources are unavailable can be known as, for example, the holidays for workers and preventive maintenance operations of workshop machines, in other cases they are unpredictable, such as illness and breakdowns. Although many studies have been dedicated to maintain the material resources in good working states, most of them do not take into account the production demands.

The fusion of production and maintenance scheduling can doubtlessly increase the agility of production systems. Yet, these two aspects have always been dealt separately generating conflicts between the two services since both perform on the same machines. Overlooking this issue can causes serious damages on the production process, which may be costly to the companies in terms of resources and customer satisfaction. There is therefore a need to develop methods making these two services collaborate to achieve a common goal.

Implementing health assessment functions (fault detection, diagnostic and prognostic functions) in production systems seems to be the appropriate way not only to analyse their failures and their origins but also to predict the evolution of degradations and future breakdowns. This consists in assessing with a given probability the duration of use of a component before it reaches the failure threshold (Desforges et al., 2017). Indeed the Prognostic and Health Management (PHM) paradigm, extending the Condition-Based Maintenance (CBM) one, has introduced the need of predicting future behavior, including the Remaining useful Life (RUL) and/or Mean Time Between Failures (MTBF) of technical systems (Ammour et al. (2017)). Thus, the prediction of future failures of the system. The use of these functions reduces the corrective and the occurrence of preventive maintenances since they are sole considered when the risk of failure of a required function (or service) is significantly high. The main goal of the PHM is to provide precise informations that helps in making adequate decisions. In the last few years, many works and methods have been proposed to evaluate and enhance the $RULs$ of components to improve the equipment availability, such as : (Heng et al., 2009), (Vachtsevanos et al., 2006), (Gouriveau et al., 2016), (Peng et al., 2010), Takai (2015), Ammour et al. (2017).

The objective of this paper is to propose a generic method to plan simultaneously the production operations and conditioned maintenance activities according to the health states of the production machines. Beside, even though a function of a machine is unavailable, the machine can still perform other operations that do not require the unavailable function. This method aims to satisfy as more as possible both services objectives. The production and maintenance are assumed to be in different locations, which adds a distributed aspect to the method.

In the following sections, we briefly review some related works. The problem formulation and operations to be scheduled are fully described in section 3. In section 4 the process for joint scheduling based on multi-agents systems is presented and explained thanks to an example described in section 5. Finally, section 6 concludes the paper and gives future works.

2. STATE OF ART

According to (Khelifati and Benbouzid-Sitayeb, 2011) the joint scheduling problem has been proven to be an NP-hard problem, which explains why most of the solving methods proposed in the literature are approximative. The approaches dealing with scheduling problems with unavailability periods can be classified into two categories: deterministic approaches and stochastic approaches. Considering the deterministic approaches, a large amount of articles deal with scheduling problems. To our knowledge all the workshop cases have been studied. Regarding the stochastic approaches, few researchers are interested in this field and the number of related works is therefore less numerous.

In (Kaabi et al., 2002) four heuristics are proposed to solve the joint scheduling problem on a single machine with systematic preventive maintenance constraints aiming at minimizing the total tardiness of jobs.

Khelifati and Benbouzid-Sitayeb (2011) have proposed a multi-objective genetic approach to schedule production and maintenance in a job-shop workshop. Another application of the evolutionary solving of joint scheduling is proposed in (Alaoui Selsouli, 2011) where the initial population is obtained by decomposition methods (Lagrangian relaxation using the sub-gradient algorithm, Danzig Wolfe by a Benders generation and decomposition algorithm). The authors have considered the "lot sizing" problem, where the objective is to determine a production plan for a set of N products over a horizon made of T period lasting τ. In the same context, Najid et al. (2011) provided a mixed integer linear programing for joint scheduling of production and systematic/corrective maintenance planning for multiple objects lot-sizing problem.

Some works use probabilities to solve the maintenance scheduling problem, like (Hnaien and Yalaoui, 2010) where the two cases: deterministic and stochastic scheduling problem via a bi-objective optimization method have been compared. The dates at which the machines become faulty are calculated according to a probabilistic law. Then an application embedded a Genetic Algorithm (GA) to solve the problem is proposed. In (Wang and Liu, 2015) the prevention of maintenance is calculated using a probabilistic function that restores the machines to their factory state "as good as new". This work propose a multi-objective mathematical formulation to model this problem and use a multi-objective GA to solve it.

In (Benbouzid et al., 2003) two strategies of scheduling are presented: the sequential strategy and the integrated strategy. The sequential strategy is made of two stages: initially it consists in scheduling the production tasks then it integrates the maintenance, taking the scheduling of the production tasks as a strong constraint. For the integrated strategy, a joint schedule is considered without any priority between production and maintenance activities. The GAs have proved their effectiveness during the simulations made by the authors. Few years later, the same authors have proposed in (Benbouzid-Sitayeb et al., 2006) the "ant colony" meta-heuristics to solve the joint scheduling problem for flow-shops.

To our knowledge, no method that takes health states of several production machines while scheduling the production activities has been proposed. However, Cassady and Kutanoglu (2003) have studied the single machine version of this problem, taking into account the degrading status of the machine, they suppose that the evolution of the degradation mode follows a Weibull distribution. They have shown that the joint scheduling strategy reduces up to 30% the tardiness of tasks comparing to the separate scheduling strategy.

Coudert et al. (2002) have developed a framework area (RAMSES-II) based on multi-agents systems enabling negotiations between services. RAMSES-II scheduler is composed of several RAMSES_Production agents, RAMSES_Maintenance agents and a blackboard which is regularly updated during the negotiation process. Each RAMSES_Production agent represents a workshop, and each RAMSES_Maintenance agent is dedicated to the scheduling of maintenance operations of three types: preventive, conditional and corrective activities. First, all producer and maintenance agents schedule their operations. Then they check whether there is a conflict, if so, an exchange of messages between the involved agents is carried out to reach a compromise that best satisfies the respective agents objectives.

In this work, we propose developments based on the research works of (Coudert et al., 2002) including some changes on the scheduling policies. Here, the agents schedule their operations according to the current and the future health states of the machines. Thus the production and maintenance operations planning is build simultaneously so that no production interruptions appear. The maintenance orders are planned only if the risk of failure of a needed function is too high during a production task and only during the unused time of the machine.

3. PROBLEM DESCRIPTION

In this paper, a joint scheduling problem in a manufacturing system is considered, where a finite set of articles $A = \{a_1, ..., a_{na}\}$ are demanded by costumers. Each article must be delivered before its due date, otherwise a tardiness cost must be paid by the producers. A full description of the production sequence of the articles is given in section 3.1.

In order to produce these articles, a set of machines $M = \{m_1, ..., m_{nm}\}$ are available in the manufacturing systems where each machines ensures one or more well-defined functions with a given capability. Each machine is a multi-components system (described in the section 3.2), processing at most one order at a time and cannot be interrupted until its completion.

In this problem we consider machines of limited availability that can be maintained if it becomes unable to perform a required function. The availability is defined as the probability that a system or a device can fulfill a given task while a given duration Frankel (2012). In the case of an unavailable function, the machine can perform other operations that only solicit its available functions.

From a maintenance point of view, we focus on the CBM

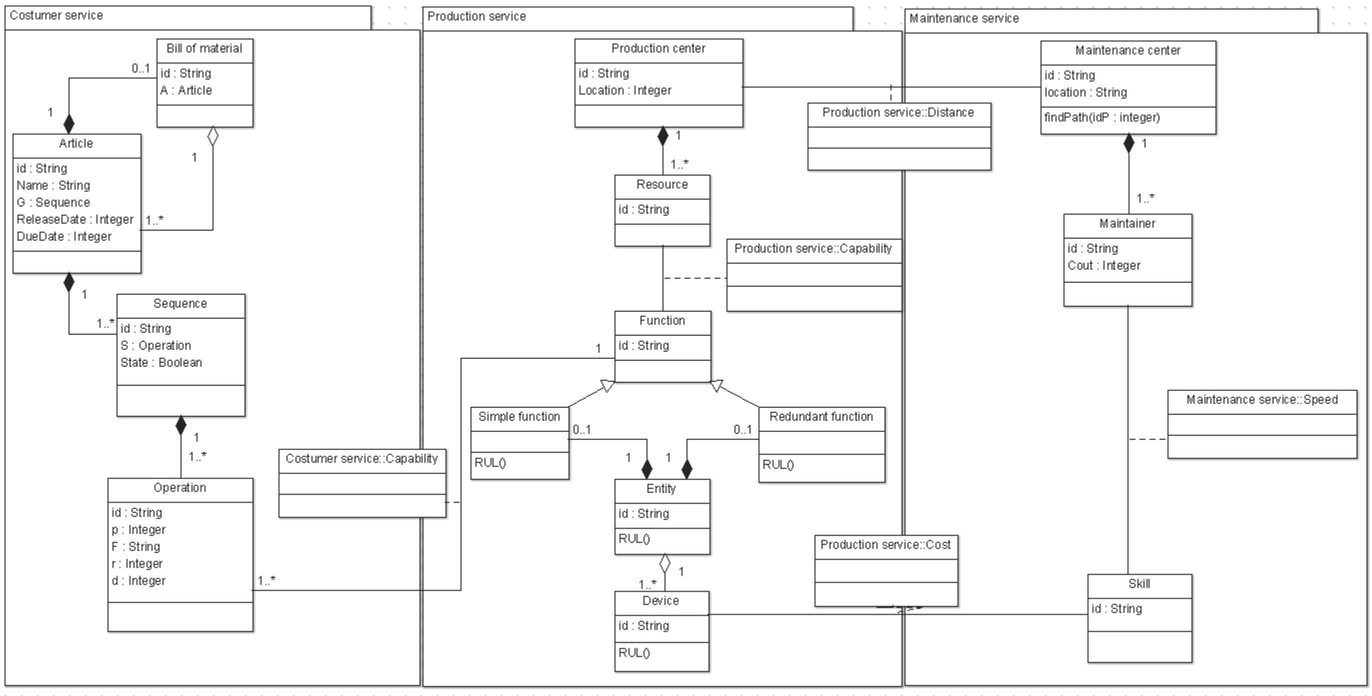

Fig. 1. Class diagram presenting the MO/production and maintenance services

activities. The production tasks and the maintenance activities are synchronously planned according to the current and the future health states of the machines defined by health assessment functions. Therefore, the production sequence interruptions are as seldom as possible.

Generally, manufacturing systems use multiple maintenance centers to repair their machines. The maintenance and manufacturing centers are not located at the same place which means there is a distance between production and maintenance centers. A maintenance center is made of a given number of maintenance resources (maintainers) that, each, has given skills which allow it to repair given types of devices within given capabilities leading to operative times. The maintainers can also be unavailable at some moments as well (holidays, deseases...). However, this unavailability periods of the maintainers are not discussed in this paper, thus they are considered as known. A class diagram of the problem and the links between the services is shown in figure 1, where the parts (a), (b) and (c) of the figure respectively represent the customer, the production and the maintenance services.

3.1 Articles description

An article is divided into a set of components that are grouped in a bill of material. The manufacturing of each component thus goes through a sequence of activities. However, it is possible that components of an article depend on each other. In such a case, the sequence of activities of a particular component cannot start until the end of the manufacturing of one or more of its components. Thus, the tree structure seems to be the most relevant to model the articles. Concretely, these components are represented by the nodes of the tree and the fabrication of the article starts from the lowest level of the tree (the leaves). The variable *state* of the sequence class in figure 1-(a) is a boolean variable equal to 1 if the current sequence can be processed, 0 otherwise, and the operations of each sequence are denoted by: $MO_j = (id_j, p_j, F_j, r_j, d_j)$, where:

- id_j : identification key of the manufacturing order.
- p_j : processing time on the quickest machine.
- F_j : the functionality required.
- r_j : release date.
- d_j : due date.
- w_j : width or importance of the operation.

3.2 Resources description

Multiple definitions has been proposed to describe what a system is. However all these definitions overlap on the fact that a system is a set of interconnected elements (devices) in order to accomplish one or several functions. Two types of systems can be distinguished, the difference between them lies in the number of devices composing them. A simple system has few devices and their behavior is fully understandable and predictable. They are often called multi-components systems. A complex system is made of many devices that collaborate to bring into operation a whole entity. In this kind of systems a simple change in one device can have far reaching consequences for the system as a whole. When a device involved in the implementation of the function fails, the machine loses the ability to perform the corresponding function when this one is simple. Nevertheless, if the function is redundant, it can still be performed as long as an another entity performing the function is available. When the system fails, it is thus necessary to determine the devices causing the failure to repair or to replace it thanks to a maintenance operation. Industrial maintenance has been introduced to ensure the reliability, availability and safety of an industrial system during its lifetime. However, the wait till failure is fixed can lead to disastrous economic consequences and can impede breaks of production cycles. Therefore, the maintenance strategies have evolved in the recent years. Industrial maintenance now gathers different methods, tools, techniques and processes to reduce maintenance costs while certifying it objectives. According to Jouin (2015) this evolution has started from the corrective maintenance through the preventive maintenance finally arriving at the CBM now extended by the PHM.

The CBM or PHM actions are planned and led according to the health states of the equipments. Thess health states are obtained by performing regularly health assessment functions for the devices and by assessing their $RULs$. This makes it possible to plan in advance the maintenance of the devices having critical $RULs$. There are three main approaches for estimating $RULs$: experience-based, model-based and data-driven approach. A comprehensive survey of these methods and bibliography is given by Gouriveau et al. (2016). However, regarding the complex systems, the sole knowledge of the RUL is not enough, according to Desforges et al. (2017) the number of $RULs$ can be very huge and it is difficult to assess the system health from RULs providing data from different types. They so propose a method based on object-oriented Bayesian networks whose inputs are local prognostics transformed into probabilities of failure within a given duration of use to assess the system health but also the health of its functions.

A maintenance order is called only when the health status of the machine is not able to perform a longer sequence of planned production operations, ie. when the production system requires a function of the machine but whose failure probability is too high so that the producer will not risk to use it. A maintenance operation will thus be joined to the planning. A maintenance order is denoted as: $TO = (M_i, C_j, t)$, where each field corresponds to:

- M_i : id of the machine
- C_j : critical component
- t : desired date of maintenance

In this work, we assume that the evolution of degradation of the devices follows an exponential law because they are easy to simulate and that the maintenance actions restore the devices or components to their "as good as new" health status.

4. METHODOLOGY

Multi-agents systems are an approach to model and develop applications in which decisions are decentralized by nature within agents. They are part of what is known as Distributed Artificial Intelligence (Drogoul, 2000). These autonomous agents interact with each other directly or indirectly through a shared space called blackboard or environement, in order to achieve their individual and collective goals (Picard, 2004). The multi-agents approaches have shown their interest in conflict situations since they can be solved by negotiation techniques, in which the compromises moderate the satisfaction and frustration of agents Archimède and Coudert (2001).

The multi-agents model proposed in this paper is inspired by the model Supervisor, Customers, Environment, Producers (SCEP) first introduced by Archimède and Coudert (1998) to solve scheduling problem. This model is developed for many types of planning activities. Thus a variety

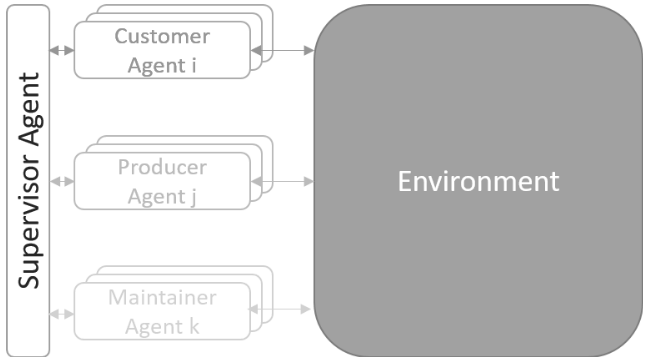

Fig. 2. SCEP&M multi-agents Model

of scheduling/planning approaches based on SCEP have been proposed in the literature. Coudert et al. (2002) have shown through RAMSES-II system the ability to distribute decision making and can also provide a framework to make several functions cooperate in the scheduling process like production and maintenance. Archimède et al. (2014) applied the distributed SCEP (DSCEP) framework to solve the shared resources scheduling problems. In (Memon, 2014) the I-POVES model has been developed for collaborative transportation planning activities that is also inherited from SCEP.

The multi-agents model, SCEP&M considered here is based on the architecture described in figure 2. A detailed description of the agents and the communication protocol between them are given in the next two sections.

4.1 Agents description

- The environment is a blackboard on which the customers, producers and maintainers broadcast their demands and/or proposals. The cooperation between customer agents, producer agents and maintenance agents is performed synchronously through the background environment agent. The positions format of the objects is : $([t_1, t_2], j)$, t_1 and t_2 are respectively the starting and completion date of the operation on the resource j.
- The supervisor is the agent who manages the auctions, controls the negotiation between the different agents and gives them access to the blackboard to distribute their requests or proposals and validate some of them.
- Each customer agent manages the construction of one order given by the customers. The customer agent associates to each operation composing the article an object in the environment. Each object in the environment concerns one and only one customer and one object can be made by several producers. The main objective of each customer agent is to respect the due dates claimed by its corresponding customer.
- Each producer agent manages one machine. It schedules the MO it is able to perform according to the machine health status it assesses and it makes the requests for the maintenance operations of devices that need them if its availability frustrate the production sequencing. It should be noted that the duration of execution of an operation may vary from one machine to another depending on its capability to perform the functions required by the productive operations.

- Each maintenance agent manages one maintainer with specific skills of one service. The maintenance agent schedules the TO according to its availability since the corresponding maintainer can be in mission for an other manufacturing service.

4.2 Communication protocol

At the beginning of each cycle, the supervisor agent invites the customer agents to display their wishes for each operation on the blackboard, it is the action A of the sequence diagram shown in figure 3. Then the supervisor sends the message 3 to give access to the producer agents so that each one lists the operations he can perform. A producer agent i schedules its list of MO according to its own rule and its machine health status during the action B. The production scheduling rules can vary according to the production system features and its optimization criteria to satisfy its objectives. Before finalizing any position for an operation, the producer agent certifies if its machine health status is able to carry it out entirely or not. If the availability of the machine enable to carry out the operation, two positions for the current operation are announced by this producer, effective (EP) and potential (PP) positions, which represent respectively the upper bound and the lower bound. A EP is associated to the result of the scheduling of all the operations according to the machine's rule, while a PP corresponds to the result of the scheduling of the current operation only.
The scheduling process of a producer agent continues until the arrival of an operation its machine will not be able to carry out completely. In this case a request for maintenance operation TO is displayed on the blackboard (message 4) requiring skills according to the device to maintain. The scheduling of the remaining operations on this machine is then suspended until the producer agent gets an answer from the maintainers for the launched TO. This answer will be maintenance proposals sended by maintainer agent, with the needed skills, with their potential and effective positions.
During the action D, the producer agents compare the different proposals received from the maintainer agents to their objectives. A producer agent can accept one effective proposal, if it is equal to the potential position. In this case the negotiation between this producer agent and the maintainer agents ends. Otherwise, an other round of proposals is started for the maintainer agents and for the TO that are not yet accepted.
When the scheduling of all operations ends, the producer agents send the message 7 to post up their proposals on the blackboard. Then, each customer agent compares during action E the different positions and validates the ones that satisfy its objectives. All costumer agents then update then their wishes for the invalidated operations such as they become the best effective position proposed for them.
Once the supervisor agent receives the information that all customer agents have ended the actions of validation, the supervisor agent activates the access for producer agent so they can read the validated positions and join them in their planning. According to the result of validation of MO made by the costumers the producers decide whether the accepted TOs must be validated or not. Several TO validation strategies can be considered such as:

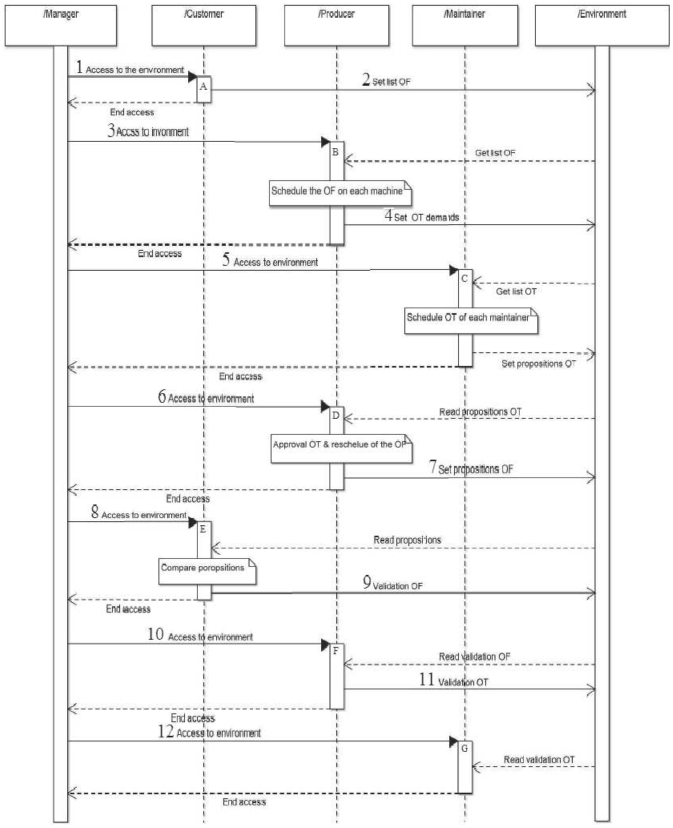

Fig. 3. Sequence diagram of the multi-agent model

- The automatic validation of TO if a proposal from the current producer agent has been validated,
- A percentage of TO must be validated at each cycle,
- The time gap between the last validated operation on the machine and the wished start date of the TO is under a certain threshold,
- etc.

After the validation of the TOs, the supervisor gives access to the maintainers so they can schedule the validated TO during this cycle (action G). At the end of the action G, the supervisor agent finishes the current cycle and starts the next one immediately.
During each cycle, the number of the MO to schedule is reduced, since during each one, the position of at least one MO is fixed. This ensures the convergence of the method as proven by Archimède and Coudert (1998).
For a better understanding of the $SCEP\&M$ functioning, an illustrative execution example of a simple case study is presented in the next section.

5. ILLUSTRATIVE EXAMPLE

In this case study, three articles must be produced in the manufacturing system following their linear routings. The description of the articles and the routing are respectively listed in table 1 and 2.
The considered shop is made of three machines that can achieve several activities like milling, turning and drilling with a given capability. The details of the resources can be found in table 3.
This machines can be repaired by three different maintenance centers, each of them gathers a set of maintainers

having defined skills with given capabilities to repair components as shown in table 4.
In order to keep the example simple, we consider that the production and maintenance scheduling is a first in first out (FIFO) rule, and TO is validated when at least one MO has been validated on this machine.

MO	Quantity	Order date	Due date	Routing
1	1	2	26	1
2	1	1	14	2
3	1	0	9	3

Table 1. Characteristics of the MOs

Routing	Operation	Activity	Duration
1	1	Milling	6
	2	Turning	8
	3	Drilling	5
2	1	Turning	8
	2	Drilling	7
3	1	Drilling	8.5

Table 2. Characteristics of the routings

Machine	Activity	Capability	component
1	Milling	1	C_{11}, C_{12}, C_{13}
2	Turning	1	C_{21}, C_{22}
3	Drilling	1	C_{31}, C_{32}, C_{33}
	Turning	1.5	C_{33}, C_{34}

Table 3. Characteristics of the machines

Center	Maintainer	Skills	Speed
1	1	C_{k1}	1
		C_{k2}	1.5
		C_{k3}	1
	2	C_{k1}	1.5
		C_{k3}	1.5
2	1	C_{k4}	1

Table 4. Characteristics of the maintainers

In the blackboard environment of the multi-agents system, 4 fields are listed, the object, wish, Eff for effective, Pot for potential and position, where:

- Object is the operation to be performed. In case of a MO, it is presented by the 3-tuple: (i, j, f), where i refers to the customers ID, j to the operation ID and f refers to the requested function. As for the TO, they are represented by: (i, C_j) such as C_j corresponds to the critical component and i to its machine's ID.
- Wish $[t_1, t_2]$ corresponds to the starting and final date desired for the corresponding operation.
- Eff and Pot $([t_1, t_2], k)$ corresponds respectively to the effective and potential position proposed.
- Position is the definitive position of the object.

At the beginning of the first cycle, the supervisor initializes the agents and gives the customers agents the access to the environment in order to display their wishes. Table 5 shows the results of the first action made by the customer agents over the environment, where the list of the objects and their corresponding wishes are listed. Then, the producer agents start their production scheduling.

Object	Wish	Eff	Pot	position
$(1,1,M)$	$[2,8]$	$\emptyset$	$\emptyset$	$\emptyset$
$(1,2,T)$	$[8,16]$	$\emptyset$	$\emptyset$	$\emptyset$
$(1,3,D)$	$[16,21]$	$\emptyset$	$\emptyset$	$\emptyset$
$(2,1,T)$	$[1,9]$	$\emptyset$	$\emptyset$	$\emptyset$
$(2,2,D)$	$[9,16]$	$\emptyset$	$\emptyset$	$\emptyset$
$(3,1,D)$	$[0,8.5]$	$\emptyset$	$\emptyset$	$\emptyset$

Table 5. Initial environment

During the scheduling process, the producer agents 2 and 3 have identified a need for a maintenance order on the components C_{21} and C_{33} at time 9 and 20.5 within a repair time equal to 11 and 10. These components must be maintained in order to fulfill entirely the production sequences.
The list of proposals received by the maintainer agents is given in table 6. Since, two maintainer agents (1 and 2) can repair the component C_{33} they both propose their services.

Object	Wish	Eff	Pot
$(2,C_{21})$	$[9,20]$	$([9,21],1)$	$([9,21],1)$
$(3,C_{33})$	$[20.5,30.5]$	$([21,31],1)$	$([20.5,30.5],1)$
		$([20.5,35.5],3)$	$([20.5,35.5],3)$

Table 6. Propositions for the TO

A choice of position for the object $(3, C_{33})$ must then be taken by the producer agent. For the component C_{21}, one maintainer only can repair it, the position proposed for it is therefore settled. The results of the TO acceptance process is given in table 7.

Object	Wish	Eff	Pot	position
$(2,C_{21})$	$[9,20]$	–	–	$([9,21],1)$
$(3,C_{33})$	$[20.5,30.5]$	–	–	$([21,31],1)$

Table 7. TO accepted

Each producer agent then resumes by the scheduling of its MOs taking into account the accepted TO, and displays the list of its proposals on the blackboard, as shown in table 8.

Object	Wish	Eff	Pot	position
$(1,1,M)$	$[2,8]$	$([2,8],1)$	$([2,8],1)$	$\emptyset$
$(1,2,T)$	$[8,16]$	$([21,29],2)$	$([8,16],2)$	$\emptyset$
		$([31,43],3)$	$([8,20],3)$	
$(1,3,D)$	$[16,21]$	$([50,55],3)$	$([16,21],1)$	$\emptyset$
$(2,1,T)$	$[1,9]$	$([1,9],2)$	$([1,9],2)$	$\emptyset$
		$([2.5,20.5],3)$	$([1,13],3)$	
$(2,2,D)$	$[9,16]$	$([43,50],3)$	$([9,16],3)$	$\emptyset$
$(3,1,D)$	$[0,8.5]$	$([0,8.5],3)$	$([0,8.5],3)$	$\emptyset$

Table 8. Propositions for the MO

The customer agents then compare the different positions received. Since the effective and potential positions given by producer agent 1 and corresponds to the customer wish, the given position is then fixed for the object 1. It is the same for its proposal to the last object and those given by producer agents 2 and 3 to the 4^th and the 6^th objects. As for the other operations, another scheduling is processed by the agents.

The final solution obtained after the last cycle of the process is presented in table 10, and the corresponding Gantt diagram is shown in figure 4.

Object	Wish	Eff	Pot	position
MO				
$(1,1,M)$	$[2,8]$	$-$	$-$	$([2,8],1)$
$(1,2,T)$	$[8,16]$	$([21,29],2)$ $([31,43],3)$	$([8,16],2)$ $([8,20],3)$	$\emptyset$
$(1,3,D)$	$[16,21]$	$([50,55],3)$	$([16,21],1)$	$\emptyset$
$(2,1,T)$	$[1,9]$	$-$	$-$	$([1,9],2)$
$(2,2,D)$	$[9,16]$	$([43,50],3)$	$([9,16],3)$	$\emptyset$
$(3,1,D)$	$[0,8.5]$	$-$	$-$	$([0,8.5],3)$
TO				
$(2,C_{21})$	$[9,20]$	$-$	$-$	$([9,21],1)$
$(3,C_{33})$	$[20.5,35.5]$	$-$	$-$	$([21,31],1)$

Table 9. MO and TO validation

Object	Wish	Eff	Pot	position
MO				
$(1,1,M)$	$[2,8]$	$-$	$-$	$([2,8],1)$
$(1,2,T)$	$[8,16]$	$-$	$-$	$([8.5,20.5],3)$
$(1,3,D)$	$[16,21]$	$-$	$-$	$([38,43],3)$
$(2,1,T)$	$[1,9]$	$-$	$-$	$([1,9],2)$
$(2,2,D)$	$[9,16]$	$-$	$-$	$([31,38],3)$
$(3,1,D)$	$[0,8.5]$	$-$	$-$	$([0,8.5],3)$
TO				
$(2,C_{21})$	$[9,20]$	$-$	$-$	$([9,21],1)$
$(3,C_{33})$	$[20.5,35.5]$	$-$	$-$	$([21,31],1)$

Table 10. Environment at the end of the last cycle

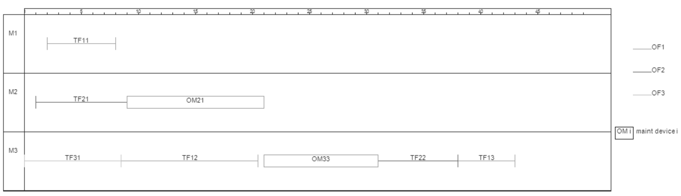

Fig. 4. Gantt diagram of the joint scheduling

Noticing from the final solution presented in figure 4 that production and maintenance activities are well scheduled with no overlapping. However, since all the maintenance activities launched at by producers at each cycle are validated, some of them would not be necessary like OM_{21}, which increases the total maintenance cost. The activity OM_{21} has been launched by producer 2 at the first cycle because the health state of the machine could not execute both activities $TF_{(1,2)}$ and $TF_{(2,1)}$. But, in the end, the activity $TF_{(1,2)}$ has been fixed on machine 3, and so the OM_{21} is no longer needed. In more complicated cases, this lake of control can cause serious damages in the manufacturing system like the break of the production process. Therefore, some maintenance validation strategies should be integrated.

6. CONCLUSION

We show in this work how the use of health assessment functions can help to manage conflicts between the production and maintenance services. A SCEP&M multi-agents system is proposed, where the sequences of production operations and condition-based maintenance activities are built simultaneously during each cycle of the process. Further strategies for the scheduling made by each producer agent and for validating maintenance proposals are under investigations and will be subject of future papers, in order to increase the agility of the production system. In our future works, we expect to improve the method by gathering the maintenance tasks such as the requests for maintenance. This could be modeled by sets of TO and not only one. The gathering of the TO could significantly reduce maintenance costs due travelling expenses that would be less numerous.

REFERENCES

Alaoui Selsouli, M.M. (2011). *Modélisation et résolution d'un problème de la planification conjointe de production et de maintenance*. Ph.D. thesis, Nantes.

Ammour, R., Leclercq, E., Sanlaville, E., and Lefebvre, D. (2017). State estimation of discrete event systems for rul prediction issue. *International Journal of Production Research*, 55(23), 7040–7057.

Archimède, B. and Coudert, T. (1998). A multi-agent scheduling approach for the flexible manufacturing production systems. *IFAC Proceedings Volumes*, 31(32), 143–148.

Archimède, B. and Coudert, T. (2001). Reactive scheduling using a multi-agent model: the scep framework. *Engineering Applications of Artificial Intelligence*, 14(5), 667–683.

Archimède, B., Letouzey, A., Memon, M.A., and Xu, J. (2014). Towards a distributed multi-agent framework for shared resources scheduling. *Journal of Intelligent Manufacturing*, 25(5), 1077–1087.

Benbouzid, F., Varnier, C., and Zerhouni, N. (2003). Resolution of joint maintenance/production scheduling by sequential and integrated strategies. In *International Work-Conference on Artificial Neural Networks*, 782–789. Springer.

Benbouzid-Sitayeb, F., Varnier, C., and Zerhouni, N. (2006). Résolution du problème de l'ordonnancement conjoint production/maintenance par colonies de fourmis. In *6ème Conférence Francophone de MOdélisation et SIMulation, MOSIM'06. Modélisation, Optimisation et Simulation des Systèmes: défis et opportunités.*, sur CD ROM, 10–pages.

Cassady, C.R. and Kutanoglu, E. (2003). Minimizing job tardiness using integrated preventive maintenance planning and production scheduling. *IIE transactions*, 35(6), 503–513.

Coudert, T., Grabot, B., and Archimède, B. (2002). Production/maintenance cooperative scheduling using multi-agents and fuzzy logic. *International Journal of Production Research*, 40(18), 4611–4632.

Desforges, X., Diévart, M., and Archimède, B. (2017). A prognostic function for complex systems to support production and maintenance co-operative planning based on an extension of object oriented bayesian networks. *Computers in Industry*, 86, 34–51.

Drogoul, A. (2000). *Systèmes multi-agents situés*. Ph.D. thesis, Université Pierre et Marie Curie, Paris.

Frankel, E.G. (2012). *Systems reliability and risk analysis*, volume 1. Springer Science & Business Media.

Gouriveau, R., Medjaher, K., and Zerhouni, N. (2016). *From Prognostics and Health Systems Management to Predictive Maintenance 1: Monitoring and Prognostics*. John Wiley & Sons.

Heng, A., Tan, A.C., Mathew, J., Montgomery, N., Banjevic, D., and Jardine, A.K. (2009). Intelligent condition-based prediction of machinery reliability. *Mechanical Systems and Signal Processing*, 23(5), 1600–1614.

Hnaien, F. and Yalaoui, F. (2010). Optimisation biobjectif d'ordonnancement et de maintenance dun atelier flow-shop. *MOSIM 2010*.

Jouin, M. (2015). *Contribution au pronostic d'une pile à combustible de type PEMFC-approche par filtrage particulaire.* Ph.D. thesis, Université Bourgogne Franche-Comté.

Kaabi, J., Varnier, C., and Zerhoni, N. (2002). Heuristics for scheduling maintenance and production on a single machine. In *Systems, Man and Cybernetics, 2002 IEEE International Conference on*, volume 5, 5–pp. IEEE.

Khelifati, S.L. and Benbouzid-Sitayeb, F. (2011). A multi-agent scheduling approach for the joint scheduling of jobs and maintenance operations in the flow shop sequencing problem. In *International Conference on Computational Collective Intelligence*, 60–69. Springer.

Memon, M.A. (2014). *Transportation interoperable planning in the context of food supply chain*. Ph.D. thesis, INP, Toulouse.

Najid, N.M., Alaoui-Selsouli, M., and Mohafid, A. (2011). An integrated production and maintenance planning model with time windows and shortage cost. *International journal of production research*, 49(8), 2265–2283.

Peng, Y., Dong, M., and Zuo, M.J. (2010). Current status of machine prognostics in condition-based maintenance: a review. *The International Journal of Advanced Manufacturing Technology*, 50(1), 297–313.

Picard, G. (2004). *Méthodologie de développement de systèmes multi-agents adaptatifs et conception de logiciels à fonctionnalité émergente*. Ph.D. thesis, Université Paul Sabatier Toulouse III.

Takai, S. (2015). Robust prognosability for a set of partially observed discrete event systems. *Automatica*, 51, 123–130.

Vachtsevanos, G.J., Lewis, F., Hess, A., and Wu, B. (2006). *Intelligent fault diagnosis and prognosis for engineering systems*. Wiley Online Library.

Wang, S. and Liu, M. (2015). Multi-objective optimization of parallel machine scheduling integrated with multi-resources preventive maintenance planning. *Journal of Manufacturing Systems*, 37, 182–192.