Modeling and simulation of maintenance strategies using stochastic Petri nets

C. Bérenguer, E. Châtelet & Y. Langeron
Université de technologie de Troyes
12 rue Marie Curie - BP 2060
10010 Troyes cedex - FRANCE
christophe.berenguer,eric.chatelet,yves.langeron@utt.fr

A. Despujols
EDF - R&D Division
6 quai Watier
78401 Chatou - FRANCE
antoine.despujols@edf.fr

Abstract

In this communication, we present a structured and modular framework for the modeling and performance assessment of complex maintenance policies for multicomponent systems based on stochastic synchronized Petri nets.

1 Introduction & problem statement

Maintenance people have generally choices to make between various alternatives when they work out the preventive maintenance programs. On critical systems EDF applies a Reliability Centred Maintenance method, taking into account the possible consequences of failures and the collected experience feedback. However the maintenance program is based in a qualitative way on experts opinion. Until now, RCM method does not make it possible to estimate, nor to compare quantitatively various alternatives. The objective of this work is to model and to simulate the maintenance programs in order to provide quantitative results which could support choices between different maintenance tasks and frequencies. Associated with Monte Carlo simulation, event-based modeling tools and, more precisely, stochastic Petri nets offer an efficient solution to this kind of problem. We propose in this paper a two-stages modeling framework based on synchronized stochastic Petri nets for complex maintenance policies. The first stage of this work consisted in establishing a generic model of equipment (component) which represents the operational states (operation, shutdown, standby, disable state), the physical states (up state, obvious fault, hidden fault, degraded state...), and the various maintenance tasks carried out (external inspection, internal inspection, scheduled replacement, test, repair...). On the basis of this generic model, the second stage consists in representing a system of several equipments and simulating its behaviour when a given maintenance strategy is applied, so as to estimate the maintenance costs and the resulting system unavailability. The proposed method is structured and modular. Following a classical top-down approach, it makes it possible to build simple models which can be validated independently, and then associated in order to simulate complete systems. This paper presents the generic modeling of equipment and the approach which is implemented to model complete systems. The proposed modeling approach has been validated on a turbo-pump lubricating system.

2 Modeling the maintained system with Petri nets

The aim of this section is to present a generic methodology based on stochastic synchronized Petri nets (SSPN) adapted to maintained systems modeling. After some introductory remarks on Petri net modeling, this presentation is divided in two paragraphs corresponding to the two main modeling levels, i.e. generic modeling of a maintained component and system-level modeling.

2.1 Introductory remarks on Petri net modeling for maintenance

Monte Carlo simulation is widely used in reliability or performability assessment studies, see e.g. (Dubi 2000; Borgonovo, Marseguerra, and Zio 2000; Barata, Guedes Soares, Marseguerra, and Zio 2002). For systems reliability and availability studies, stochastic synchronized Petri nets (SSPN) (Lindemann 1998; Ajmone Marsan, Balbo, Conte, Donatelli, and Franceschinis 1995) offer a powerful and versatile modeling tool (Malhotra and Trivedi 1995; Dutuit, Châtelet, Signoret, and Thomas 1997; Hosseini, Kerr, and Randall 2000; Rochdi, Driss, and Mohamed 1999; Simeu-Abazi and Sassine 1999), which can be used jointly with Monte Carlo simulation, with several desirable properties:

- Modeling the behavior of a component with SSPN allows to take into account any lifetime and repair law, without any restriction to the "classical" exponential law (constant rate).
- Dynamic process systems, for which the physical behavior and the probabilistic failure behavior are dependent, can be modeled in an efficient way with SSPN. This dynamic feature of SSPN make it possible to model in a realistic way failure scenario and associated defense barriers, and complex maintenance policies (condition-based maintenance policies, resources conflicts, ...).
- An event-based modeling approach (like the SSPN) avoids the combinatorial explosion encountered with state-based (Markov) modeling approach and it is possible to construct event-based simulation models for large systems. The size of a SSPN-based model grows linearly with the size of the system, whereas the state-based model size grows exponentially with the system size. However, to take full advantage of the compactness of Petri nets models, one has to observe good modeling practices and a structured modular modeling approach should be adopted, especially in the proposed context with operational, physical and maintenance tasks modeling.
- With SSPN, the modeling task can be progressive and incremental : a model for a complex system can be built using several component models as elementary bricks. Moreover, adding or removing a component to the system does not require the development of a new model as it is often the case with state-based approaches
- Finally, using SSPN as modeling tool for performance assessment with Monte Carlo simulation techniques makes the analysis and interpretation of raw simulation results easier for the maintenance decision-maker.

The main contribution of this work is the joint modeling of a complex maintenance policy (both at the component and at the system levels) and of the functional and dysfunctional behavior of a complex multicomponent system for the performance assessment of the maintained system (maintenance costs,). This complete model can then be used as decision tool to improve the maintenance decisions on the system. To our knowledge, no established methodology has been reported in the literature for this kind of problem and this work can be seen as a preliminary study to validate a modeling framework for complex maintenance policies on complex systems based on Petri nets. In order to avoid the inflation of the size of the model, we propose a hierarchical, incremental and modular modeling structure on four levels : one component level, and three system levels (system operation model, system dysfunctional model and system maintenance model).

2.2 Generic modeling of a maintained component

The basic component-level model is developed for each component of the system. We propose a generic and modular modeling structure for maintained components which includes the Petri nets describing the degradation and maintenance processes of a generic component. Even though it is desirable to have only one generic component model, our experience has shown that it can be useful to distinguish between passive and active components. The generic model takes into account both the physical states (nominal, degraded, hidden or pending failure, actual failure, partial or complete failure) and the functional states (in maintenance, hot/cold spare, operating, waiting state due to the lack of resource, ...) of a component. The degradation process (degradation detected by inspection, by test, by control, sudden failure) are also modeled. At this component-level, a Petri net model is associated with each of the maintenance tasks defined for a component : systematic preventive maintenance (periodic replacement), condition-based maintenance operations (inspection, test, control) and corrective maintenance. More complex maintenance policies (e.g. opportunistic maintenance) are defined at the system-level with help of messages. Finally, the Petri net for the evaluation of the maintained component availability is defined at this level.

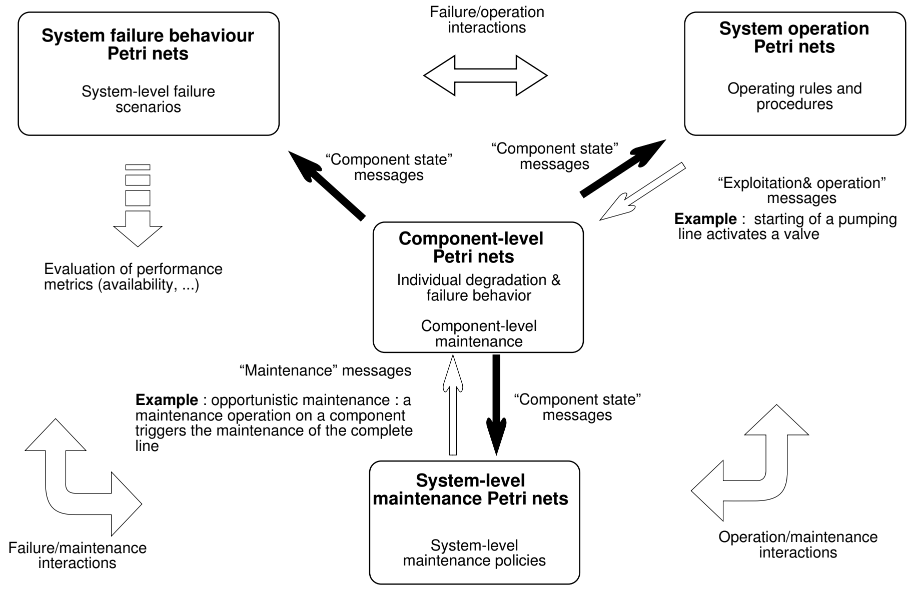

Figure 1: Structured framework for maintenance modeling with Petri nets

The SSPN use classical properties of Petri nets to treat the sequential and parallel processes, with stochastic and deterministic behaviours and "messages", (Dutuit, Châtelet, Signoret, and Thomas 1997; Lindemann 1998). These messages are used to characterize the interaction between processes (Boolean conditions) which are described by different elementary Petri nets. They are able to synchronize the Petri nets modeling the behaviour of a component but also to characterize the state of components and the stage of the maintenance actions (inter-component interactions). An adequate codification of these messages is helpful to obtain an easily understood model (for example, if the component i is in operation, the corresponding message i-01 is true, or exhibits a visible degradation, message i-02 is true, etc.).

2.3 System-level modeling

At the system level, three modeling levels are developed to describe completely the system behavior: system dysfunction modeling level, system operation modeling level and system maintenance modeling model.

- *"System dysfunction" modeling level* : this modeling level describes all the degradation/failure scenarios at the system level with one or several Petri nets. Obviously, this global model rests on all the component-level models. The global performance indicators of the maintained system can be evaluated at this level by using specific places in the Petri nets.

- *"System operation" modeling level* : Obviously, the operating behavior of the system cannot be described by the simple juxtaposition of the component-level models: it is necessary to take into account all the possible interactions and dependences between components. The aim of the system operation modeling level is to describe the nominal behavior and the operating rules of the system. The Petri nets of this modeling level force (through messages) the Petri nets of the component modeling level to interact and to evolve according to the needs of the system: activating of a required component, stopping of a superfluous component, ... At this level, one can model cold spare equipments, activating of defense systems in case of an equipment failure, stopping of a line in case of maintenance of one of its component, ...

- *"System maintenance" modeling level* : At the component modeling level, only individual maintenance procedures have been considered. Maintenance strategies at the system level are taken into account at the system maintenance modeling level. For example, the Petri nets of this level are designed to model maintenance operations grouping procedures which are used to take advantage of economies of scale due to economic or technical dependences between components (opportunistic maintenance). Petri nets modeling resources sharing and availability problems (repair teams, specific tools, spare parts stocks) are also integrated at this level.

The interactions between the different modeling levels are implemented with synchronization messages :

- Component-level Petri nets send messages on components states (failure, degradation level, unavailability for maintenance) to the Petri nets of the three other levels which evolve according to these messages and send possibly feedback messages.
- The "system operation" level can send message to the component-level Petri nets to require the activating of a standby component or the stopping of an auxiliary component that has become useless after the repair of the main equipment.
- The "system maintenance" level send messages to the component-level Petri nets to force the maintenance of a component coupled together with a component already in maintenance.

The proposed modeling approach based on Petri nets allows a modular optimization of the maintenance procedure. The global optimization of the maintenance procedures on the system would certainly require the development of specific multiobjective optimization procedures.

3 Application example : turbo-pump lubricating system

The proposed modeling approach has been validated on a simplified turbo-pump lubricating system of a nuclear power plant with 20 interacting components including pumps, filters, pressure and temperature sensors, valves, ...

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