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Modeling the Time-Based Maintenance Strategies with Petri Nets

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Abstract—**The appliance of any maintenance strategy can considerably reduce the risks of failures, which can significantly improve the system's performability, i.e. its ability to perform in a given operational environment in the presence of failures. The paper aims to elaborate on the two most dominant time-based maintenance strategies in use today, including the preventive and the predetermined ones, by proposing corresponding stochastic Petri Net models. Such models can provide solid frameworks for the evaluation of the efficiency of both approaches vis-à-vis a variety of input parameters. In addition, the proposed models can provide valuable insights into the dynamics of the two maintenance strategies by carrying out various 'what-if' analyses regarding different working scenarios.**

Keywords - maintenance strategy, modeling, stochastic Petri Nets, preventive maintenance, predetermined maintenance

I. INTRODUCTION

Web services today rely on critical Internet infrastructure, comprised of data centers, server farms, networking equipment, communication facilities, transmission media, software, etc. that are responsible for hosting, storing, processing, and providing the information that comprises websites, apps, and content. The Industry 4.0 paradigm encompasses the utilization of a myriad of networked IoT devices, robots, sensors, automated machines, and computers. All of these hardware components, including the software that gears it up, have to be continuously and appropriately maintained to keep them up and running. Since failures are inevitable phenomena in the tech world, risks and threats of both hardware and software failures are omnipresent, so they have to be rationally accepted and dealt with, in terms that they have to be properly identified/recognized, analyzed/evaluated, and controlled/managed. Denial and deliberate ignorance of thoughtful planning and non-undertaking risk management activities can cause damage and can incur severe consequences not only to tangible assets (hardware, software, data) but also to intangible ones (company's reputation and image, customers' trust and loyalty), leading towards financial losses due to customer dissatisfaction and dissipation. Therefore, risks cannot be underestimated, but rather they have to be treated proactively and efficiently.

In this regard, the paper focuses on time-based maintenance strategies that can be thought of as risk management approaches that can significantly help in mitigating the risks of physical assets' failures. These include three variations of preventive maintenance strategies as well as the predetermined maintenance, as a special case of preventive maintenance.

The paper is structured as follows. Section II briefly elaborates on the most prominent research related to modeling various maintenance strategies with Petri Nets. Section III presents the proposed stochastic Petri Net models that capture the essence of two major time-based maintenance strategies: preventive and predetermined maintenance. The last section discusses the benefits and drawbacks of the presented models and concludes.

II. Related Research

Managing risks of failures through the application of various maintenance strategies has become a subject of extensive research in recent years, fostered by the need to optimize maintenance costs and increase systems' availability and reliability. Much of this research has been carried out using various classes of Petri Nets (PNs), which have all proven to provide powerful graphical and mathematical formalisms suitable for algorithmic modeling and evaluation of complex discrete-event dynamic systems and processes exhibiting features such as parallel/concurrent execution, blocking, mutual exclusion, iterative repetition, and choice making. In this context, PNs have been utilized with the general aim to quantify the effects of various maintenance strategies on particular systems in practice.

The research based on the utilization of Petri Nets for maintenance purposes stretches back to 1998 when they were used to assess early failure detection and fault isolation, for district heating and cooling system's health monitoring and improvement of preventive maintenance [1] and in 1999 when they were used for building a model and an algorithm to find the minimal cut-sets of a coherent fault tree [2], as well as to evaluate various maintenance strategies in manufacturing systems [3]. Later on, in 2004, Petri Nets were used to model and analyze scheduled maintenance systems [4], and in 2009, they were used to carry out research on maintenance processes' modeling techniques vis-à-vis the evaluation of specific maintenance performance indexes [5].

During the last decade, the research on maintenance modeling using PNs has dramatically intensified, involving various classes of PNs, including Generalized Stochastic Petri Nets (GSPNs) [6] [7] [8], Colored Petri Nets (CPNs) [9] [10] [11] [12], and Deterministic and Stochastic Petri Nets (DSPNs) [13].

Lately, Petri Nets were used to model and evaluate the preventive maintenance processes in technological facilities [11] and aircraft [12] in 2021, to help improve the reliability and availability of an electric power system's infrastructure [14] (2021), as well as to plan and optimize maintenance logistics of small hydroelectric power plants [15] in 2022. Reference [16] proposed a methodology to properly define the optimal structure and properties of reduced complex Petri Net models used in maintenance modeling (2022). An overview of the major maintenance strategies, including their corresponding generic stochastic Petri Net models that can be utilized for availability and reliability analysis of the modeled systems vis-à-vis various input parameters and working scenarios, can be found in [17] (2022).

III. Petri Net Models of Time-Based Maintenance Strategies

Time-based maintenance strategies refer to those preventive strategies where the scheduling of the next planned maintenance operations is based solely on time-lapse and not on other factors. The subsequent four maintenance strategies belong to this category. What follows is a brief description of each one. All the models utilize the class of Deterministic and Stochastic Petri Nets (DSPNs) [18] [19] and are developed and validated using the TimeNET 4.5 software tool.

A constituent part of all presented DSPN models is the sub-model representing the modeled system, which is subject to a certain time-based maintenance strategy, as shown in Fig. 1, Fig. 3, Fig. 5, and Fig. 7. The system is prone to failures. As such, it may undergo a series of consecutive failures and repairs, thus alternating between two possible states/modes: operational (a token in the place *P_sys_WORK*) and non-operational (a token in the place *P_sys_FAIL*). The failures occur with a rate of λ_{sys} = 1/MTTF (MTTF stands for Mean Time to Failure), denoted by the firing of the exponential transition *T_sys_MTTF*, and repairs last, on average, MTTR time units (MTTR stands for Mean Time to Repair), meaning that the exponential transition *T_sys_MTTR* fires with a rate of μ_{sys} = 1/MTTR, the repair rate.

A. *Preventive Maintenance without Time Shifts*

This approach includes a routine maintenance plan according to which maintenance operations always occur at predetermined, fixed time points to keep the equipment and assets functioning, thus avoiding costly unplanned downtimes and reducing or eliminating their unavailability due to unexpected equipment breakdowns. The time points when preventive maintenance is scheduled are fixed, no matter whether a system failure occurred previously or not.

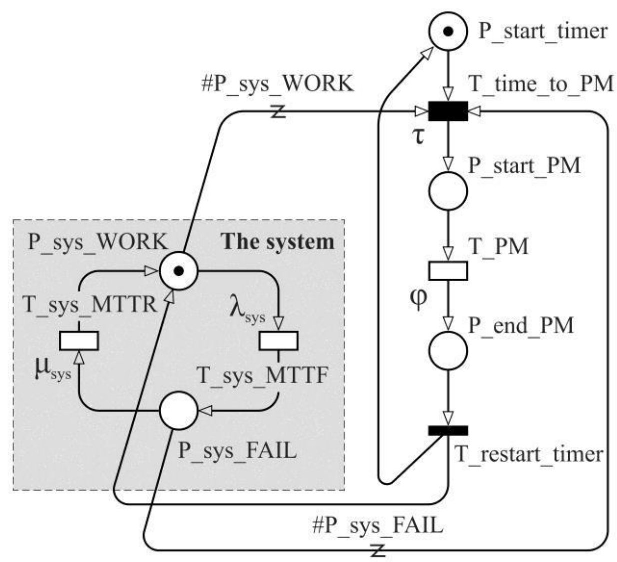

Figure 1. DSPN model depicting a preventive maintenance of a generic system without time shifts
(Source: Authors' representation)

The DSPN model depicted in Fig. 1 portrays the execution of a preventive maintenance plan for a generic system without time shifts.

At time point t = 0, when the system starts functioning, the deterministic transition *T_time_to_PM* becomes enabled, and it fires after a fixed amount of pre-set time τ (time to preventive maintenance), which puts a token into the place *P_start_PM*. The preventive maintenance lasts, on average, 1/φ time units, where φ is the firing rate of the exponential transition *T_PM*. When preventive maintenance ends, the firing of the immediate transition *T_restart_timer* puts a single token into the place *P_sys_WORK* (meaning that the system reverts to the operational mode) and also puts a single token into the place *P_start_timer* (meaning that the next preventive maintenance is scheduled to be carried out again in τ time units).

The DSPN model allows for the system to undergo a preventive maintenance session while it is being repaired (a token in place *P_sys_FAIL*). In this particular case, the ongoing corrective maintenance is being interrupted and replaced by the preventive maintenance, since they both coincide, and it is assumed that the system is being repaired during the latter one.

Fig. 2 shows one possible evolution of the dynamics of the modeled system. The points t_{Fi} (i = 1, 2, ...) denote time points when a failure occurred, ΔT_{Ci} (i = 1, 2, ...) are the periods of corrective maintenance, and t_{Pi} (i = 1, 2, ...) are time points when next preventive maintenance starts. Starting from t = 0, the time points t_{Pi} (i = 1, 2, ...) are always scheduled in regular time intervals with a duration of τ time units after the termination of the previous successfully executed preventive maintenance session, no matter whether a failure has occurred previously or how many failures have happened up to the time point when a preventive maintenance

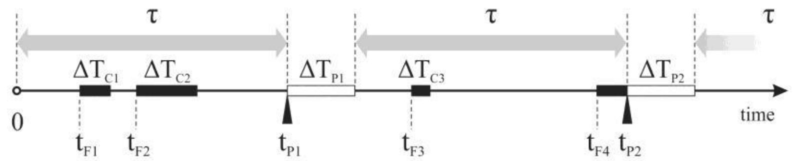

Figure 2. Possible evolution of the preventive maintenance without time shifts
(Source: Authors' representation)

session is being scheduled. Each preventive maintenance session lasts, on average, $\Delta T_{Pi} = 1/\varphi$ time units ($i = 1, 2, ...$).

B. *Preventive Maintenance with Time Shifts*

Contrary to the previous approach, this one allows for the period to the next scheduled preventive maintenance to start immediately after the finish of the last corrective maintenance, if any. In such a case, the beginning of the time to the next preventive maintenance session shifts i.e. is postponed. If no failure occurs, the maintenance plan is completely identical to the one without time shifts.

The DSPN model depicted in Fig. 3 describes the preventive maintenance of a generic system with time shifts.

In a case of a failure (a token in the place *P_sys_FAIL*), the ongoing time to preventive maintenance is suspended (no token in the place *P_start_timer*). When the corrective maintenance session ends (firing of the exponential transition *T_sys_MTTR*), the system becomes operational (a token in the place *P_sys_WORK*) and, simultaneously, the time to the next preventive maintenance session is restarted (a token in the place *P_start_timer*).

If no failure occurs until the beginning of the preventive maintenance session (a token in the place *P_start_PM* after firing of the deterministic transition *T_time_to_PM*), a preventive maintenance session is being conducted that lasts, on average, $1/\varphi$ time units, where φ is the firing rate of the exponential transition *T_PM*. After the successful conclusion of the preventive maintenance session (a token in the place *P_end_PM* after firing of the exponential transition *T_PM*), the firing of the enabled immediate transition *T_restart_timer* puts a token in the place *P_sys_WORK* (meaning that the system becomes operational again) and also puts a token in the place *P_start_timer* (denoting the start of the period to the next preventive maintenance that will last τ time units if not canceled by a failure).

One possible evolution of the dynamics of the modeled system is given in Fig. 4. After the first failure that occurs at the time point t_{F1}, corrective maintenance took place, which lasts for ΔT_{C1} time units. Its end restarts the time to the first preventive maintenance session that should now start at the time point $t_{P1}(2)$ instead at the time point $t_{P1}(1)$. Meanwhile, at time point t_{F2} the system suffers another failure, which takes ΔT_{C2} time units to be resolved via a corrective maintenance session. The end of the second repairing session shifts the beginning of the period to the first preventive maintenance session again, which should now start at the time point $t_{P1}(3)$. After τ time units, no failure happens, so the first preventive maintenance session can finally begin at the time point $t_{P1}(3)$. After the time-lapse of ΔT_{P1} time units, it successfully concludes, so the time to the next (second) preventive maintenance session has

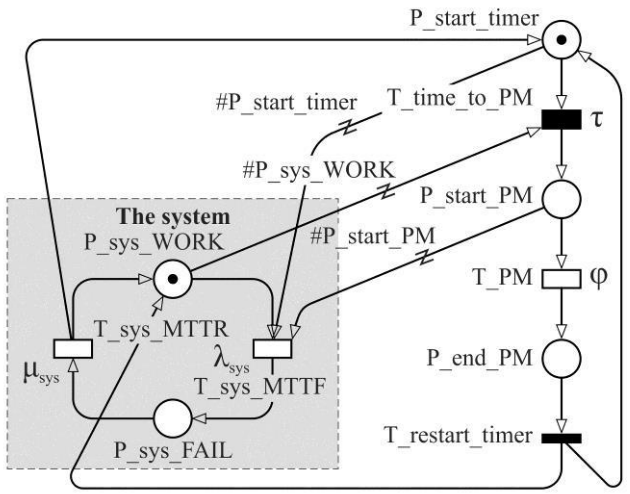

Figure 3. DSPN model depicting a preventive maintenance of a generic system with time shifts (Source: Authors' representation)

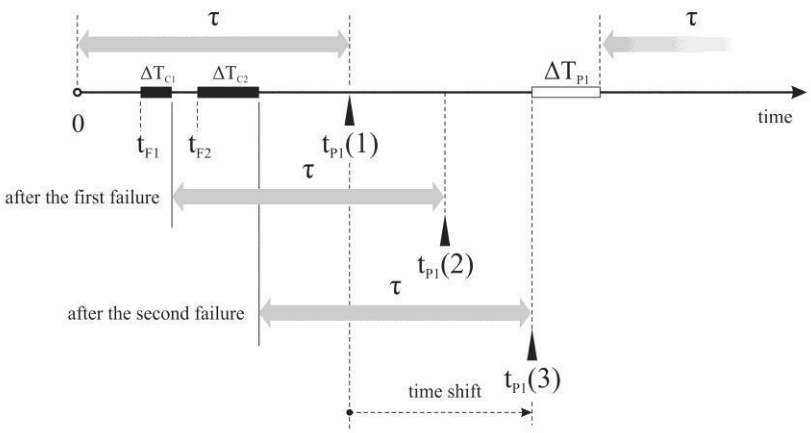

Figure 4. Possible evolution of the preventive maintenance with time shifts (Source: Authors' representation)

been set up. This way, the beginning of the first preventive maintenance session is postponed from time point $t_{P1}(1)$ to $t_{P1}(3)$.

C. *Preventive Maintenance with Dynamic Scheduling*

Dynamic scheduling refers to the possibility of either prolonging or shortening the time to the next preventive maintenance session, based on the information on whether previously a failure has occurred or not. Starting from the given initial value for the time to the next preventive maintenance session, if a failure occurs, the time until the next preventive maintenance will be shortened, otherwise, it will be prolonged. In the case of consecutive failures and/or non-failures, the continuous shortening and/or prolonging can include up to $\pm N$ steps ($N \geq 1$), starting from the initially specified time to preventive maintenance.

Fig. 5 shows a DSPN model of a system that undergoes a preventive maintenance plan with dynamic scheduling of maintenance sessions. The initial, yet default time to the first preventive maintenance is set to τ_2 time units (a token in place *P_start_timer2*). If no failure occurs during this period, preventive maintenance is being carried out that lasts, on average, $1/\varphi$ time units, given that φ is the firing rate of the exponential transition *T_PM*. After the successful completion of the preventive maintenance session, the time to the next preventive maintenance progressively increases and is set to τ_3 time units (a token in place *P_start_timer3*), where $\tau_2 < \tau_3$. The time to the next preventive maintenance remains τ_3, as soon as there are no failures. Once a failure occurs, the time to the next preventive maintenance will be gradually reduced, first to τ_2 time units (the default one), and then to τ_1 time units ($\tau_1 < \tau_2$) in the case of subsequent system failures. The time to the next preventive maintenance remains τ_1, as soon as there is a series of consequent failures. If no failure occurs, the time to the next preventive maintenance session will be prolonged first to τ_2 time units, and then again to τ_3 time units. In this particular case, the shortening/prolonging may include $N = \pm 1$ step from the initially specified time to preventive maintenance, i.e. three different periods, however, more steps can be involved.

One possible evolution of the system dynamics, intrinsic to this particular configuration, is shown in Fig. 6, where the initial time to the first preventive maintenance session is scheduled in τ_2 time units. During this period, a failure occurs at the time point t_{F1}, and the corrective maintenance session lasts for ΔT_{C1} time units. This, however, does not exclude the first preventive maintenance session starting at the time point t_{P1} and lasting for ΔT_{P1} time units. When it finishes, a new preventive maintenance session is scheduled, but now in τ_1 time units ($\tau_1 < \tau_2$). The second preventive maintenance session starts at the time point t_{P2} and lasts for ΔT_{P2} time units. Since no failure occurred during this period, the beginning of the third preventive maintenance session is scheduled not in τ_1, but in τ_2 time units. For the same reason, the fourth preventive maintenance session is scheduled not in τ_2, but now in τ_3 time units ($\tau_2 < \tau_3$).

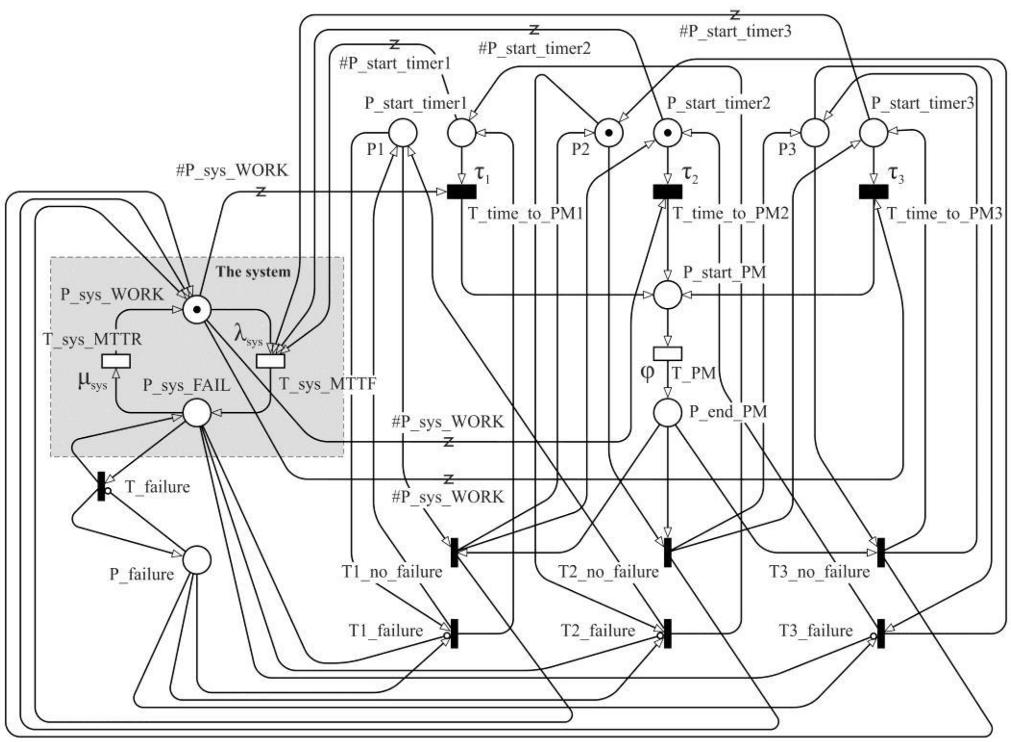

Figure 5. DSPN model depicting a preventive maintenance of a generic system with dynamic scheduling
(Source: Authors' representation)

D. *Predetermined Maintenance*

Predetermined maintenance can be considered a special case of preventive maintenance without time shifts. It refers to the practice of simply following the system manufacturer's maintenance action plans and guidelines, including when to do inspections and maintenance operations, as opposed to a preventive maintenance plan scheduled by the maintenance team. This usually consists of a finite (i.e. preset, predetermined) number of maintenance sessions carried out in the first few years of a new asset's exploitation lifetime. The periods between any two consecutive maintenance sessions are usually irregular; in most cases, they progressively increase.

The DSPN model portrayed in Fig. 7 resembles a system that is subject to a predetermined maintenance plan that includes three maintenance sessions, scheduled after τ_1, τ_2, and τ_3 time units (in general, $\tau_1 \neq \tau_2 \neq \tau_3$). These are the firing times of the deterministic transitions *T_time_to_PMi* (i = 1, 2, 3). The firing of each of these transitions indicates the beginning of a preventive maintenance operation, that lasts, on average, $1/\varphi_i$ (i = 1, 2, 3) time units, where φ_i (i = 1, 2, 3) are the firing rates of exponentially distributed transitions *T_PMi* (i = 1, 2, 3). Because of the different activities that need to be carried out in each

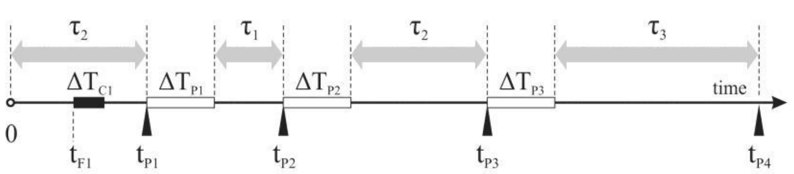

Figure 6. Possible evolution of the preventive maintenance with dynamic scheduling
(Source: Authors' representation)

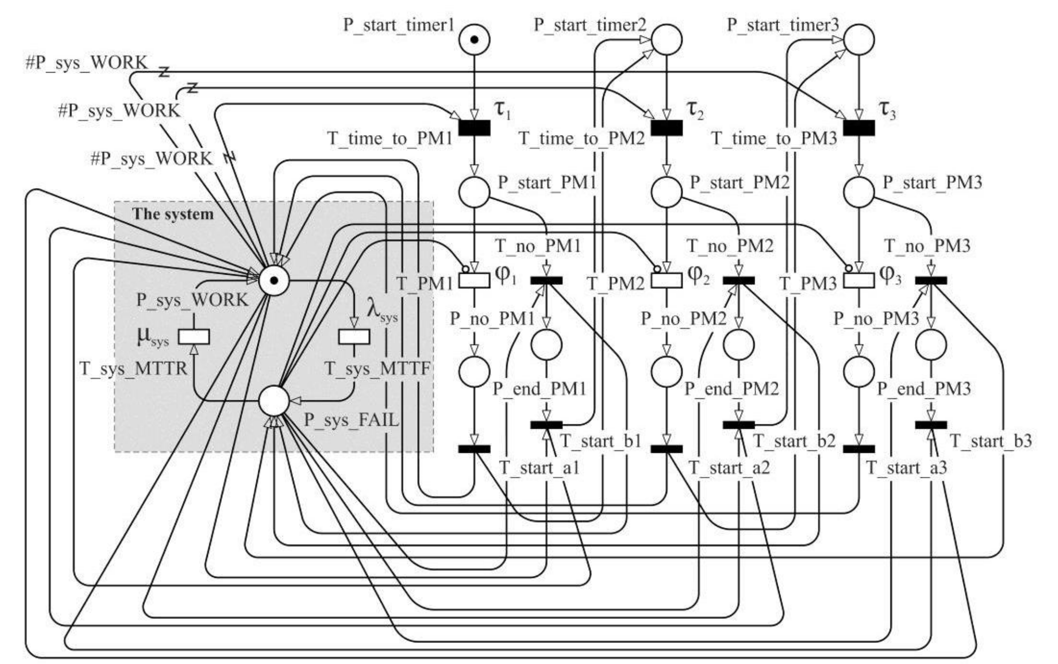

Figure 7. DSPN model depicting a predetermined maintenance of a generic system (Source: Authors' representation)

preventive maintenance session, the duration of each maintenance session is set to be different, so that, in general, $\varphi_1 \neq \varphi_2 \neq \varphi_3$.

The successful termination of the preventive maintenance session, denoted by a token in the places *P_end_PMi* (i = 1, 2, 3), enables the immediate transition *T_start_ai* (i = 1, 2, 3), which, after firing, not only restores the working condition of the system (a token in the place *P_sys_WORK*) but also initiates the time lapse until the next predetermined maintenance session (a token in the place *P_start_timer_j*, j = 2, 3), that equals τ_2 and τ_3 time units, respectively.

If the predetermined time τ_i (i = 1, 2, 3) to the next preventive maintenance session expires during the repairing phase of the system after a failure occurs (a token in place *P_sys_FAIL*), the preventive maintenance session will be omitted because of the ongoing corrective maintenance process. In this case, the immediate transition *T_no_PMi* (i = 1, 2, 3) becomes enabled and fires, so that a token goes to the place *P_no_PMi* (i = 1, 2, 3). As soon as the repair of the system concludes (by firing the exponential transition *T_sys_MTTR*), the immediate transition *T_start_bi* (i = 1, 2, 3) becomes enabled and fires, which instantly initiates the time-lapse until the next predetermined maintenance session.

After the completion of the last scheduled predetermined maintenance session, the system continues to alternate between two states: the operational one (a token in the place *P_sys_WORK*) and the non-operational one (a token in the place *P_sys_FAIL*).

Fig. 8 illustrates one possible evolution of the system's dynamics undergoing predetermined maintenance encompassing three pre-set preventive maintenance sessions.

IV. CONCLUSION

So far, various classes of stochastic PNs have been successfully used to model complex maintenance processes in a variety of applications due to their semantic power, huge versatility, and high applicability. The hereby presented DSPN models comprise a small subset demonstrating an efficient, powerful, flexible, yet highly intuitive approach to modeling the dynamic behavior intrinsic to various time-based maintenance strategies, applicable to a wide gamut of systems in practice. Depending on the actual system being modeled, all presented DSPN models, which

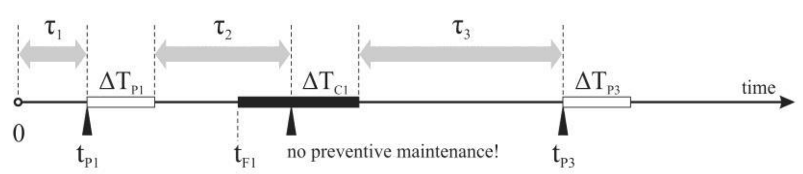

Figure 8. Possible evolution of the predetermined maintenance with three pre-set sessions
(Source: Authors' representation)

are generic by nature, can be further improved and/or specialized by including additional elements and features to capture a specific behavior. However, this could increase the model's complexity and the likelihood of its computational intractability, which is an obvious drawback. On the other hand, all these models can be used for the evaluation of specific measures vis-à-vis several input parameters (λ_{sys}, μ_{sys}, φ, τ, τ_1, τ_2, etc.) to provide significant insights regarding the reliability and availability aspects of a system, as well as the efficiency and cost-effectiveness of a particular maintenance strategy.

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