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APPROACH TO REMOTE MAINTENANCE MANAGEMENT OF DISTRIBUTED INDUSTRIAL COMPLEXES

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ABSTRACT

We describe in this paper the characteristics of remote maintenance systems and set up their bases. We also present its basic principles through a general structure model of the system to be managed. A heuristic-based optimization algorithm is proposed to solve the online preventive maintenance resources allocation problem for a distributed system based on the remote maintenance systems' generic architecture and given an availability target for a distributed system. This algorithm allocates the resources to minimize the cost of discharge of preventive maintenance tasks by considering precedence constraints among consecutive standby tasks and their emergency. The criteria for job emergency and priority were used to solve this problem while scheduling the right order tasks. Tasks are allocated according to resource availability along with load balancing. Computational results illustrate the efficiency of the approach implemented on different system configurations.

Keywords: remote, maintenance, availability, optimization, flow-time, scheduling, and allocation

NOTATION

N is the total number of plants in the system

N_k : number of assets of plant k

E_{ik} : asset i of plant k

λ_{ik} : failure rate of E_{ik}

μ_{ik} : repair rate of E_{ik}

s_{ik} : duration of a preparatory work on E_{ik}

p_{ik} : duration of a maintenance job on E_{ik}

M : number of resources in the overall system

$A_{ik}(t)$ is the availability of E_{ik} at time t

α_{ik} : threshold on E_{ik} 's availability

τ_{ik} : theoretic time between consecutive interventions on E_{ik}

$t_{m,ik}$: theoretic starting time of the m^{th} intervention on E_{ik}

$T_{m,ik}$: theoretic end of the m^{th} intervention on E_{ik}

C_{tot} : cost of critical states on the scheduling horizon

1. INTRODUCTION

The methods of maintenance activities management have much evolved in the last few years. Companies tend to limit corrective maintenance, rather suitable to react to equipment failures, to the benefit of preventive one. More advanced companies implement predictive or proactive maintenance (Rao, 1996) using monitoring tools. This strategy privileges the concept of maintenance service against classical maintenance.

In the sequel, we will focus on the maintenance management of industrial production facilities distributed on different plants. For such configuration, the technical and economic effectiveness of the maintenance requires organization and management based on network information systems, making it possible to ensure functions able to enhance distance between the plants (Tromp, 2000): communication, exchange of data and information, remote monitoring, remote diagnosis, maintenance jobs planning and tasks scheduling, risk management, etc.

In a competing context where the customers' requirements become increasingly precise and measurable in terms of the right price, the remote maintenance systems allowing management and remote control of the maintenance activities appear better adapted to obtain the best cost/effectiveness ratio. The remote maintenance management then seems well suited for large distributed industrial complexes and companies that outsource their maintenance services. It thus becomes essential to model and analyze the remote maintenance systems for optimal management. Unfortunately, research works in this field are rare and not generic. Authors often use different system concepts and other evaluation methods. This situation complicates the comprehension of their approaches and highlights the lack of a standard model. Simultaneously, it is essential to model the maintenance processes to optimize their management in real-time, given the requirements for the equipment availabilities concerning the available means.

This paper's prime objective is to examine the existing remote maintenance systems for distributed production facilities. The aim is to understand their principles, study their characteristics (Kolski & Millot, 1993), and deduce a model considering their particular constraints.

The second objective of the paper is to propose a first approach to modeling and optimization of maintenance processes in a context of real-time scheduling of preventive actions and real-time resource allocation to the maintenance interventions on distributed industrial complexes (Koole, 1995), (Frostig, 1999), (Seshardi & Pinedo, 1999).

2. REMOTE MAINTENANCE MANAGEMENT

2.1 Characteristics of a remote maintenance

Above all, let us recall that the strategies mainly used in maintenance management are corrective, preventive, predictive, and proactive types. The two last types include conditional techniques (surveillance, detection, isolation, diagnosis, state evaluation, and decision making). Also, they have planning activities and scheduling tasks of maintenance, which require adequate and sometimes specialized resources in terms of human resources, spares, and means for interventions. The remote maintenance, which uses the same classical maintenance strategies, consists of some traditional maintenance actions' remote control. Besides, it requires technicians with the necessary and minimum qualifications and with easily adaptable skills. Remote maintenance systems are already in development in several areas:

For instance, in the computer systems area, the «PCAnywhere» software was developed by SYMANTEC for remote maintenance. It allows intervening on distant workstations in distress, operating from a server. On request of the workstation in distress, the intervener uses specific software functions to remotely perform failed software repair via a communication network, starting from a server or master-station to reach all the workstation files and applications.

In the military field, remote maintenance systems have been developed to ensure a high maintenance service level for weapon systems. They are based on integrated and intelligent sensors systems, information systems, integrated logistics, and hierarchical organization of the remotely controlled maintenance processes. For instance, following the equipment state's assessment by the integrated sensors and diagnosis systems, maintenance technicians close to the material carry out urgent interventions. In the event of no successful result, the assistance of a plant master-technician is requested. In the event of no-satisfaction, the data relating to the material are transmitted to a processing expert center. This center analyses the problem and proposes solutions that are used later to feed the unified information database. This center processes the data, manages the equipment's logistics support, and advises on line the maintenance operations to field technicians.

Several similar projects exist in the medical area. The SAMED project particularly aims to study, conceive, construct, and implement a generic remote infrastructure software and material for remote-medicine applications: remote monitoring, remote maintenance, and various medical and research activities. Its distant maintenance objectives are to ensure the safe operation of the multiple applications installed at the patient residence, provide automatic self-monitoring applications, and download possible news configurations in the medical equipment through telecommunications networks. The medical assistance equipment sensors are continuously «tested» by the local information system, which is equipped with tools for remote control of the equipment functions. Thus, any anomaly is transmitted to the medical expert center, which immediately sends a technical team to regulate or repair the sensor or equipment. This system reduces the non-necessary displacements of technicians.

Other remote maintenance systems are based on concepts similar to those presented above, but very few are used in the industry area. All the information and communication systems technologies are now available to develop similar systems in the industrial area. Many investigations are currently launched to develop methods suitable for the industrial requirements (IMS Center), (Lee, 2001).

2.2 Generalization of the remote maintenance management principles

Apart from the particular applications, the existing remote maintenance systems use concepts with some common points. The remote maintenance system always consists of 3 essential and distinct parts. The structure and the composition of such a system depend on its organization (Derman et al., 1980). For example, the choice of the different categories of resources (material, spares, human) is determined by the performance required for the production facilities. Indeed, these resources management constitutes an important factor of the facilities' availability and the maintenance costs (Berg, 1995) (Lam, 1999) (Park, 1979). One can distinguish three categories of resources: repairmen (human resources), means of intervention (intervention work equipment), spare

parts, and consumables (material resources for replacement). The first type of resources can be classified by specialty and skill, which lead to job assignment and load balancing problems (Koole, 1995) (Frostig, 1999) (Seshardi & Pinedo, 1999). Indeed, the technician skill is an influent factor of the intervention durations and the service level, and the cost.

2.3 Technical aspects of the problem

Remote maintenance of distributed industrial complexes requires the constant knowledge of the production facilities state on each plant, which implies at least three constraints related to the plants:

- 1) Remote monitoring and diagnosis of the facilities' state (using automatic software).
- 2) Transmission of information to the expert center (using appropriate communication tools).
- 3) Real-time decision making in job scheduling, resources allocation (using qualified people)

In this paper, the information system will be assumed to be entirely available. Design such a system remains delicate, own to the difficulties related to the integration of specific requirements:

- 1) High safety and reliability levels for the information system and the instrumentation (data-collection systems, integrated and intelligent sensors, database, software applications, ...)
- 2) Reliability and robustness of the state monitoring equipment, techniques, and methods (periodic inspection, online monitoring or conditional monitoring, ...)
- 3) Robustness of the diagnosis techniques and methods (tendencies monitoring, use of a model, pattern recognition, signature, artificial intelligence, ...).

2.4 Resources management

Resources management is a classical problem in maintenance management (Frostig, 1999) (Koole, 1995) (strategy selection, tasks planning, job scheduling, resource allocation, etc.) Although complex and fundamental, the problem of optimal management of production facilities' maintenance activities is tackled by very few scientists working in the maintenance area (Seshadri, & Pinedo, 1999) (Sinuany-Stern, 1999). Remote maintenance systems must thus solve three main problems in the following order: diagnosis of equipment, evaluation of information, scheduling, and allocation of tasks to resources. Therefore, we propose an original approach of real-time tasks scheduling and maintenance resources allocation in the next section.

Among the few published works on this topic, the main focus is on systems composed of single machines or machines with series-parallel configuration. In this respect, we mention the recent work of Bennour *et al.* (2001), which is based on graph theory and integrates maintenance policies into the working cycle of the machine. Weinstein and Chung (1999), on their part, proposed a mixed-integer linear model, which incorporates preventive maintenance into the production policies. This method aims at minimizing cost and the deviation of production in contrast to maintenance-free production policies. Regarding preventive maintenance, we can also mention the heuristic method of Qi *et al.* (1999) based on the Shortest Processing Time (SPT) priority rule to minimize the makespan in a production policy. They studied the problem of scheduling parallel-machines where preventive maintenance jobs are performed on each machine, just as in Lee & Chen (2000). Graves & Lee (1999) and Qi *et al.* (1999) proposed a branch and bound method to minimize the weighted completion time of jobs based on the partition formulation of single machines' problem.

3. SCHEDULING THE MAINTENANCE TASKS AND ALLOCATING RESOURCES

Let us consider an industrial complex comprising several plants working independently and in parallel (*i.e.*, one plant's unavailability does not affect other plants' availability). Each plant is composed of several assets in serial all the plants share the resources. Thus, at any moment, a resource can be brought from a plant to another. The main problem then is to dynamically evaluate the resource needs at plant levels to establish priorities. The aim is to allocate the resources as optimally as possible at a minimum cost and minimum unavailability targets for each of the complex plants.

Note that in general, preventive maintenance job flow-time relative to one asset increases with the delay time concerning the critical starting dates of jobs for a fixed number of resources. The number M of resources is less than the total number of assets in the system $\Sigma_i(N_i)$. But in the case of jobs having more than two assets, the scheduling, which gives the least delay concerning the critical starting dates, is not necessarily done according to the least flow time.

We assume in our investigations that jobs are executed without preemption and that the setup times s_{ik} of jobs are small enough to be incorporated into the job's duration. We consider time windows over which independent plant unavailability and maintenance operation costs must be minimal in our approach.

3.1 Modeling of the problem

Due to the system's structure (plant independence, plant composed of series assets), a constraint is imposed on asset unavailability at each plant to reduce plants downtime to the allowed minimum. A high unavailability threshold $1-\alpha_{ik}$ for a given availability α_{ik} in $]0; 1[$ is then defined for each asset E_{ik} . An asset E_{ik} that has worked for a specific time with no breakdown and whose unavailability has reached the threshold $1-\alpha_{ik}$ should be shutdown for preventive actions. Under this condition, the asset is assumed to be renewed after maintenance. Subject to this constraint, the objective is to minimize the system preventive maintenance cost. At the end of the time-window $[0, H_1]$ denoted W_1 , the system's state gives the beginning state of the second window $[H_1, H_2]$ denoted W_2 , and so on. Without loss of generality, we assumed exponential behavior law for the assets. Thus from the instant t_0 , the availability of the equipment E_{ik} is given by the expression

$$A_{ik}(t) = \frac{\mu_{ik}}{\lambda_{ik} + \mu_{ik}} + \frac{\lambda_{ik}}{\lambda_{ik} + \mu_{ik}} \exp[-(\lambda_{ik} + \mu_{ik})(t - t_0)] \quad (1)$$

Now, let us consider time-windows of the same length over which the maintenance cost must be minimized. Starting from time window W_1 , one minimizes the cost over each time window through the following steps.

1. Determine the critical instants t_1, t_2, t_3, \dots of assets preventive jobs over the time-window W_1 .
2. Allocate the resources to jobs at the critical instants.

From the initial instant t_0 , the unavailability condition stated above ($1-A_{ik}(t) \geq 1-\alpha_{ik}$) gives the critical time τ_{ik} from which a preventive action must be carried out on E_{ik} . This condition could be expressed as $A_{ik}(t) \leq \alpha_{ik}$, and using the asset E_{ik} 's availability expression in (1) yields the condition $t \leq t_0 + \tau_{ik}$,

$$\tau_{ik} = -[\lambda_{ik}(1 + \rho_{ik})]^{-1} \ln[\alpha_{ik}(1 + \rho_{ik}) - \rho_{ik}] \quad (2)$$

where $\rho_{ik} = \frac{\lambda_{ik}}{\mu_{ik}}$

If no action is carried out on E_{ik} , its unavailability will grow toward a given threshold $1-\alpha_{ik}$. Hence, in the ideal case, if the m^{th} maintenance job on E_{ik} ends at time $T_{m,ik}$, in the time window W_1 , the next intervention on E_{ik} should be scheduled for time $t_{m+1,ik} = T_{m,ik} + \tau_{ik}$. Then, assuming processing time Mtp_{ik} and set up time s_{ik} for jobs on E_{ik} , the completion time of the $(m+1)^{\text{th}}$ job on E_{ik} is $T_{m+1,ik} = T_{m,ik} + \tau_{ik} + s_{ik} + Mtp_{ik}$.

Let us assume that after the critical time, the asset will work with a higher probability of failure and that each time-unit spent by E_{ik} in such a critical state has the cost d_{ik} . We need to minimize the total cost $C_{tot}(W_1)$ relative the times spent by the system in critical states over the time-window W_1 :

$$C_{tot}(W_1) = \sum_{k=1}^N \sum_{i=1}^{N_k} \left(\sum_{m/t_{m,ik} \in W_1} d_{ik} (T_{m,ik} - t_{m,ik}) \right) \quad (3)$$

To simplify, let us assume that the costs d_{ik} are the same for all the assets and are equal to d , then instead of $C_{tot}(W_1)$, we can consider as objective-function $C_{tot}'(W_1)$ given by

$$C_{tot}'(W_1) = \sum_{k=1}^N \sum_{i=1}^{N_k} \left(\sum_{m/t_{m,ik} \in W_1} (T_{m,ik} - t_{m,ik}) \right) = \frac{1}{d} C_{tot}(W_1) \quad (4)$$

Instead of minimizing $C_{tot}(W_1)$, one just has to minimize $C_{tot}'(W_1)$. We then have to solve a scheduling problem with M resources, in which $T_{m,ik} - t_{m,ik}$ corresponds to jobs' flow time, and which can be stated as follows:

(P1): Minimize $C_{tot}(W_1)$ with the M resources

This problem can also be formulated in terms of scheduling as:

(P2): Minimize the total flow time (eventually weighted by the d_{ik}) on M parallel machines.

However, the problem (P2) is different from the classical problems of flow time minimization on a particular point. This property is the first to be considered in the following section. The problem thus formulated has other properties, which are also described in the sequel.

Propriety 1: A precedence constraint links jobs relative to the same asset.

Indeed, if $T_{m,ik}$ is the end of the m^{th} preventive action on E_{ik} , then the beginning $t_{m+1,ik}$ of the $(m+1)^{st}$ work is determined by $t_{m+1,ik} = T_{m,ik} + \tau_{ik}$ where τ_{ik} is as defined in expression (2).

Property 2: Problem (P1) is NP-hard.

Taking advantage of the particular case where the precedence constraint described in property 1 is not considered in problem (P2) and where jobs have the same weight d_{ik} equal to d reduces problem (P2) to problem (P2'), i.e.:

(P2'): *Minimize the total flow time of jobs with unequal release dates on M parallel machines.*

(P2') is NP-hard (Lenstra et al., (1977) and remains NP-hard even in the case where preemption is accepted (Du et al., 1991). It has been proved that (P2') is NP-complete (Bruno et al., 1974). So, (P2) and (P1) are NP-hard.

Therefore, our aim is not so much to find an exact solution to problem (P1), but to find a method for its resolution the best. Now, when the precedence constraints are relaxed, and the jobs are assumed to be available at time $t_{m,ik}$, one may resort the branch and bound heuristic developed in Yalaoui (2000) for its resolution.

3.2 Resolution of the problem

Let us recall that the problem under consideration consists of allocating M resources to maintenance actions on the assets of a system composed of N plants. The aim is to minimize the cost of the total time spent by the system in critical states. This problem is transformed into a flow-time minimization problem in which precedence relationships link jobs. We have proved that the problem is NP-hard. Our target now is to find the appropriate heuristic method to solve it. For this, we resort to the PRTF function (Priority Rule for Total Flow-time) initially introduced by Chu (1990) and Chu (1992) to solve the job-scheduling problem for single-machine. It has been adapted later to the problem of parallel machines. The PRTF function is defined in the following section.

3.3 Definitions and proprieties

Definition 1 (Chu, 1990): Let us consider a set of jobs to be scheduled at time t on a machine. The job j has a release date r_j and a processing time p_j . The associated PRTF function is defined as follows

$$PRTF(j, t) = 2 \max(r_j, t) + p_j$$

With this definition, Chu (1990) proved the following theorem:

Theorem 1: Consider a problem in which two jobs j and j' must be scheduled on a machine that is available after time t , and the aim is to minimize the total flow-time. We suppose that $PRTF(j, t) \leq PRTF(j', t)$. Let π be a schedule in which the job j is scheduled before the job j' and π' be another schedule in which j' is scheduled before j , then π gives a better solution than π' .

The PRTF also has another exciting propriety for our problem (Adzakpa et al.). The following theorem summarizes this propriety:

Theorem 2 (Adzakpa et al.): In scheduling, considering Theorem 1 implies that we also respect the order of the interventions on an asset E_{ik} , whichever it is. In other words, for $m < m'$ and for any asset E_{ik} , theorem 1 allows to schedule the m^{th} intervention on E_{ik} before the m'^{th} intervention.

So, comparing $PRTF(t_{m,ik}, t)$ and $PRTF(t_{m',ik}, t)$ comes to comparing $t_{m,ik}$ and $t_{m',ik}$. Now $t_{m,ik}$ is less than $t_{m',ik}$ (because $m < m'$). Finally, we have $PRTF(t_{m,ik}, t) \leq PRTF(t_{m',ik}, t)$. Hence, Theorem 1 allows the scheduling of jobs on any asset in the appropriate order.

Apart from the function PRTF, we also consider the emergency of the jobs scheduling as defined in the following section.

Definition 2: Let $\Delta_{ik}(t)$ denote at time t the duration between t and the end of the last preventive job on the asset E_{ik} before time t and let us assume that it is the $(m-1)^{st}$ work (cf. figure 3). Thus, we denote Urgent(t) denote at time t the job set satisfying the condition $\Delta_{ik}(t) \geq \tau_{ik}$.

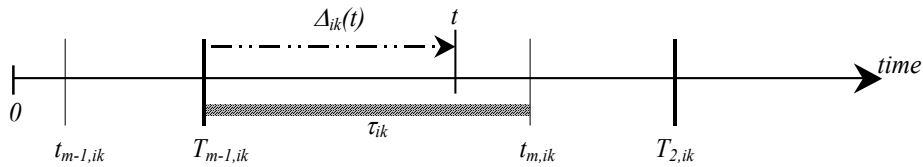


Figure 3. Definition of $\Delta_{ik}(t)$

We then derived a heuristic algorithm for job scheduling and allocation based on the PRTF function to solve the problem, taking advantage of theorems 1 and 2 and the emergency of the preventive actions. The aim is to find a trade-off between the cost minimization throughout the flow-time minimization and the time the equipment spent in critical states. The corresponding algorithm is summarized as follows.

Algorithm for job scheduling and resource allocation

At any time t when a resource is available, the job to be scheduled is the one with the least value of the PRTF in the set $Urgent(t)$ at that time. If the set $Urgent(t)$ is empty, then the job to be scheduled is the one with the least value of the PRTF in the set of all the jobs not yet scheduled. If at least two resources are available at a given time, the job should assign to the resource available earlier, and if there is more than one resource, when the resource with the least index is selected.

Theorem 3 (complexity of the algorithm): The algorithm's complexity is $O(N'^2)$, where N' is the total number of maintenance interventions theoretically calculated on the set of all the assets.

Let's recall that the algorithm enables dynamic online allocation decisions, taking account of the fact that the release date of a job depends on the end of another preventive action. The allocation decisions are then made *online*.

3.4 Numerical experimentation

The processes described in the above section have been programmed in the C language and tested on a UNIX station of the type Compaq AlphaServer ES40 DEC6600 with 2048 MB RAM.

The systems' availability parameters were randomly generated for the programs' numerical implementation and assessment. The failure rates and the repair rates have been generated according to Gauss laws. The availability thresholds must be chosen in the interval $]0, 1[$ and should not be greater than the limit availability of the assets $\mu_{ik} / (\lambda_{ik} + \mu_{ik})$, where λ_{ik} and μ_{ik} are respectively the i_k index equipment's failure rate and repair rate. Hence, the availability thresholds have been calculated from the failure and repair rates using relation (1). One can use allocation methods (Calibra et al., 1995) (Elegbede et al., 2003) to apportion target reliability or maintainability to the facility components. The processing times were calculated from the repair rates and preventive actions set up times.

We programmed the algorithm in two different ways. The first program allocates the resource, considering job emergencies and job priority criteria based on the PRTF function. The second program considers only the PRTF criterion function. In both programs, only the date of the first job relative to each asset is known at the beginning. The release dates of the following preventive actions are determined each time a job is ended, enabling the *online* implementation of these programs. Both Prog1 and Prog2 are implemented online and correspond respectively to the proposed algorithms with emergency and without emergency criterion. The corresponding mean flow-times and the mean delay times are calculated based on the different system configurations' overall interventions. The evolutions of the mean flow-time and the mean delay-time are plotted in Figure 4.

Different numerical experimentations have been performed with varying numbers of resources for each benchmark system with various configurations (systems respectively composed of 20, 30, 50, 80, and 100 assets) and taking the day as a time unit. Both programs' running time does not exceed 1 CPU second for a time-window of 365 days in all system configurations. This time is equal to 173 CPU seconds for Prog1 on a time-window of 10 000 days, in the case of a system composed of 1000 assets with 40 resources.

We use the following notations to characterize the results: Prog1 allocates the jobs considering the emergency and PRTF criterion function; Prog2 allocates the jobs considering only the PRTF criterion function.

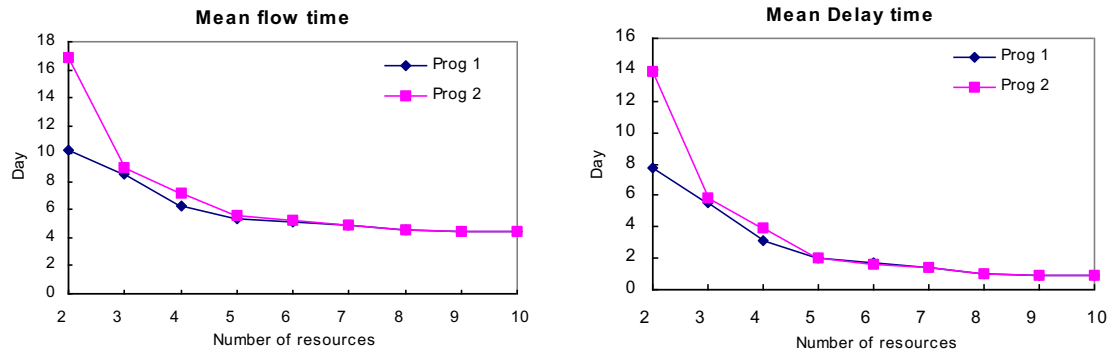


Figure 4. Mean flow-time and mean delay times of jobs in the case of 80 assets

Analysis of the flow-times and the mean delay times from critical dates: one can observe from the curves generated by Prog1 that the mean delay times of interventions show the smallest values for a low number of resources compared to those generated by Prog2. Both plots decrease monotonously toward zeros when the number of resources increases. The same observation can be done on the curves of mean delay time.

We also notice that in the particular case where, at a decision date, there is only one job to be scheduled, the decision rules of Prog1 and Prog2 are the same as the decision based on the Earliest Starting Time priority rule. However, the advantage of Prog1 against Prog2 is evident for a low number of resources. Prog1, based on job emergencies, enables the system to satisfy the availability requirement. Besides, we observe that the number of total jobs performed remains quite the same, even when the number of resources increases.

4. CONCLUSION

Let us recall that the objective of remote maintenance management, instead of adapted to large size and distributed systems, is to ensure the optimal availability of all production plants of an industrial complex through the availability of the means, competencies, and adequate resources at a lower cost. Thus, remote maintenance management of the distributed industrial complexes leads finally to considerable reductions in the operation and maintenance costs. Remote control of the maintenance interventions requires the implementation of several powerful tools, among which:

- 1) diagnosis tools whose effectiveness rely above all on the selection, the collection, the analysis, and the processing of suitable data to synthesize relevant decision-making information
- 2) reliable communication networks and information systems. The new technologies of information and communication may be coupled with the advanced Artificial Intelligence tools that enable to evaluate and predict the states of the equipment
- 3) computerized maintenance activities planning, and real-time resources allocation as well as maintenance interventions and tasks scheduling.

Concerning the last point, we presented in this paper an efficient algorithm tool based on a heuristic method for online implementation. It enables to handle preventive maintenance activities on distributed systems. Resource allocation to preventive maintenance activities is comparable to the parallel machine scheduling problem with jobs having different release dates. The problem is NP-hard. The proposed algorithm considers the jobs emergency and priority criteria to optimize the scheduling decision. The proposed algorithm has low complexity, and this was proved and confirmed through the different running times of the corresponding program fed by simulated parameters. As a logical extension of this work, future investigations will embrace other classes of resource systems, non-identical distances between the different assets, and the corrective maintenance tasks scheduling.

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