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صيانة معدات لتداول الحاويات باستخدام شبكات بيتري الوقتية

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الخلاصة

لضمان السلامة في الميناء البحرية، ينبغي أن يتم العديد من أنشطة الصيانة كل عام. أنشطة الصيانة المتكررة وتأخر إنجازها يسبب انخفاض في جودة الخدمة ويتطلب مبالغ كبيرة من المال. لذلك، هناك حاجة إلى دراسة جدولة الصيانة في الميناء البحرية.

الهدف من هذه الدراسة هو إنجاز وتصميم وحدة الصيانة على أساس شبكات بيتري لمعدات نقل الحاويات. في هذا السياق، نقترح أداة جديدة تستند الى الوقت للصيانة. وتشمل هذه الأداة قطع الغيار، فريق صيانة وعملية التدهور.

Maintenance processes for container handling equipment using P-time petri nets

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ABSTRACT

To ensure the safety in seaport terminal, many maintenance activities should be done every year. However, frequent and delayed maintenance activities would cause low service quality and require large sums of money. Therefore, a study of maintenance scheduling in seaport is needed to be carried out. The aim of this paper is the study and the design of a maintenance module based on Petri nets (PNs) for container handling equipment. In this context, we propose a new P-time Petri net for maintenance (PTPNM). This tool includes spare parts, maintenance group and deterioration process. The PTPNM can give a true expression of the system operation process by introducing time, which is suitable for process indexes calculation and evaluation such as equipment maintenance, support resources utilization, mission success rate and average waiting time.

Keywords: Deterioration process; recovery; scheduling; seaport equipment; spare part.

INTRODUCTION

Generally, manufacturing systems operate in dynamic environments, where usually many inevitable events may occur and cause a change in the scheduled plans. Examples of such unpredictable and unexpected events are machine failures, arrival of urgent jobs, due date changes, etc.

The problem of maintenance scheduling in the presence of undesirable events is of great importance for the successful implementation of real scheduling systems. However, in recent years very few works have been published in this area. In this paper, we focus on maintenance scheduling, based on P-time Petri nets in seaport terminal, when an unexpected event occurs.

At production level, machine maintenance is inevitable. It directly influences the production rate, product quality, and machine availability (Chang *et al*., 2006). If the production schedule does not consider maintenance, the determined planning will be seriously interrupted, because of the occurrence of machine breakdowns. In seaport terminal, every handling equipment require maintenance, and the maintenance policy directly affects the machine's availability. Consequently, it influences the container transit operation. In this connection, maintenance should be considered in distributed scheduling. The objective of this paper is to propose P-time petri nets for modeling the maintenance process in seaport terminal to heuristically solve the maintenance scheduling problem. This tool is able to identify and select maintenance activities in seaport terminal.

The remainder of this paper is organized as follows. The second section uses the scientific literature to describe the position of the proposed approach in the state of the art. A functional description of container terminal is detailed in Section 3. The fourth section begins by presenting the formal definition of P-TPN as a modelling tool and summarizes the problem of maintenance scheduling in seaport container terminal. Afterward, an original recovery approach based on P-time PN's is presented. Finally, conclusions and proposed future studies are presented.

RELEVANT LITERATURE

PNs have evolved into a powerful and mature field of maintenance research that enjoys wide applications in fields such as control (Cam *et al*., 2014), modeling, behavioral analysis (Morinaga *et al*., 2014), and decision aiding.

Over the last few decades, maintenance based on Petri nets has come to represent an active area of research focused on the reliability theory, as recently presented by Fouathia *et al*. (2004). The author proposes a Petri net-based stochastic model for the simulation and evaluation of complex maintenance activities for a power system. The main objective of this modeling approach is to develop a decision-aiding tool, in order to improve the maintenance and renewal decisions. In this application the Petri nets model takes into account the different constraints influencing the maintenance and renewal policies.

For the purpose of controlling and optimizing practical maintenance processes, Shiting *et al*. (2009) analyze the characteristics of the maintenance processes of ships. The method of processes modeling is based on Petri net (PNs), in order to describe the practical maintenance processes.

Other studies have investigated the problem of maintenance scheduling. Considering the uncertainties in both deterioration and maintenance process, Zhang *et al*. (2013) propose a Petri-net based simulation-optimization model for maintenance scheduling. A genetic algorithm based approach is used to get the satisfying solution of the timetable of the maintenance activities, taking into account total possession time, component deterioration and solution feasibility.

In order to ameliorate the feasibility and effectiveness of a maintenance support system, Jiangqiang *et al*. (2013) use timed Petri nets (TPN). The simulations' results prove that TPN is suitable for process indexes evaluation such as equipment maintenance, support resources utilization, mission success rate and average waiting time.

Andrews *et al*. (2014) describe a modeling process to predict the state of the railway track geometry based on the Petri net method. The PN model has been used to investigate the effectiveness of the asset management strategy employed to maintain the geometry of the section to an acceptable standard. The model incorporates the deterioration process of the track and its dependence on the maintenance history, together with all intervention options for inspection, repair and renewal.

Each one of these works has covered some aspects of maintenance. However, few works nowadays concern about how to use a combination of them to give a systematic procedure for maintenance of manufacturing system with time constraints, as seaport terminal, using P-Time Petri nets. Therefore, an original recovery approach including the time constraint will be presented for the maintenance of seaport equipments.

PRESENTATION OF SEAPORT TERMINAL

Functional description

It is admitted that container terminal is a complex system including the berthing of the vessel, the stevedoring (unloading or uploading) of containers, the transit of containers, the stacking of containers, and the use of bunkering service before starting another voyage etc. (Roh *et al*., 2007). Any factor can influence the stay time of ships in port. In this paper, we focus on three important factors: stevedoring of containers, transit and container stacking. Generally, these tasks are performed by some specific handling equipment. We assume that three types of equipment are used for import or export container as shown in Figure 1, such as quay cranes (QCs), automated intelligent vehicles (AIVs), and automated yard cranes (AYCs).

- Import operation: when a ship arrives at a quay in a container terminal, the import containers are lifted by QCs and moved to an AIV. The full AIV is used for transporting the container from the QCs operation space to the container stacks. Near the container stacks, an AYC picks up the container from the AIV and stacks it to the storage place. Figure 1 illustrates the process with two ships full of import containers berthing by the quays.
- Export operations: When one empty AIV arrives at the container stacks, an AYC picks one export container from the stacks and put it on the AIV. This export container is carried by the AIV to the appropriate QC which will lift the container to the ship.

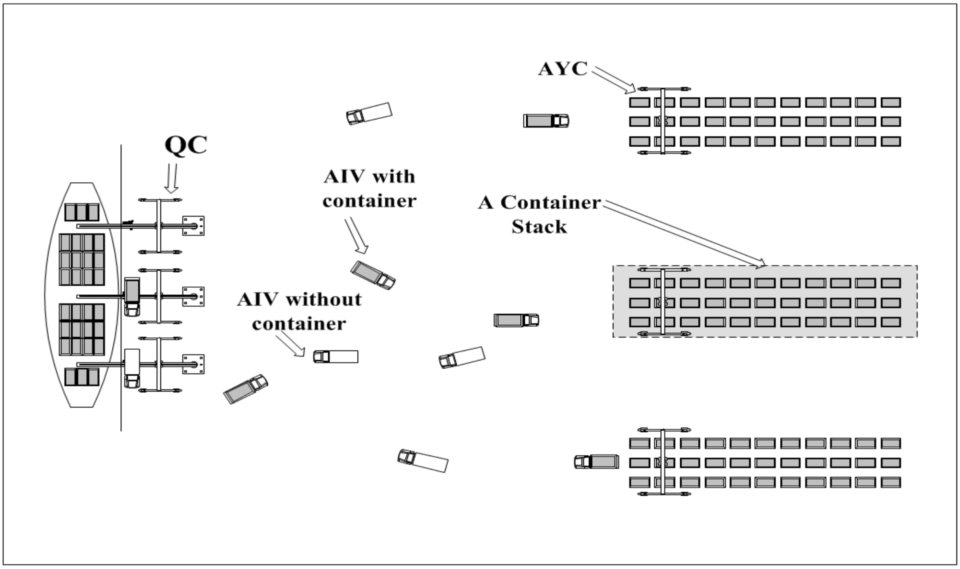

Fig. 1. Overview of container transit in a container terminal

As shown in Figure 1, a ship full of import containers berths by the quay for unloading work. Three QCs are assigned to unload containers, and several AIVs are assigned to take the containers from QCs to AYCs. There are also some container stacks for storing the containers momentarily. For each stack, one AYC is assigned to take the container from the AIVs and to put the container on the stacks. In the beginning, only the import containers are removed from ships to stacks, but when there is enough empty space on the ships, the export containers can be taken to the ships at the same time to shorten the anchor time of ships in seaport. In this paper, only the import container transportation is modelled. However, the export of containers is just a reverse process compared to the import activity.

In this paper, we try to prove that the cyclic scheduling technique can be well applied to the maintenance of a medium sized seaport. Cyclic scheduling is defined as a set of activities that can be repeated for infinite number of times (Draper *et al.*, 1999). More precisely, if X(n) is the starting time (or ending time) of one activity, and n means the repeat numbers, then there is a constant C (called the cycle time, which is the inverse of the periodic output rate) and one integer k such that

$$\mathbf{X(n+k)=X(n)+k*C} \text{ for } \mathbf{n\in N, k\in N^{+}, C\geq 0} \tag{1}$$

It is assumed that, in our work, only the 1-cyclic scheduling (k=1) technique is studied. It is admitted that 1-cyclic scheduling is more easy to be controlled, because as long as the scheduling of system is known in just one cycle time C, we could predict all the activities of system in the entire schedule.

Containers transportation sketch map

The model studied in this paper is based on the container transit operations shown in Figure 1. A sketch structure of the model is given in Figure 2. There are 3 QCs operation spaces (C1, C2, C3) and 3 AYCs operation spaces S1, S2, and S3. In each of the above 6 places, at most only one AIV is permitted to stay in, considering the confined space and other safety reasons. For doing the container transit, the AIVs can choose the shortest path between the known original place and the destination place of containers (the direct line between two points), and they can maintain their trajectory and avoid collisions by a sensor location system. As shown in Figure 2, five paths are given such as C1-S1, C2-S1, C2-S2, C3-S2, and C3-S3. We suppose that the paths guarantee a bi-direction pass for AIVs, which implies the path is wide enough for two AIV's side by side running in contrary direction. S1, S2, C2, and C3 are shared space of more than two paths at the same time.

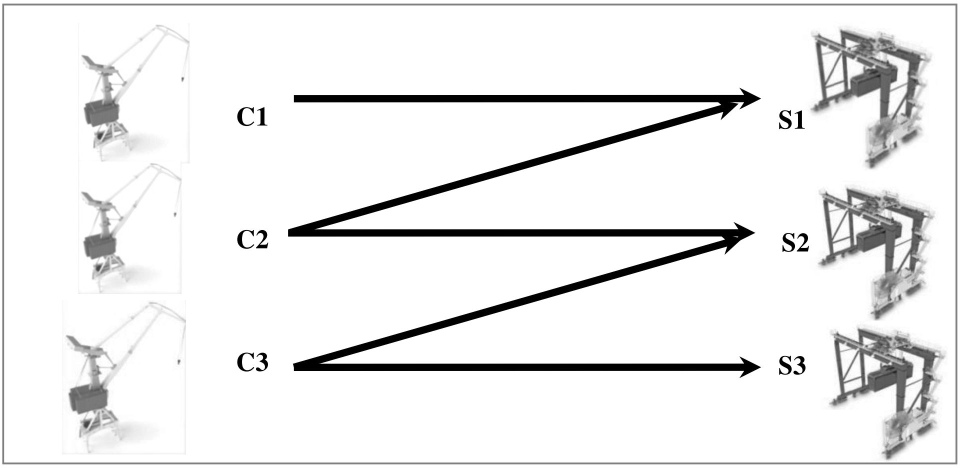

Fig. 2. The sketch structure of container transit

Operations in containers transit

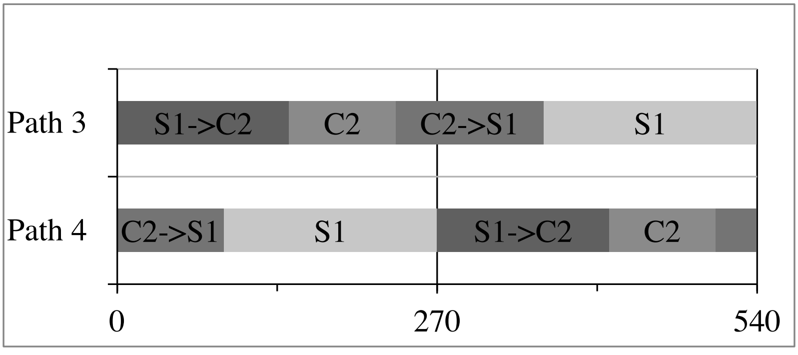

Fig. 3. Precedence constraints associated to the paths 3 and 4

Figure 3 presents the precedence relations of operations in container transit process, and can easily model the time windows associated to each container handling operation (loading, unloading and transport). The full set time intervals of loading, unloading and transfer operations (Figure 2) are computed using the CPLEX 12.5 on a computer with Intel (R) at 1.6 GHz and 1 Go RAM.

For 1-cyclic scheduling, the activities are repetitive in a cycle time period. So it just needs to study the processing activities in one cycle time instead of considering the activities in the whole production period.

Let us take the example of the elementary path 3 with quay cranes 2 (C2) as its first equipment. As shown in Figure 3, the cycle time associated to each path is 540 unit time (u.t).

In the studied container terminal, it costs about 120 u.t for cranes to finish loading or unloading work; thus, the time window for QCs and AYCs is set as [90,180] time unit. The distance between QCs and AYCs is supposed to be about 500 meters, and the velocity of AIV is 5m/s. The time window for the AIVs to pass the paths without intersections is [100, 600].

However, in the studied seaport terminal, each ship has more than 3000 containers, and 25 AIVs are available to do the unloading work. Figure 4 represents an efficient allocation and scheduling of quay-side (quay cranes), yard (automated intelligent vehicles) and land-side resources (automated yard cranes).

The QC's operation space represents the starting and finishing time of each job (e.g., loading and unloading a container) in a set of jobs assigned to quay cranes servicing a vessel (Figure 4). Likewise, the AIV's space depicts the starting and finishing time of each yard job (e.g., transit of a container from its current position to a different position in the yard or to a QC or a truck) in a set of yard jobs assigned to a fleet of autonomous straddle carriers servicing quay cranes and lorry. X1 is an intersection of C2-S3 and C3-S2.

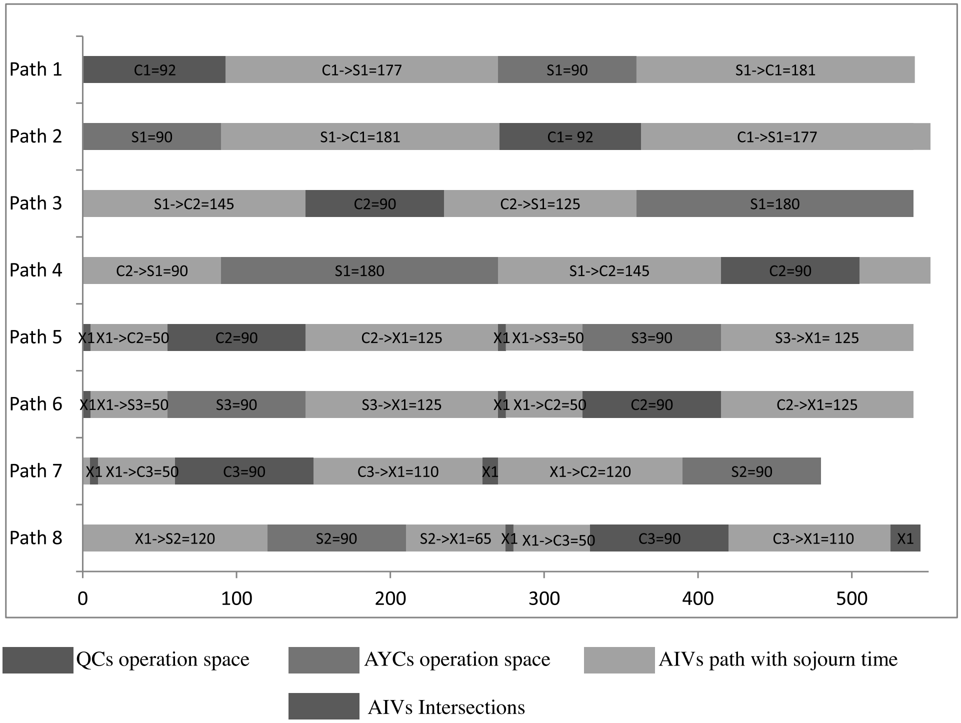

Fig. 4. Scheduling of container transit operations

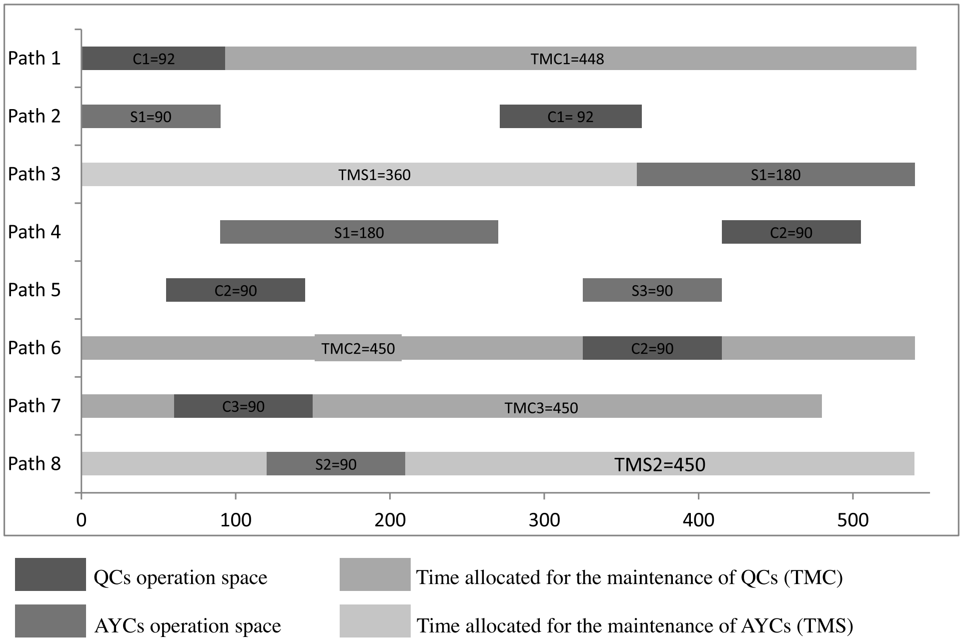

Fig. 5. Maintenance scheduling of seaport handling equipment

Maintenance scheduling

The proposed scheduling (Figure 4) reveals periods of inactivity of seaport equipment (intervals stop). The main objective is to try to take advantage of these periods of inactivity to start additional jobs such as predictive and corrective tasks. This method is referred to as "static insertion" (introduction of tasks, when the machine is available). Thus, this procedure allows to insert the projected jobs in periods of machine availability, without changing the initial scheduling solution.

The introduction of the maintenance tasks must necessarily take into account the production constraints. The insertion problem is therefore to propose a new sequence of operations for a problem of scheduling task farms, to which is added a set of Oij operations (i: operation index; j: equipment index). These operations (Figure 5) represent the time allocated for the maintenance of seaport handling equipment. The scheduling model (Figure 5) consists of the assignment of maintenance jobs to quay cranes (QCs) and to automated yard cranes (AYCs). These maintenance operations will be modeled by a P-time PN's, which will be presented in the next section.

P-TIME PN FOR MAINTENANCE PROCESS

Overview of the problem

Ideally, managers of seaport transit companies aim to maintain handling equipment during their idle time to avoid extracting them from service. In practice, this ideal situation is subject to constraints such as the unexpected breakdowns of equipments, daily incoming maintenance tasks and the change in availability of maintenance resources (Zhou *et al.*, 2004). Normally, the transit company schedules its incoming maintenance orders in advance to take place in a specific time period.

Given a set of maintenance tasks, it is interesting to find good schedules for all jobs to minimize the total out-of-service time and to simultaneously accommodate the unexpected events. Therefore, the specific objectives of the maintenance model, associated to seaport equipments, are: to minimize the interruptions in the handling equipment operating/service schedule and to maximize the utilization of the maintenance resources.

This paper proposes to use P- time PNs for the maintenance of seaport supplies. This tool includes times constraints. The time constraints include: seaport equipment service schedules, maintenance scheduling and equipment availability.

Formal definition of P-Time PN

P-time Petri nets (P-TPNs) have been proven to be a powerful modeling tool for various kinds of discrete event systems with time constraints, and their formalism provides a clear means for presenting simulation and control logic. This paper proposes to use them to the maintenance scheduling of seaport terminal equipment. In other words, they will be used to reduce the effect of breakdown and maximize the availability of seaport supplies.

Definition 1: Khansa *et al*, 1996

The formal definition of a P-TPN is given by a pair $< R; I >$ where:

- R is a marked Petri net,
- $I : P \rightarrow Q^{+} \times (Q^{+} \cup \{+\infty\})$

  $p_i \rightarrow IS_i = [a_i, b_i]$ with $0 \leq a_i \leq b_i$.

IS_i defines the static interval of staying time of a mark in the place p_i belonging to the set of places P (Q^{+} is the set of positive rational numbers). A mark in the place p_i is taken into account in transition validation when it has stayed in p_i at least a duration a_i and no longer than b_i. After the duration b_i the token will be dead. So, a token in p_i is available for transition validations if and only if its stay time q_i falls within the interval $[a_i, b_i]$ (Figure 6).

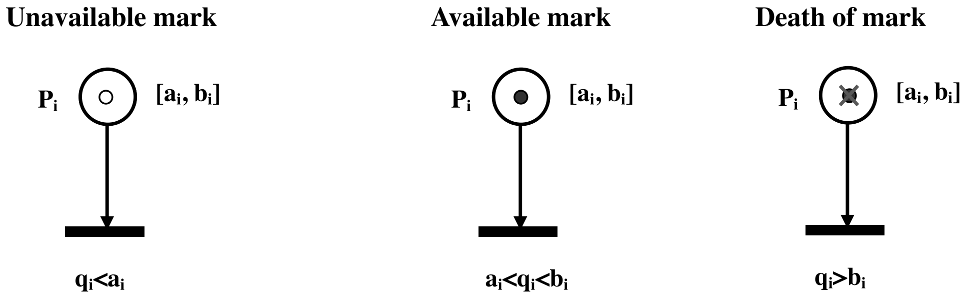

Fig. 6. States for a mark

Maintenance processes based on P-Time Petri Nets

The P-time Petri net for maintenance (PTPNM) consists of five parts (subnets) (Figure 7). The first part “A1” is the subnet of the deterioration process. The second part is the subnet for the maintenance resources. The third subnet represents the maintenance policies. The fourth part “A4” describe the spare parts inventory status and the last subnet is associated to the maintenance planning.

A) Deterioration process (A1)

Generally equipment (machine) has two statuses: working or failed. It is not possible to wait until the component deteriorates to an unrepairable status, because it may be very unsafe when it is working in this condition and the cost for the disruption of seaport traffic will be immense. Hence, it would be better to repair or replace the components before they deteriorate to an unacceptable condition.

A subnet model (A1) representing this deterioration process is shown in Figure 7. Two places “P1” and “P2” stand respectively for two systems states, working and failed status. The location of the token indicates the state in which the system resides. The firing of the transition “T1”, indicates the transition from a normal operating state to a dysfunction state.

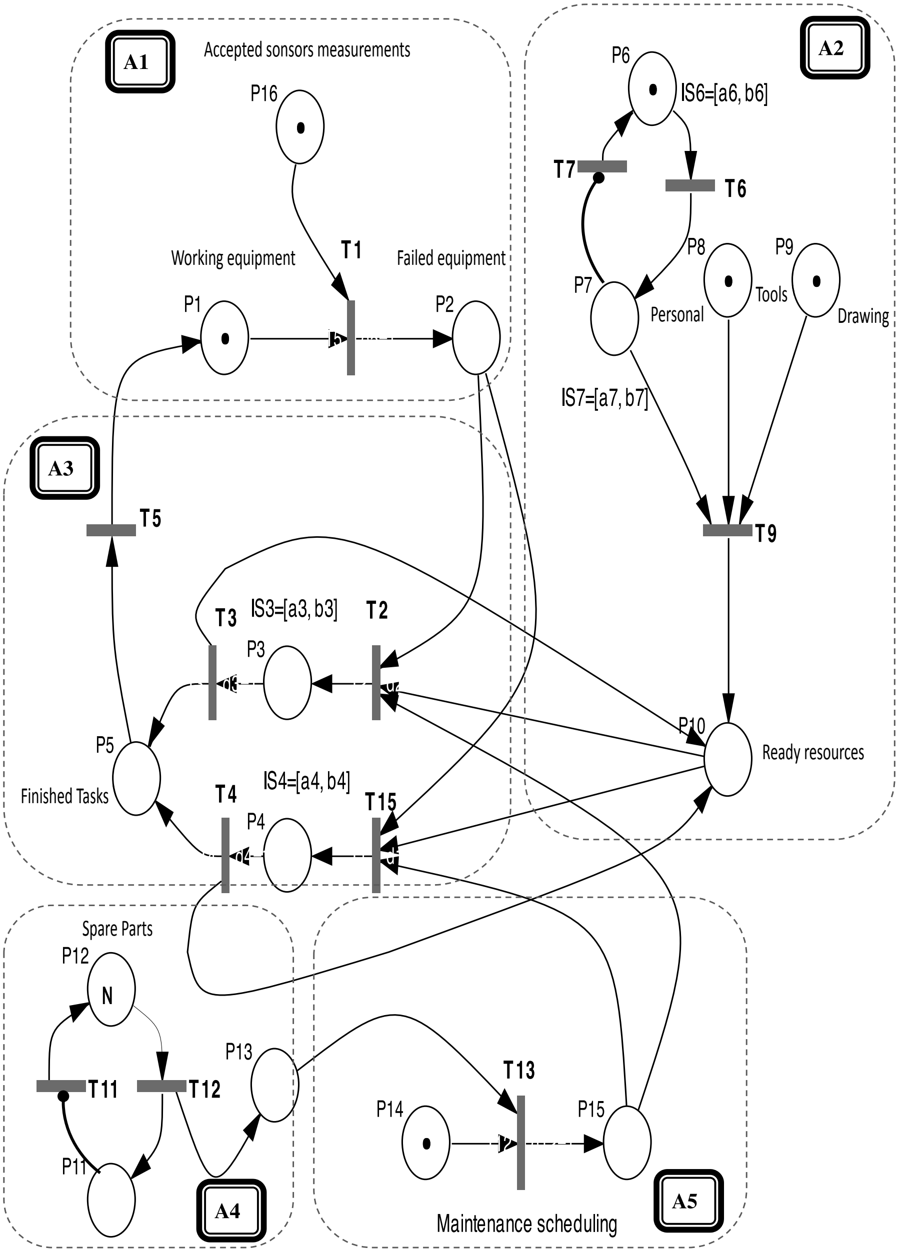

Fig. 7. P-Time Petri Nets for modeling maintenance process

The mark in place “P16” represents acceptable sensors measures. An unmarked place means a rejected measure and an acceptable working status. The sensor’s measures represent dynamic information received from the planning service and the tracking service.

B) Maintenance resources (A2)

The subnet “A2” associated to maintenance resources is constituted by three elements: personnel, tools and drawings. According to block A2, when a failure occurs and if drawing, maintenance teams and tools are ready, the repair work can be started (Figure 7).

The P-time PN represents the status of maintenance group: rest (place P6) and work (place P7) (Figure 7). The static intervals associated to places “P6” and “P7” can generally be determined, such as 12 hours stands for maintenance group work during the day and 12 working hours during the night. Transition “T6”stands for the maintenance group state transformation from resting to working, “T7” stands for the maintenance group state transformation from working to resting.

C) Maintenance strategies (A3)

This block aims to maintain or re-establish an entity to a specific state. The maintenance policies can be classified in two categories: corrective (place P3), and preventive (place P4). For all cases, triggering a maintenance operation is a decision process based on the state (measured or estimated) of considered resources (place P16).

According to Figure 7 (subnets A3), the transition “T2” stands for the maintenance process, when the component is in the triggered condition. The transaction “T15” stands for the maintenance process, when the component is in the unrepairable condition. If there are enough maintenance resources (enough mark in Place P10), the transition “T2” (resp. T15) will be triggered, if there is preventive maintenance (resp. corrective maintenance).

The subnet “A3” associated to the maintenance process is based on the P-time Petri-net. The time windows associated to places P3 and P4 represents the durations of maintenance activities (starting and ending time of each operation). The time constraint represents the uncertainty in maintenance processes, which depends on gravity of failure and the availability of maintenance resources and spare parts.

D) Spare parts (A4)

As a failure occurs, the system suffers one of two types of failures based on a specific random mechanism: type-I (repairable) failure is rectified by a minimal repair, and type-II (non-repairable) failure is removed by a corrective replacement (Chang *et al.* 2014). The Subnet “A4” associated to spare parts station is shown in Figure 7. The marking associated to the place “P12” represent the number of spare parts, which decrease with the maintenance gradually and the inhibitor arc depicts the supply of spare parts by the store.

Overall, the subnet (A4) represents the replacement policy allowing to reduce the catastrophic breakdown risks and operating costs. The replacement policy is defined as a basic and simple policy, which requires that the unit will be replaced upon failure, at a predetermined age or at a planned time “t”.

E) Maintenance scheduling (A5)

The fifth part is the subnet for maintenance scheduling. Scheduling involves the allocation of resources to tasks over time, subject to temporal and capacity constraints (Zhou *et al*., 2004).

The notion of maintenance schedule of seaport handling equipment refers to the assignment of resources to a task in one or several connected discrete time intervals and a decision-making process with the objective of optimizing one or more targets.

According to diagnosis information, the role of this subnet (A5) is to decide about maintenance policy, to activate urgent procedures and finally to trigger recovery procedures.

In the beginning (Figure 7) a token is in the place “P14”. The transition “T13” depict the planned start time of this component and it is determined, when the solution is given. When the token enters into the place “P15”, it identifies that maintenance is required for this component.

Maintenance processes for container handling equipment

- According to Figure 7, the maintenance process associated to handling equipment is able to activate urgent procedures and decide about the selective maintenance decision (corrective or preventive maintenance).
- Our study makes the assumption that the supervised system is modeled by P-time Petri nets: The seaport terminal is considered as manufacturing workshops with time constraints. When the interval constraints (unloading, uploading and transit of containers) are exceeded, there is an error. In our study, an error means a gap between measured and computed time intervals by the scheduling task. Based on the above statements, an error is sometimes referred to as an incipient failure. Therefore maintenance action is taken, when the system is still in an error condition, i.e. within acceptable deviation and before failure occurs. Thus, this study employs the control of static interval in order to perform early failure detection.
- At the occurrence of a dysfunction in handling equipment (quay cranes, automated intelligent vehicles or automated yard cranes), it is important to react in real

time to maintain the productivity and to ensure the safety of the system. It has been shown that the knowledge of time constraints associated to each operation has a significant contribution regarding this type of problem, since it makes the supervision and the maintenance more efficient.

CONCLUSIONS

This paper develops a generalized selective maintenance model based on P-time PNs, which can be used to identify maintenance activities that optimise system requirement. The selective maintenance model can be applied to any industrial system. The resulting models allow to identify maintenance policy and to avoid critical scenarios in such systems.

Concerning the maintenance scheduling, we opted for a static insertion policy. This procedure allows us to insert the projected maintenance jobs in periods of machine availability, without changing the initial scheduling solution jobs. This method of integration shows how to integrate unforeseen and urgent job.

In the proposed maintenance model, the P-Time PNs was used to describe the dynamic behavior of the equipment, the scheduling, and the maintenance policy. The time constraints in maintenance process represent the availability of resources and the duration of maintenance tasks.

Our future work will focus on two main areas. Firstly, as uncertainty is a critical concern in port operations, we will investigate dynamic maintenance scheduling (without predicted moment of maintenance task). Secondly, we would develop an algorithm allowing reducing the total possession time of maintenance and maximizing the equipment availability.

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