An Overview of Maintenance Strategies Using Petri Net Models

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Abstract. The accelerated change in technology, industries, and social patterns and processes, caused by ubiquitous digitalization, increased interconnectedness, and smart automation, commonly referred to as Industry 4.0 revolution, has posed greater challenges to system maintenance issues than ever before. By describing various cost-effective practices to keep systems' equipment operational, and therefore highly available, maintenance remains the cornerstone set of activities that prevent equipment or facility from failing, keeping it in a good work condition, which is a key premise to carry out its mission. The paper aims to provide an overview of various maintenance strategies, supported by proposed Petri Net models. Such simulation models are suitable for carrying out performance and availability analysis of the strategies, based on a plethora of input parameters. The suggested Petri Net models provide solid frameworks for investigating the effectiveness of various maintenance strategies applied to a wide gamut of systems.

Keywords: maintenance strategies · modeling · stochastic Petri Nets

1 Introduction

In the Industry 4.0 era, which denotes a profound digital transformation of manufacturing/production, related industries, and value creation processes, the maintenance of cybersecurity systems, augmented reality systems, Big Data systems, IoT systems, Cloud computing systems, autonomous robots, and all other cyber-physical and control systems used in complex system integration, simulation, communication, networking, and additive manufacturing processes becomes of utmost importance. The maintenance of such systems aims to attain high levels of systems dependability, reliability, and availability features. Only the proper and on-time maintenance of networked systems that can flawlessly communicate with other one scan enable continuous and efficient ways of utilization, production, value creation, and real-time optimization. Recognizing the huge significance of systems maintenance in today's digitalized environment, the paper aims to shed light on some of the most common maintenance strategies by providing their corresponding generic simulation models, based on the utilization of various

I. Karabegovic et al. (Eds.): NT 2023, LNNS 687, pp. 470–477, 2023.
https://doi.org/10.1007/978-3-031-31066-9_52

classes of stochastic Petri Nets, such as Generalized Stochastic Petri Nets (GSPNs) [1, 2] and Deterministic and Stochastic Petri Nets (DSPNs) [3, 4]. These can serve as suitable frameworks to perform various types of 'what-if' analyses vis-à-vis different input parameters.

2 Maintenance Strategies

Defined as being a 'choice', a "means to say no to certain kinds of things" or simply "choosing what not to do" (Michael Porter), strategy, in general, "is not the consequence of planning, but the opposite: its starting point" (Henry Mintzberg). It is a general plan to achieve one or more long-term or overall goals under conditions of uncertainty. Strategy is essential because the resources available to attain the goals are typically limited, so setting objectives and priorities, deciding which steps to take to attain the goals, and mobilizing resources to carry out the actions are all vital aspects of strategy [5]. Having a strategy is a necessary component of any kind of activity, since "without strategy execution is aimless; without execution, strategy is useless" (Morris Chang). In this regard, maintenance strategy can be defined as a methodology approach, which identifies the sequence of essential activities that have to be completed to keep the used system running properly, by providing scheduling information and being assigned to as many activities as needed, with a single aim "to achieve the agreed plant operating pattern and product quality, within the accepted plant condition and safety standards, and at minimum resource cost" [6]. As such, maintenance strategies are designed to increase productivity, efficiency, reliability, and quality while extending/improving assets' life, health, and safety, and decreasing/reducing asset failures, repair costs, and operational expenses [7]. When adopting a certain maintenance strategy, choosing the most appropriate one is crucial since multiple factors have to be taken into consideration to provide continuity of operations and risk management. These include (1) economic factors, which are related to minimizing the costs of both repair and downtime in case of failure, (2) evaluation of the failure's repercussions in terms of economic, environmental, etc. effects to determine the significance of avoiding failures, (3) assessment of the likelihood of failure that can be useful in adjusting maintenance plan/schedule, and (4) evaluation of time-related characteristics (time horizon, shift factor) that can help in defining the maintenance strategy. The rest of the paper addresses the three basic maintenance strategies [8], including (1) Reactive; (2) Preventive; and (3) Condition-based maintenance.

2.1 Reactive/Run-to-Failure/Run-to-Breakdown/Failure-Based Maintenance

This strategy, based on the concept of corrective maintenance, is named 'reactive' because the maintenance of a given system occurs as a reaction (consequence) to its failure (cause), i.e. there is no maintenance until there is no failure. This strategy is frequently used when the failure has minimal influence and/or is simple to fix. Figure 1 and Fig. 2 show GSPN (Generalized Stochastic Petri Net) models capturing the reactive maintenance approach applied to a whole system and to a system that includes a single sub-system, respectively. The system depicted in Fig. 1 alternates between two opposite states: a working condition (a token in the place *P_sys_WORK*) and a non-working condition (a token in the place *P_sys_FAIL*). The system is operational until a failure occurs after an average of MTTF (Mean Time to Failure) time units. The failures of the system happen with a rate of $\lambda_{sys} = 1/MTTF$. When a failure happens, corrective maintenance takes place within MTTR (Mean Time to Repair) time units, on average. The rate of repairing the system is $\mu_{sys} = 1/MTTR$. The values of λ_{sys} and μ_{sys} are firing rates of the exponential transitions *T_sys_MTTF* and *T_sys_MTTR*, respectively.

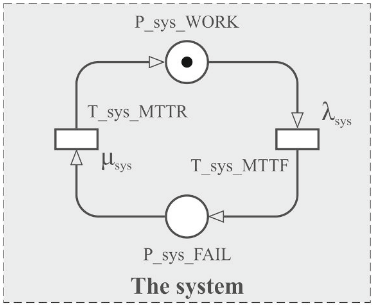

Fig. 1. Generalized Stochastic Petri Net (GSPN) model of reactive maintenance of a system

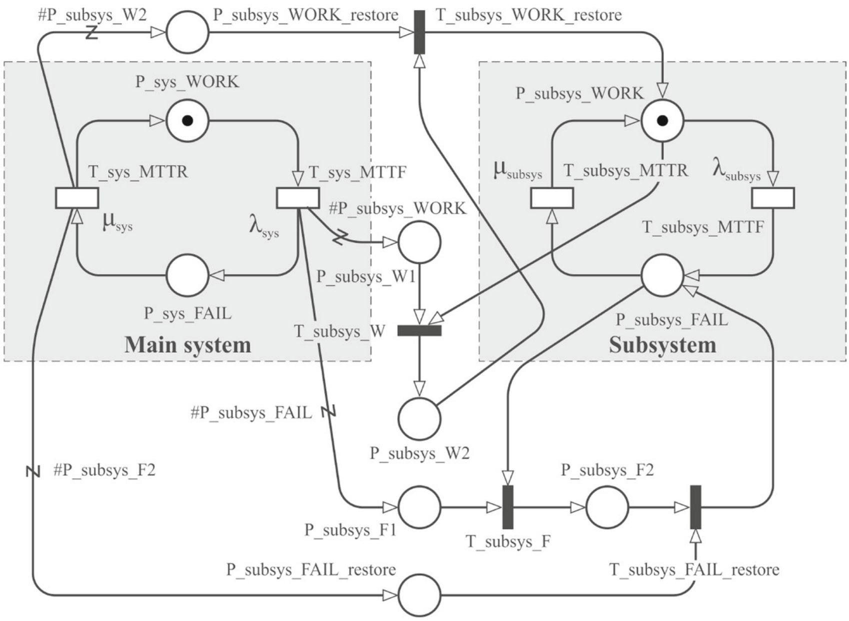

Fig. 2. Generalized Stochastic Petri Net (GSPN) model of reactive maintenance of a system with a single non-critical subsystem (Source: Authors' representation)

The GSPN model in Fig. 2 depicts the main system with a non-critical subsystem. Whenever the main system fails, the subsystem becomes non-operational; after the corrective maintenance of the main system, the subsystem restores its operation. However, the failure of the non-critical subsystem (a token in the place *P_subsys_FAIL*) does not affect the operation of the main system, which continues to work despite the failure of the subsystem; the failed component gets operational (a token in the place *P_subsys_WORK*) as soon as corrective maintenance takes place.

2.2 Preventive Maintenance

Based on an old saying stating that "an ounce of prevention is worth a pound of cure", preventive maintenance is a strategy that takes into consideration a schedule/plan of assets' inspections and actions to detect and resolve minor faults before they become major concerns. The schedule can be based either on time or on asset usage. In addition, two other maintenance strategies, the predictive and prescriptive ones, belong to this type; however, they will not be taken into consideration in this study.

Two distinctive DSPN (Deterministic and Stochastic Petri Net) models of preventive maintenance based on time are portrayed in Fig. 3 and Fig. 4.

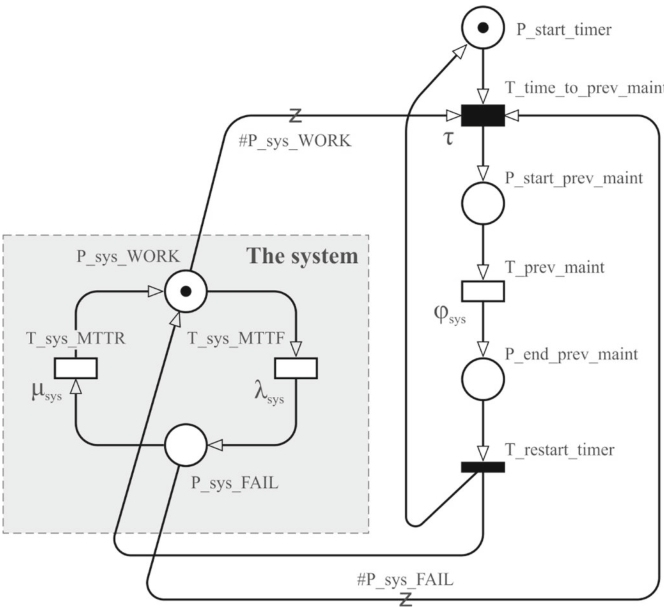

Fig. 3. Deterministic and Stochastic Petri Net model of a system undergoing preventive maintenance based on pre-determined time, with no time shifts (Source: Authors' representation)

The first one (Fig. 3) shows a system that can be subject to failures and consecutive corrective maintenance actions, but it is also subject to preventive maintenance actions scheduled in a pre-determined manner and fixed in time (no time shifts), regardless of whether corrective maintenance occurred or not.

The second DSPN model (Fig. 4) portrays a system that can be subject to failures and consecutive corrective maintenance actions, but it is also subject to preventive maintenance actions scheduled in a pre-determined manner. The difference with the previous model in Fig. 3 is that the next preventive maintenance is scheduled right after the last corrective maintenance occurred, so preventive actions are not fixed in time but rather shifted in time, depending on whether corrective maintenance occurred. In both cases, the time to the next preventive maintenance is determined by τ, the delay of the deterministic transition *T_time_to_prev_maint*. The preventive maintenance lasts, on average, $1/\varphi_{sys}$ time units and is resembled by the exponential transition *T_prev_maint*.

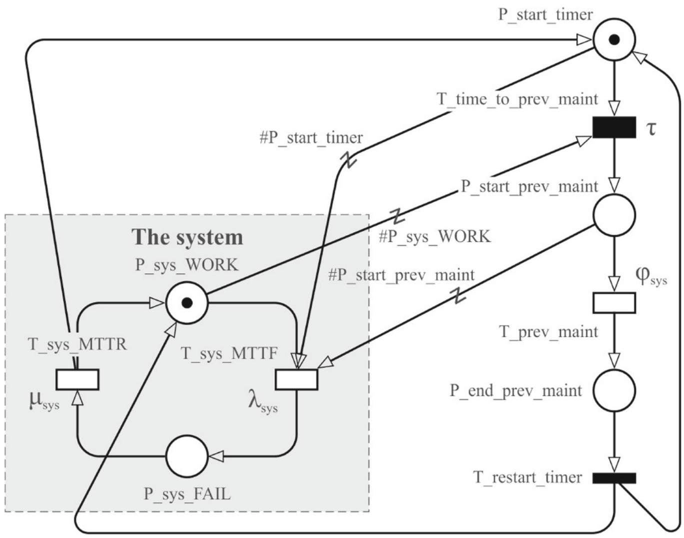

Fig. 4. Deterministic and Stochastic Petri Net model of a system undergoing preventive maintenance based on pre-determined time, with time shifts (Source: Authors' representation)

The DSPN model in Fig. 5 depicts preventive maintenance of a system based on usage.

The system alternates between two states: a working state and a state of being idle, that last for τ_w (deterministic transition *T_working*) and τ_i (deterministic transition *T_idle*) time units, respectively. Each firing of the transition *T_working* puts a single token in place *P_how_many_times*. The immediate transition *T_start_prev_maint* fires only when the total number of tokens in the place *P_how_many_times* (i.e. *#P_how_many_times*) becomes equal to the total pre-defined number of tokens in the place *P_ref_value*, which means that preventive maintenance occurs after a certain number of times the system was used/working (in this particular case, every $N = 3$ times).

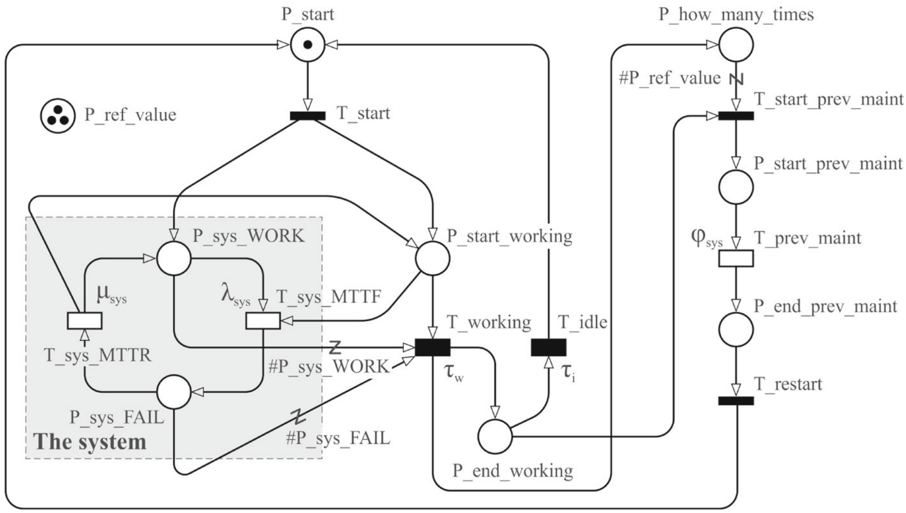

Fig. 5. Deterministic and Stochastic Petri Net model of a system undergoing preventive maintenance based on usage (Source: Authors' representation)

In general, an important factor in choosing preventive maintenance as a strategy may be low maintenance costs compared to failure impact. The aim is to schedule maintenance operations before the occurrence of a failure to reduce failure chances.

2.3 Condition-Based Maintenance

Condition-based maintenance is based on constant or continuous monitoring of asset conditions and checking for any deviations that might indicate the beginning of a failure. Deviations may include one or more parameters such as temperature, vibration, speed, power, and moisture, and refer to exceeding a pre-defined maximum limit, failing below a pre-determined minimum limit, or both. This type of strategy can be employed in operations where failure is predictable and the cost is substantial. The latter may be true in circumstances when a failure might result in an interruption of critical operations or when maintenance itself is costly.

A DSPN model of a system that is subject to condition-based maintenance is shown in Fig. 6.

In the modeled system, the deterministic transition *T_check* fires after τ time units, which means that a particular system condition is checked every τ time units. On the other hand, the firing of the exponential transition *T_condition* is a Poisson process, which occurs with a rate of η_{cond}, i.e. after $1/\eta_{cond}$ time units on average, which is a mean time to an occurrence of a deviation from the specified condition. When a deviation occurs, a token is put in the place *P_condition_YES*; otherwise, this place contains no token. Given this, the firing of the immediate transition *T_no_cond_detected* occurs only if there is no token in the place *P_condition_YES* and if there is a token in the place *P_check_END*, meaning that the checking of the system's condition did not detect any deviation. Contrary to this behavior, the firing of the immediate transition

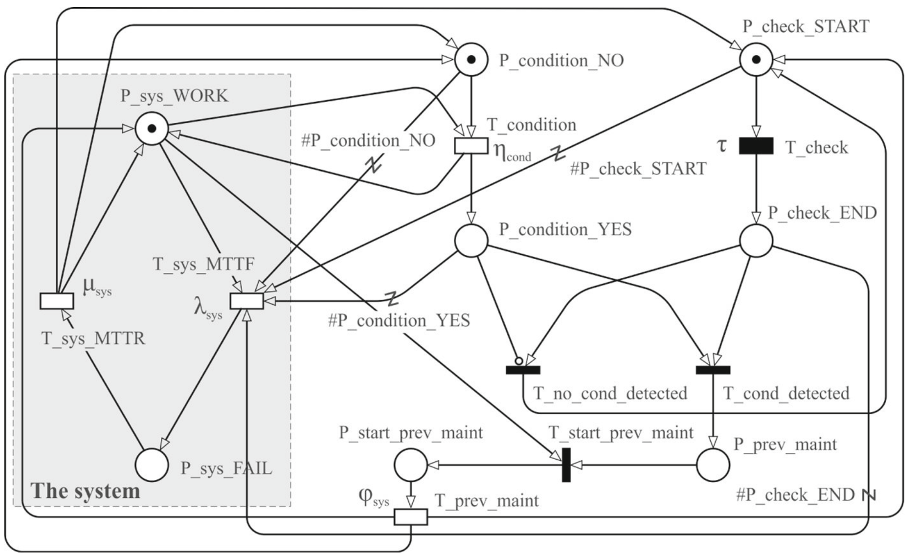

Fig. 6. Deterministic and Stochastic Petri Net model of a system undergoing condition-based maintenance (Source: Authors' representation)

T_cond_detected occurs only if there are tokens in the places *P_condition_YES* and *P_check_END*, meaning that the system checking detected a deviation of the observed working condition from its normal values. In this case, preventive maintenance is being initiated (a token in the place *P_prev_maint*) that lasts for $1/\varphi_{sys}$ time units on average (a firing of the exponential transition *T_prev_maint*). After the preventive maintenance, the system is put again in the working state (a token in the place *P_sys_WORK*), and there is no deviation of the observed parameter (a token in the place *P_condition_NO*), whilst the monitoring of the observed parameter continues in regular time intervals (a token in the place *P_check_START*).

3 Conclusion

In the exceedingly digitalized environment that involves a myriad of systems, components, devices, machines, computers, robots, sensors, etc. the role of effective maintenance has become even bigger and more significant. Based on the corrective and preventive maintenance processes, representing the two basic types of maintenance procedures/actions, the main objective of maintenance is to preserve a system's capability to provide a reliable, dependable, safe, and highly available service to all of its users. On the other hand, various maintenance strategies, which are deterministic plans specifically intended for equipment preservation and maximizing equipment uptime and facility performance while balancing the associated costs, can help in finding out the most suitable and cost-effective approach to cope with potential failures, having in mind that different assets need different, yet sometimes unique maintenance strategies.

The paper addressed some of the most prominent maintenance strategies; however, there are more of them that were not mentioned, such as predetermined, predictive, and prescriptive maintenance. However, it should be notified that the latter two cannot be represented as Petri Net models since the first one of them is based on the analysis of a vast amount of data coming from multiple sources, and the second one of them uses artificial intelligence (AI) and machine learning (ML) to not only proactively predict when maintenance will be needed, but also to suggest potential maintenance solutions.

As per the validity of the hereby presented simulation models, it was checked and confirmed by TimeNET, a dedicated software tool for modeling and analysis of several classes of stochastic Petri Nets.

Future work vis-à-vis the presented models includes conducting a stationary analysis and obtaining steady-state probabilities, as well as the computation of various performance metrics for various input parameters that can help in conducting 'what-if' analyses regarding various working scenarios.

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