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Age-dependent maintenance planning based on P-time Petri Nets for Seaport equipments

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***Abstract*— This paper deals with the control of maintenance of a container handling equipment in seaport terminal. In the category of the seaports concerned by this paper, the operations have temporal constraints which must be imperatively respected. The violation of these constraints can affect the production rate. The objective of this study is to integrate failure rate and machine age to decide about the selective maintenance decision. The proposed maintenance approach will increase the availability of the studied seaport terminal and reduces the labour costs of terminal operators. In the proposed model, the failure rate of a machine depends on its age; hence, the maintenance policies are machine-age dependent.**

***Keywords*— maintenance scheduling, seaport terminal, failure rate, age.**

I. Introduction

Many products or systems deteriorate with age and are also subject to random failures. Therefore, for more expensive and critical systems, it is important to determine the optimal maintenance and replacement policy to reduce the catastrophic breakdown risks and operating costs [1].

The main objective of this paper is to integrate failure rate, cycle time of elementary circuits and the machine age to decide about the selective maintenance decision of the handling equipments in seaport terminal.

The seaport container transport is assumed herein to be described by P- time Petri Nets. In our approach, the decision variables are the cycle time of elementary circuits and the machine age. In seaport container transport each machine is subject to a maximum machine age M. Machine age is defined as the cumulated operating time. If the machine age reaches M, various maintenance policies have to be carried out right after the completion of the operating operation.

The paper is organized as follows. Section 2 provides a brief overview of related work in maintenance of Flexible Manufacturing Systems (FMS). A functional description of container terminal is detailed in Section 3. The fourth Section, introduces the maintenance approach based on machine age. Afterward, the problem of maintenance of seaport equipments is tackled. An original recovery approach based on P-Time Petri Nets is presented. Finally, section 5 provides a conclusion and summary of the study.

II. Literature review

There have been many works proposed for maintenance of FMS. Some researchers adopted the machine age to indicate measure and estimate the machine condition.

Among many related researches, Proschan et al. [2] introduced a traditional age replacement maintenance policy which replaces a system at failure, or at age T, whichever occurs first. Several extensions of this policy have been made by Chien [3].

Kenne [4], presented an improved replacement policy based on preventive and corrective maintenance rates Control : By controlling both production and maintenance, a stochastic optimization model with three decision variables (production rate, preventive and corrective maintenance rates) and two state variables (age of the machine and stock) is built.

Chang [5], presents a replacement model with age-dependent failure type based on a cumulative repair-cost limit policy, whose concept uses the information of all repair costs to decide whether the system is repaired or replaced.

Recently, Shey et al. [6] proposed a discrete replacement model for a two-unit system subject to failure rate interaction and shocks. The objective is to determine the optimal number of minor failures before replacement that minimizes the expected cost rate.

Other treatment models for imperfect maintenance have been proposed. The most relevant efforts among them being the probabilistic approach [7], [8], the cumulative damage shock model [9], and the other applied models [10], [11], [12].

III. SEAPORT CONTAINER TRANSPORT

A. *Presentation of Seaport Container Transport*

It is admitted that the container terminal is a complex system including the berthing of the vessel, the stevedoring (unloading or uploading) of containers, the transit and the stacking of containers [13].

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 equipments. We assume that three types of equipment are used for import or export container as shown in Fig. 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. Fig. 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 containers 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.

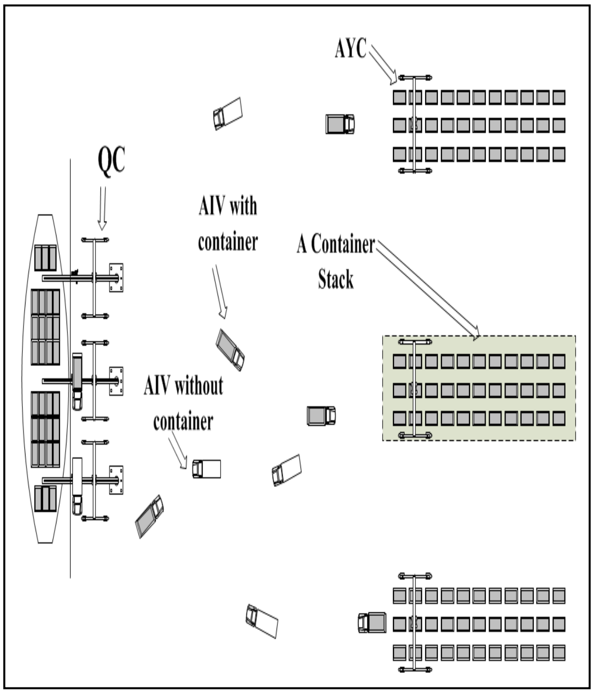

Fig. 1 Overview of container transit in a container terminal

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 [14]. 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

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

It is assumed that, in our work, only the 1-cyclic (k=1) scheduling technique is studied. Factually, the 1-cyclic container transit can be described as a P-time strongly connected event graph (PTSCEG). Here, the PTSCEG is a P-time Petri net in which each place is assigned with a time window. If the sojourn time of tokens is out of the time window, the transitions cannot be fired.

B. *Modelling of Seaport container terminal*

1) *Definitions*

In the model, two kinds of elementary circuits are studied. One is the process circuit, and the other is the shared space status circuit.

Definition 1: Elementary circuit of PTSCEG is the path which can connect all the nodes of this path as a cycle without repeating any nodes of this path.

Definition 2: Process circuit is a kind of elementary circuit which represents the operation cycle of containers' transit process between QCs and AYCs.

Definition 3: Shared space status circuit is a kind of elementary circuit which represents the status change cycle of a shared space.

However, before the presentation of more content, let us consider some notions.

- $\boldsymbol{G}$: the PTSCEG model
- $\boldsymbol{G_i}$: ith elementary circuit represents process circuits or shared space status circuits, $k\in \mathbf{N}^{*}$,
- $\boldsymbol{p_{ij}}$: jth place of $\boldsymbol{G_i}$, the places stand for the operation space of QCs, AYCs, the intersections, the paths, and the free status of a shared space $j\in \mathbf{N}^{*}$,
- $\boldsymbol{t_{ij}}$: jth transition of $\boldsymbol{G_i}$
- $\boldsymbol{q_{ij}}$: the sojourn time of one token in $\boldsymbol{p_{ij}}$, $\boldsymbol{q_{ij}} \geq 0$
- $\boldsymbol{a_{ij}}$: the lower bound of $\boldsymbol{q_{ij}}$, $\boldsymbol{a_{ij}} \geq 0$
- $\boldsymbol{b_{ij}}$: the upper bound of $\boldsymbol{q_{ij}}$, $\boldsymbol{b_{ij}} \geq 0$
- $\mathbf{C}_{\mathbf{demand}}$: the cycle time for cyclic scheduling respecting the customer's demand, $C_{demand} > 0$
- $\mathbf{W}^{\mathbf{limit}}$: limited number of tokens for all the process circuits. Factually it stands for number of all the available AIVs in the container terminal, $W^{limit} \in \mathbf{N}^*$

2) *PTSCEG model*

The P-time Petri net is used to model the containers transit process with time window in shared cranes, operation space and the paths. However, the P-time Petri net here is a PTSCEG, each place having only one input transition and only one output transition. In this model, firstly, the 5 paths are modelled, then, the paths will be connected by the shared crane operation space places as shown in fig. 2.

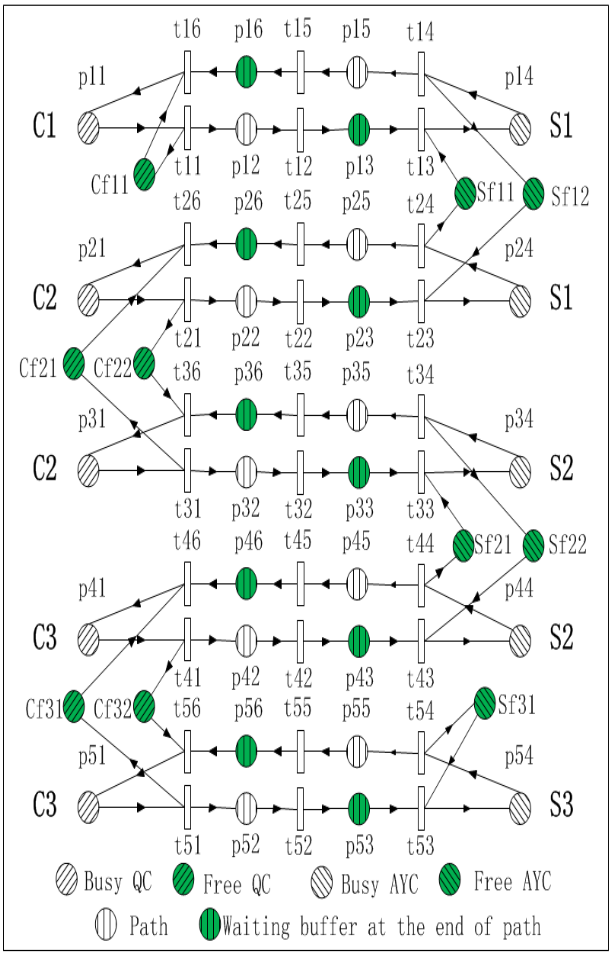

Fig. 2 PTSCEG model for container transit

Let us denote the process circuits C1-S1, C2-S1, C2-S2, C3-S2, and C3-S3 as G_1, G_2, G_3, G_4 and G_5 respectively. The QC operation space is the first place of G_i. Firstly, let us take the process circuit G_1= p11, t11, p12, t12, p13, t13, p14, t14, p15, t15, p16, t16 as an example to explain how to model a path. P11 is the busy QC place which stands for the used QC operation space C1, and Cf11 is the QC free status place which stands for C1 is available for a unloading work. And p14 is the busy AYC place which stands for the used AYC operation space. P12 is the path place in direction from C1 to S1, and p15 is the path place in direction from S1 to C1. P13 and p16 are the waiting buffer places in the end of path. So when a AIV finishes the passage of a path and its container loading or unloading place is still used, the AIV should wait a while until the cranes are available.

IV. MAINTENANCE OF SEAPORT CONTAINER TRANSPORT

A. Problem description

The main objective of this paper is to integrate failure rate, cycle time of elementary circuits and the machine age to decide about the selective maintenance decision of the handling equipments in seaport terminal.

In the seaport terminal, the machine age equals the cumulated processing time of operations. After doing a number of operations, each machine (Quay Cranes, Automated Intelligent Vehicles or Automated Yard Cranes) requires a time for maintenance. The conceptual idea of this paper is represented in Fig. 3.

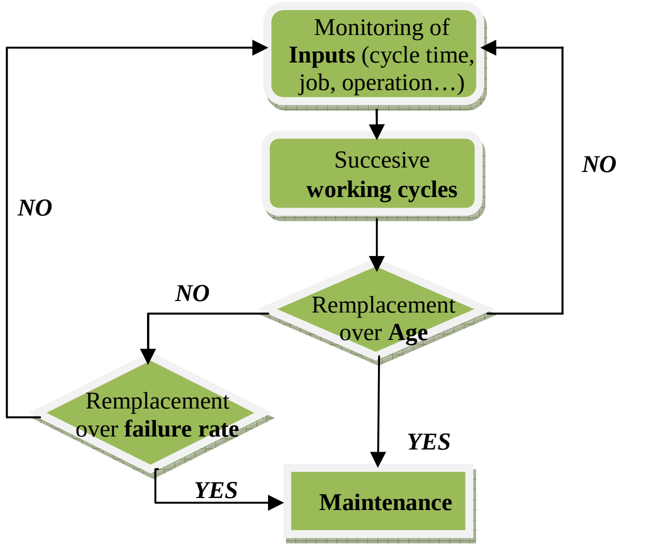

Fig. 3 The flow sheet for the maintenance of seaport container terminal

B. Framework of the proposed maintenance approach

1) Replacement over age

In the distributed FMS, each factory has Mf number of machines that each machine can produce limited number of products [14]. Each job has up to N_i number of operations, and each operation can be performed on more than one suitable machine with different processing time. In our study we considered that the seaport terminal is consists of three factories:

- Factoty 1: Stevedoring of containers,
- Factory 2: Transport of containers,
- Factory 3: Container stacking.

Each factory has one machine:

- Quay Cranes (QCs) associated to factory 1. The job allocated to QC is uploading/unloading containers
- Automated Intelligent Vehicles (AIVs) associated to factory 2. The AIV is used for transporting the container from the QCs operation space to the container stacks.
- Automated Yard Cranes (AYCs) associated to factory 3. His job is to pick up the container from the AIV and stack it to the storage place.

The following notations are used to describe the problem studied throughout the papers [15] and [16].

In Table 1 there is shown how to formulate the problem. The machine age is given by the following expression:

$$A_{MF} = \sum_{j=1}^{m} \sum_{i=1}^{N} N_i * (TE_{ij} - TS_{ij}) + MT_{MF} \qquad (2)$$

TABLE 1. FORMULATION OF PROBLEM

Mf	Number of machines in factory f	A_{Mf}	Age of machine M in factory f
Ni	Number of operation i of job j	*j*	Index of job, j=1,…,m, where m is the number of job
TS_{ij}	Starting time of operation i of job j	TE_{ij}	Ending time of operation i of job j
MT_{Mf}	Maintenance time allocated to a machine M in factory f	*A*	Maximum machine age

Refer to the above definition each machine is subject to a maximum machine age A. The machine age is defined as the cumulated operating time. If the machine age reaches A, maintenance has to be carried out right after the completion of the operating operations. After maintenance, the machine age will be reset to 0 as shown in Fig. 4.

In seaport container transport, each machine can perform various operations with different operating lead times (deposit, lifting, transport,…). After doing a number of operations, each machine requires a time for maintenance. The machine age equals the cumulated processing time of operations and cumulated time allocated to the maintenance.

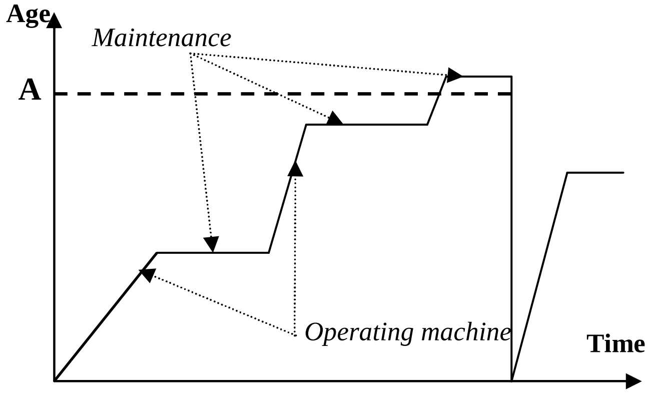

Fig. 4 Modelling of the maximum machine age A

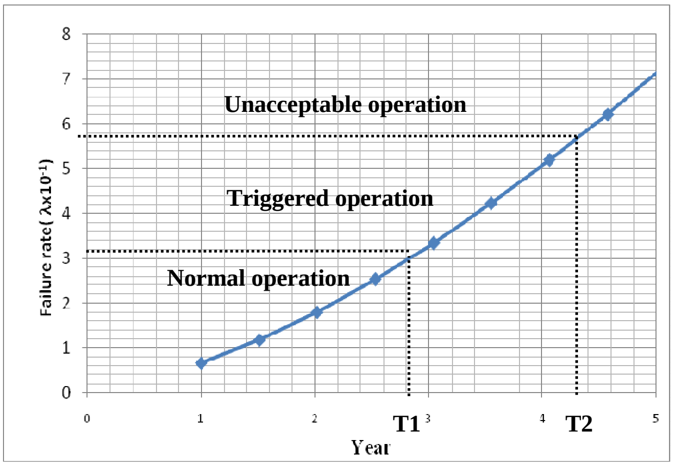

Fig. 5 Operating mode

2) Replacement over failure rate

Generally, in FMS, most components will not fail suddenly but deteriorate from a good condition to unacceptable condition. In studied system, the operation mode is divided into three phases; normal, triggered and unacceptable operating condition, as shown in Fig. 5.

The triggered operating is the deteriorated point (T1) that can be detected by existing methods and devices. But the component would be functional in the triggered condition until it deteriorates to the unacceptable operating mode. Normally, the interval between triggered and unacceptable operating, called time window, is uncertain.

C. *Maintenance of seaport equipments*

1) Determination of temporal intervals

Factually, the model in Fig. 2 is a P-time Petri Net, so the time window for each place should also be given, as shown in Table 2.

For each place, let us denote $[a_{ij}, q_{ij}^{e}, b_{ij}]$ the lower bound of the time window, the expected sojourn time of tokens, and the upper bound of the time window, respectively.

2) Determination of sojourn time

Now let us suppose that there are 5000 containers on the ship to be imported in, and for each path 1000 containers should be transported. The demanded cycle time of elementary circuits, C_{demand}, is 7 minutes (C_{demand} =7 min). And there are 5 paths, so the demanded production rate is 5 containers per 7 minutes for the system.

We suppose W^{limit} =15, 15 AIVs are available for the 5000 containers task. We could give a 1-cylic schedule with the expected sojourn time respecting the time windows, using 10 AIVs, as shown in Table 3.

TABLE 2. TIME WINDOWS $[a_{ij}, b_{ij}]$ FOR PLACES (UNIT IN SECOND)

Busy QCs	Free QCs	Busy AYCs	Free AYCs	From QC to AYC		From AYC to QC	
				Path	Waiting buffer	Path	Waiting buffer
P11 [90, 100]	Cf11 [0,+∞]	P14 [80, 90]	Sf11 [0,+∞]	P12 [210, 220]	P13 [0, 360]	P15 [210, 220]	P16 [0, 360]
P21 [90, 100]	Cf21 [0,+∞]	P24 [80, 90]	Sf12 [0,+∞]	P22 [300, 350]	P23 [0, 360]	P25 [300, 350]	P26 [0, 360]
P31 [90, 100]	Cf22 [0,+∞]	P34 [80, 90]	Sf21 [0,+∞]	P32 [210, 220]	P33 [0, 360]	P35 [210, 220]	P36 [0, 360]
P41 [90, 100]	Cf31 [0,+∞]	P44 [80, 90]	Sf22 [0,+∞]	P42 [300, 350]	P43 [0, 360]	P45 [300, 350]	P46 [0, 360]
P51 [90, 100]	Cf32 [0,+∞]	P54 [80, 90]	Sf31 [0,+∞]	P52 [210, 220]	P53 [0, 360]	P55 [210, 220]	P56 [0, 360]

TABLE 3. EXPECTED SOJOURN TIME q_{ij} FOR PLACES (UNIT IN SECOND)

Busy QCs		Free QCs		Busy AYCs		Free AYCs		From QC to AYC				From AYC to QC			
								Path		Waiting buffer		Path		Waiting buffer	
P11	100	Cf11	320	P14	80	Sf11	0	P12	220	P13	0	P15	210	P16	230
P21	100	Cf21	120	P24	90	Sf12	250	P22	300	P23	30	P25	300	P26	20
P31	100	Cf22	100	P34	80	Sf21	260	P32	220	P33	0	P35	210	P36	230
P41	90	Cf31	240	P44	80	Sf22	0	P42	300	P43	70	P45	300	P46	0
P51	90	Cf32	0	P54	80	Sf31	340	P52	210	P53	0	P55	210	P56	250

3) Determination of cycle time

The total make-span for the 5000 containers task is (5000/5)*7=7000 minutes with the demanded production rate. But sometimes, the AIVs are in waiting buffer without running, and the cranes are in free status without taking containers. So the age of the AIVs is only relative to the sojourn time in path places without considering the waiting buffer places, and the age the cranes only depends on the sojourn time in Busy QCs places or Busy AYC places without considering the free status places

A/ AIV cycle time

In fig. 6, the 1-cyclic schedule for the path places used by 10 AIVs is shown.

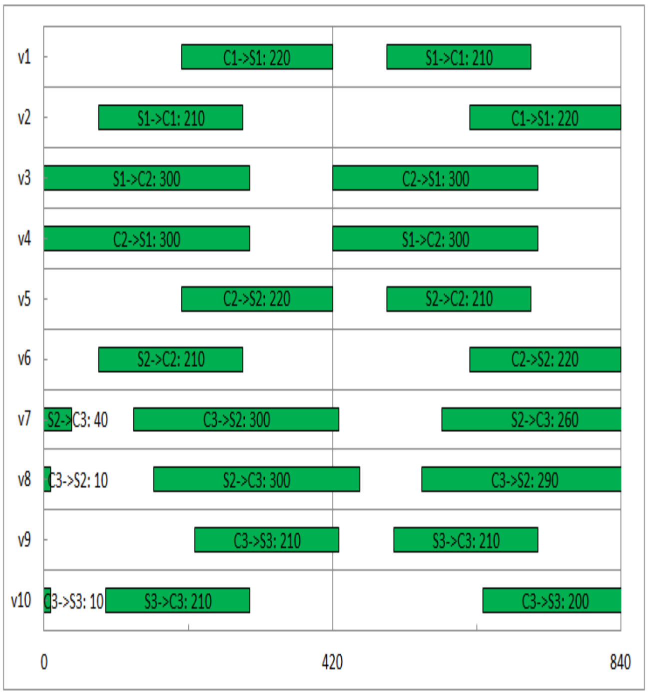

Fig. 6 The 1-cyclic schedule for the paths places with path directions and sojourn time

B/ QC cycle time

In fig. 7, the 1-cyclic schedule for busy QCs is shown.

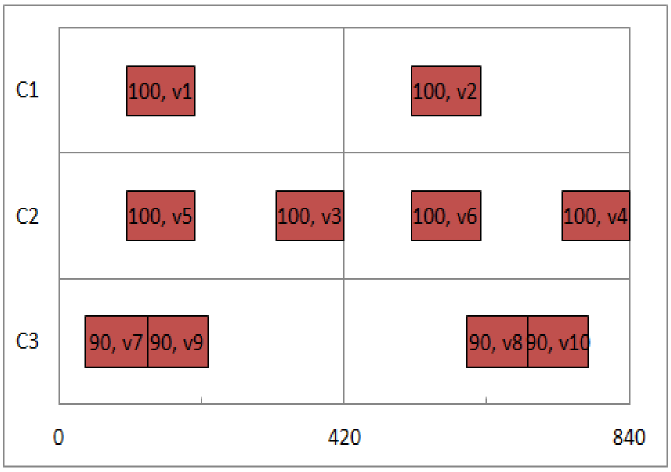

Fig. 7 The 1-cyclic schedule for busy QCs places with path directions and sojourn time

C/ AYC cycle time

In fig. 8, the 1-cyclic schedule for busy AYCs is shown.

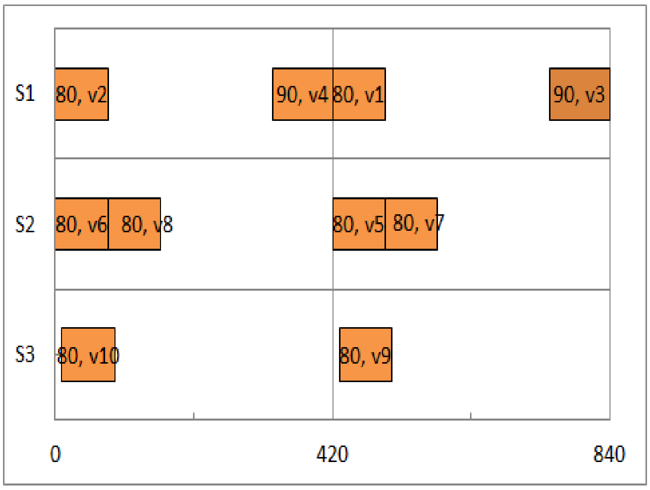

Fig. 8 The 1-cyclic schedule for busy AYCs parking vehicles and sojourn time

Based on the fig. 7, 8 and 9, we can easily calculate the age for AIVs, QCs and AYCs in one cycle time 420 seconds. For example, the age of v1 is (210+220)/2=215 seconds. If we can get the age of v1 in one cycle time 7 minutes (420 seconds), then we can get the age of v1 in 5000/5=1000 cycles or in the make-span 1000*7=7000 minutes. In the waiting time of AIVs or the free status of cranes, the maintenance can be inserted.

V. CONCLUSIONS

In this paper, we have proposed an approach for maintenance of the transit equipments in seaport terminal. The new recovery approach is based on the study of machine age the cycle time of elementary circuits. Our study makes the assumption that the supervised system is modeled by P-time Petri nets. The paper proposes an adaptive technique dedicated to the maintenance of manufacturing systems with time constraints based on machine age.

At the occurrence of a dysfunction in seaport handling equipment, 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 the effective sojourn time of the token has a significant contribution regarding this type of problem, since it allows the computing of machine age. This is quite useful for the maintenance task.

It is interesting as further research to incorporate the issues of maintenance and repair strategies in order to avoid loss in production due to equipment failure. This last problem needs a specific approach, because of the production loss which occurs when maximum time constraints are not fulfilled anymore.

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