CHEMICAL ENGINEERING TRANSACTIONS

VOL. 77, 2019

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Genserik Reniers, Bruno Fabiano
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ISBN 978-88-95608-74-7; **ISSN** 2283-9216

DOI: 10.3303/CET1977041

Dynamic RAMS Analysis Using Advanced Probabilistic Approach

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The increasing complexity of modern socio-technical systems has raised new challenges to analyze the reliability, availability, maintainability, and safety (RAMS) of oil and gas processing facilities. This paper presents a new approach to perform RAMS analysis using stochastic Petri nets modelling blocks. Those blocks are small-sized Petri nets (PN) that independently represent every component of the system. Depending on the component nature, such as repairable component periodically tested, non-repairable/replaced component, or standby component with the probability of failure to start, the PN block models the behaviour and the life cycle changes of the component and subsequently of the entire system. The PN blocks communicate through Boolean variables without being physically connected; this provides a less congested and easily trackable structure. It is observed that the proposed approach provides a robust and reliable mechanism of RAMS analysis. This work constitutes a significant step toward an integrated dynamic model for RAMS analysis. The proposed RAMS model is composed of three strong characteristics: time dependency, robustness, and explicit graphical structure.

1. Introduction

Reliability, availability, maintainability and safety (RAMS) analysis was first developed for determining the integrity of engineering design. Later on, it came to be used for performance evaluation of the installation and operations. The process facilities always considered to be complex systems due to the involvement of hazardous chemicals, pipeline clusters, assemblies, sub-systems and components, all of which are subject to failure. Therefore, it requires regular maintenance to maintain its integrity and performance (Baxter et al. 2008). Due to technological and cost limitation, it is not feasible to design a maintenance free installation or equipment. Installation or equipment deteriorate with time due to usage, wear and tear (Eti et al., 2007).

In recent decades, RAMS analysis influenced various industries and facilities, and served as an integral part of the systems' design. It constitutes a useful tool for reliability analysis (Michelsen 1998) and availability of systems (Komal et al., 2010). As far as availability is concerned, it is one of the most important performance measures, especially for those industries or facilities where equipment repair is possible (Komal et al., 2010). However, each facility or plant is subject to failures due to the lack of strategic maintenance procedures or the inability to predict the potential hazard, thus resulting in an accident. To avoid the potential hazards, periodic maintenance strategies must be applied. Therefore, maintenance is also considered to be a key factor in enhancing system performance (Madu 2005). Any activity that ensures the performance of equipment to perform its intended work is termed as maintenance (Komal et al., 2010). Failure rate and repair time are the key elements that may result in improving both reliability and maintainability of the system. Further, improving both may result in the improvement of system availability too (Nepal and Monplaisir, 2007).

The oil and gas industries have highly complex technological systems that require a strategic approach from the provider for the availability of equipment to meet the increasing demand criteria. Therefore, to implement a strategic approach to RAMS, they require deep knowledge about the system to implement probabilistic tools and methods for identifying the system performance (Corvaro et al., 2017). To evaluate the performances of a system, various methods are available, among them RAMS analysis can be used to measure key

Paper Received: 13 October 2018; Revised: 8 April 2019; Accepted: 25 June 2019

Please cite this article as: Taleb-Berrouane M., Khan F., Kamil M., 2019, Dynamic RAMS Analysis Using Advanced Probabilistic Approach, Chemical Engineering Transactions, 77, 241-246 DOI:10.3303/CET1977041

performance metrics of the system that may include MTTF (mean time to failure), MTTR (mean time to repair), MTBF (mean time between failure), EDT (equipment down time) and system availability which provides the need of the maintenance to meet the desired objectives (Sharma and Kumar, 2008).

Unlike any other probabilistic technique available, PN blocks can easily represent a large variety of component types, whether it’s periodic testing, standby system with failure to start condition, or repaired component. PN is proved to be a robust technique to study safety instrument systems (SIS) (Wu et al., 2018). In the present study, the PN blocks provide the life cycle behaviour of components and subsequently the entire system.

The novelty of the work is to illustrate how PN blocks can represent each component and its behavioural changes in continuous and time-dependent form. Moreover, the new information obtained from the system can be used to update the model and subsequently, resulting in updated failure profile of the system. The updated system profile can be used for decision making in maintenance strategies.

2. Stochastic Petri Nets with Predicates: Definition and Basic Concept

Stochastic Petri nets (SPN) are bipartite graphs which can provide intuitive illustrations of each component state in a system. It was first introduced in Carl Adam Petri’s dissertation (David and Alla, 2010). PN is a promising tool to study and model the relationships between asynchronous, co-current, distributed, parallel, non-deterministic, and/or stochastic systems (Murata 1989). The glossary notation of SPN is shown in Figure 1. As can be seen the places are drawn as circles, and transitions as rectangular bars. Arcs, connecting the former to later, are known as input directed arcs while those connecting the latter to former are known as output directed arcs.

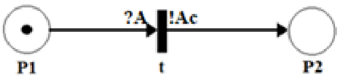

Figure 1: Simple example of SPN with predicates and assertions.

The primitives of the above notations are as follow;

- The places represent the state or conditions of a component.
- The transitions represent the change in the state/condition of a component from initial, intermediate, to final place. It is capable of modelling the dependencies between the components.
- Transition firing only occur when the multiplicity of tokens is at least equal to multiplicity of the associated input arc.
- Tokens create the dynamicity and trackability of the model
- Directed arcs decide the token from place to transition or transition to place.
- Predicates are the variables represented by “?” (e.g ?A), resulting in validation of the transition.
- Assertions (e.g.!A) are variables which update as a result of transition firing.

3. Dynamic Modelling Capability of SPN with Predicates and Assertions

To model the complex system behaviour for RAMS analysis, GRIF’s Petri nets module (SATODEV 2018) has been used in the present study. The PN blocks are capable enough to show both working and dysfunctional states of equipment. Depending on the component nature, such as, repairable systems periodically tested, non-repairable/replaced systems, or standby systems with the probability of failure to start, the PN block models the behaviour and the life cycle changes of the component and subsequently of the entire system. Further, each transition in SPN is capable for reflecting the dependencies among the equipment using stochastic or deterministic variables (Wu et al. 2018). The SPN with predicates and assertations suggested in IEC 61508 (IEC 61508-6 Functional Safety of Electrical/electronic/programmable Electronic Safety Related Systems 2010). It has pre-programmed continuous distributions available to specify the transition configuration, such as Weibull distribution, which is useful to provide installation/equipment time-dependent life cycle.

A transition can be enabled when the input place has at least equal or greater number of tokens than the multiplicities of the input arc associated with the transition. Once transition is enabled, the token moves from the input place and resides in the output place. It is worth noting that the token only resides at places, and transition defines the firing time of them. The firing time is based on the transition specifications and the token migration from input to output place depends upon the input and output functions (Zhou et al., 1990). If there are two or more output arcs from transition to places, then the token migration depends on the priority given for each arc. It is a useful feature which can be used for assigning priorities for working, repairing or testing of equipment. This simple notation is to provide better understanding for the reader about the capability of the PN blocks driven by SPN with predicates and assertion. However, in the next section, its application using a comprehensive case study will be shown.

4. Petri Nets Modelling Blocks

A PN is constituted of places, transitions, arcs and tokens. Modelling large and complex accident scenarios or reliability assessment models based on these elementary constituents can be a tremendous task for the risk or reliability analyst. This explains why the PN models are less popular, and they require an expert in modelling to build, adjust and track the models.

Table 1: Main modelling features of SPN block-based model compared to the conventional techniques.

Element of the model	FT	BN	Conventional SPN	SPN block-based model
Root cause element	Basic event (binary state)	Marginal node (multistate)	Embedded in the overall model (not specified)	A physically separated sub-network
The logic	Logic gates (AND, OR, KooN)	Conditional probability table (CPT)	One or more stochastic transitions	Mathematical variable or Boolean function
Connection	Directed arcs (acyclic)	Directed arcs (acyclic)	Directed arcs (cyclic)	Directed arcs or Boolean variables

Table 1 summarizes the main modelling features of the proposed model and compares it with the conventional techniques such as fault tree (Berrouane and Lounis 2016), Bayesian networks (Deyab et al. 2018; Taleb-berrouane et al. 2018) and the conventional SPN (David and Alla 2010). In total, six PN blocks are capable to model most of the risk and/or reliability process components.

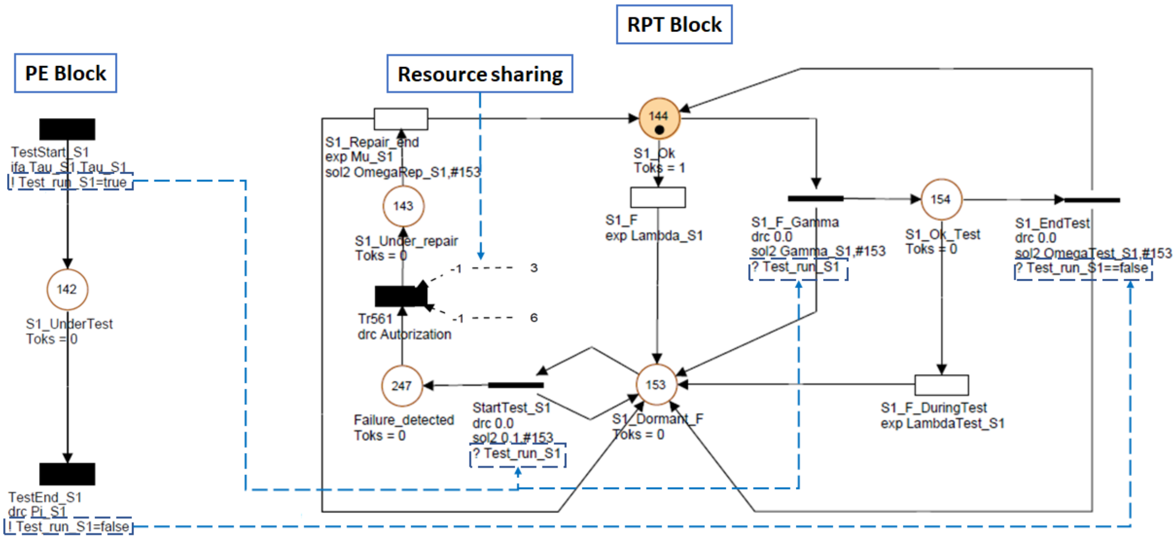

Figure 2: RPT and PE bocks and their virtual connections through the Boolean functions.

Figure 2 depicts RPT and PE blocks and highlights some of the virtual connections established through the use of Boolean functions such as “Test_run_S1”. This function communicates the time when the period test (i.e. planned event) will start and when it will end. The transition firing law “ifa”, which means “in advance appointed time” is used to generate a token at the appointed time. The two variables of the law are delay between two fires and delay of first fire respectively. The rest of the Boolean variables and parameters are summarized in Table 2 and Table 3 respectively.

Table 2: Summary of the mathematical variables and Boolean functions used in the PN blocks.

Variable	Type	Function	Involved in blocks
Test_run_S1	Boolean function	Captures the starting time and ending time of the test (i.e. periodic maintenance)	PE and RPT
Reliability_C_i	Mathematical variable	Observes the probability of having a token in the dormant failure state (e.g. places #2, #5 and #153). See equations 1 and 5.	RPT and RFS
Availability_C_i	Mathematical variable	Observes the probability of having a token in states where the component is available (e.g. running and standby)	RPT and RFS
Maintainability_C_i	Mathematical variable	Observes the probability of having a token in states where the component waiting for repair or under-repair.	RPT and RFS
High_level	Boolean function	This function triggers some transition to fire following the occurrence of a high level in a specific drum. This can be replaced with the appropriate function depending on the process system.	RPT and RFS
UE	Mathematical variable	This variable calculates the probability of TE at each moment based on the variation of the root cause elements.	TE

Table 3: Summary of the parameters in the PN blocks mostly taken from OREDA database (OREDA 2002).

Parameter	Meaning	Value/rate (h^{-1})	Appears in	Parameter
Lambda_C_i	Failure rate of component i	5.70E-07	Figures 2 and 4	Lambda_C_i
Mu_C_i	Repair rate of component i	0.1667	Figures 2 and 4	Mu_C_i
Lambda_test_C_i	Failure rate during test of component i	5.70E-07	Figure 2	Lambda_test_C_i
Gamma_C_i	Probability of failure to start	0.001	Figure 4	Gamma_C_i
Gamma_test_C_i	Probability of failure due to starting the test	0.001	Figure 2	Gamma_test_C_i
Sigma_test_C_i	Probability of detection failure	0.8	Figure 2	Sigma_test_C_i
Omega_test_C_i	Probability of maintenance failure	0.001	Figure 2	Omega_test_C_i

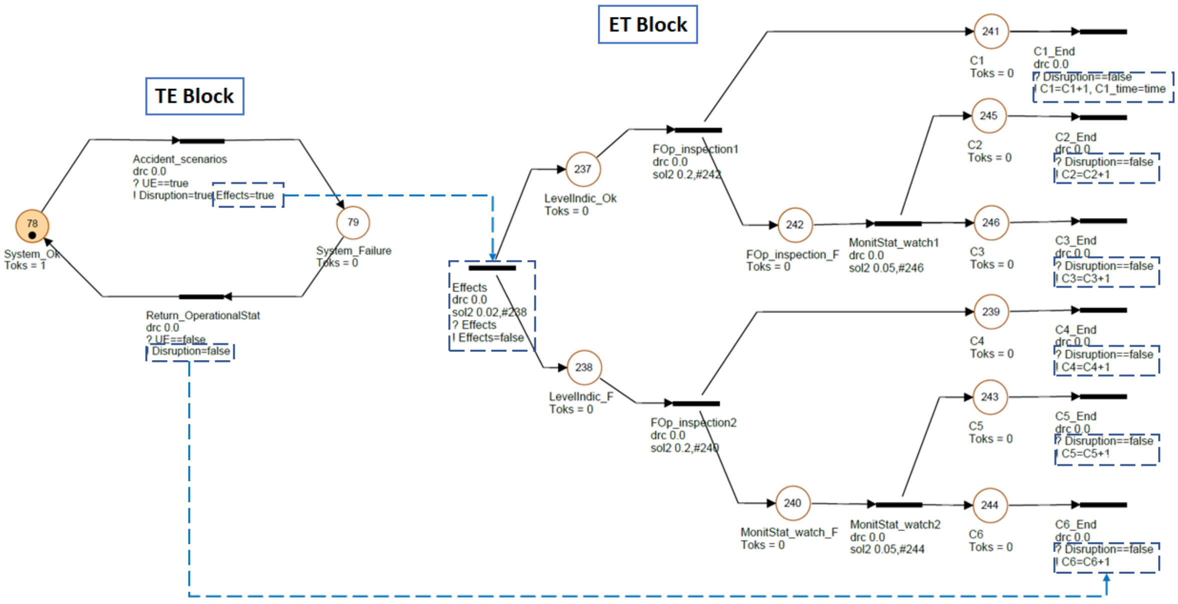

Figure 3: TE and ET bocks and their virtual connections through the Boolean functions.

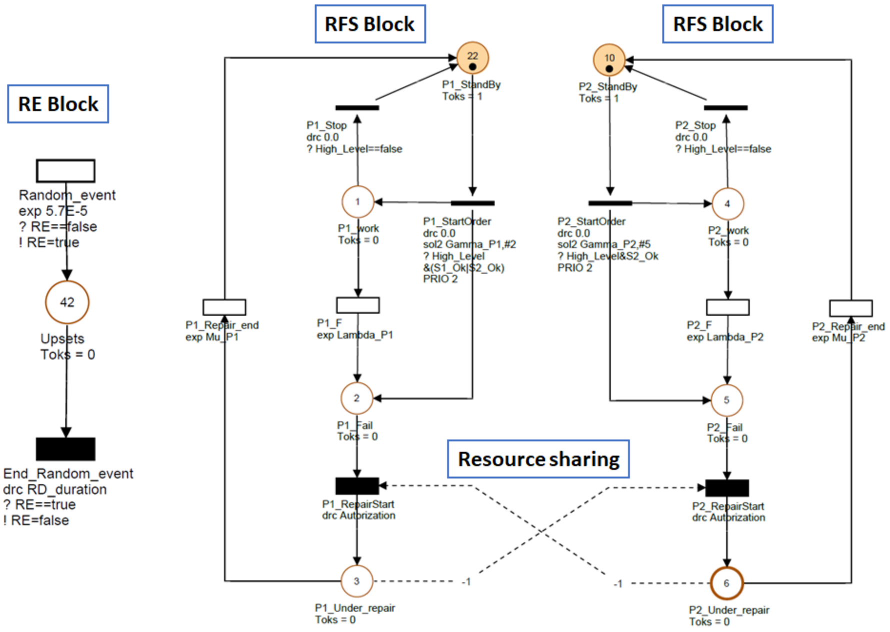

Figure 4: RE and RFS bocks and the resource sharing between two RFS blocks (redundant system).

Figures 3, 4 and 5 depict the various types of PN blocks. These figures are adapted and modified from our previous work. The reader interested in learning more about the case study can refer to the work of Taleb-berrouane et al. (2016). The resource sharing shown on Figure 2 and Figure 4 model the availability of the maintenance team (i.e. resource) to repair the failing component. Based on the PN block-based model, RAMS parameters for each component can be calculated in the form of mathematical variables as follows:

- RPT block (one component only) in Figure 2:

Reliability: $R(t) = 1 - P_c$ (#2) (1)

Operational availability: $A = \frac{\text{Time (\#1) + Time (\#22)}}{\text{Overall observed time}}$ (2)

Maintainability: M = Time (Authorization) + Time (#3) (3)

Safety index: $S = P_c$ (#2) × Criticality index (4)

Where "P_c" is the cumulative probability of having a token in a specific place. In the example "#153" means "place number 153". Time (#143) means the cumulative average time, calculated based on Monte Carlo simulation, of a token in place number 143. The criticality index is a parameter, not included in this model, that assesses the level of criticality subsequent to the failure (i.e. failure consequences). In Figure 3, the consequences C3 and C6 are considered to be the hazardous situations that alter the plant safety and/or integrity.

- RFS block in Figure 4:

Reliability: $R(t) = 1 - P_c$ (#153) (5)

Operational availability: $A = \frac{\text{Time (\#144) + Time (\#154)}}{\text{Overall observed time}}$ (6)

Maintainability: M = Time (#247) + Time (#143) (7)

Safety index: $S = P_c$ (#153) × Criticality index (8)

RAMS parameters for the overall system can be extracted from the TE block in Figure 3:
Reliability: $R(t) = 1 - P_c$ (#79) (9)

Operational availability: $A = \frac{1 - \text{Time (\#78)}}{\text{Overall observed time}}$ (10)

Maintainability: $M = \sum_{C=1}^{n} \text{Time (C1\_Authorization)} + \text{Time (C1\_under\_repair)}$ (11)

Safety index: $S = [P_c$ (#246) + P_c (#244)] × Criticality index (12)

Some specific details may need to be adjusted to suit some process systems; but the conceptual design of the PN blocks have a large applicability for process systems.

5. Conclusions and Future Directions

In this paper, a new approach for RAMS analysis using a PN block-based model was proposed. In total, six block types were developed to model repairable component periodically tested, random and planned events' occurrence, standby component with the probability of failure to start, end-state event or top event and the event tree structure. The PN blocks communicate through Boolean variables without being connected by any arcs and transitions. This arrangement results in a less congested and easily trackable model. In addition, it was demonstrated how an extended form of stochastic PN can be used to overcome the structural complexity and state explosion limiting the use of PN for risk and reliability modelling. In upcoming work, the proposed modelling approach will be applied for a complex process system for extended testing and verification.

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