Performance Analysis of Complex Manufacturing System using Petri Nets Modeling Method

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Abstract. The Petri nets modeling method is a powerful tool for the performance analysis of industrial systems. The main factor which makes it more effective among the various popular simulation methods is the ability to deal with the real working conditions. The data obtained from such a manufacturing system is generally full of uncertainties and the Petri nets modeling method deals with this data to reflect the real behavioral pattern of different sub-systems installed in the plant. The Petri nets-based simulation method provides the availability of the sub-systems for a long time period by running the plant in virtual manners. The results obtained through the analysis can be utilized to identify those sub-systems which highly affect the system availability and separate maintenance planning for each sub-system can reduce the production loss due to unavailability of any sub-system for performing its intended task. The proposed methodology has been demonstrated in this paper using a complex repairable manufacturing system.

Keywords: Petri Nets, Performance analysis, Steady-state availability, Manufacturing system.

1. Introduction
The new emerging industrial systems are entirely focused on assuring the maximum output and higher quality of product through the advancement in engineering systems under the concept of performability. The prime objective of utilizing the available resources is also a fundamental need for the satisfaction of higher expectations. The complexity of these industrial systems is even higher, recognizing the demand for automation and large systems, consisting of series-parallel sub-systems of higher configuration is a true challenge for system analysts. Besides this, making the optimum balance between the large initial investments and continually maintaining high standards of the competitive market is another test for the industrialists. Knowing the reality of actual situations, performance analysis of industrial systems is the only way to move ahead toward the predefined targets. The proposed simulation method for different industrial systems has been used to evaluate system performance. Adamyan and He [1] suggested that system reliability and safety depend not only on the failed states but also on the sequence of failures. For this, they have presented a methodology to determine the occurrence of failures using Petri nets. Bahl et al. [2] utilized the Petri nets approach to determine the behavior of distillery plant through the variation in input parameters of various components and suggested the most critical component which highly influences the plant availability. Florin et al. [4] presented a study on the Petri
nets model which includes stochastic behavior of timed transition firing choice and provides an approximate solution for a case example of bus allocation. Garg and Sharma [5, 6] applied the Petri nets and Lambda-Tau methodology for RAM analysis of the complex system of urea manufacturing industry. They have also performed the sensitivity analysis for the system in terms of system availability and reliability against the different combinations of input parameters. Kumar et al. [8] used the Petri nets modeling method for the performance assessment of a milk processing plant. They have also performed the profitability analysis for this system. Kumar et al. [9, 10] used the Markov modeling method to analyze the system performance. They have also used the GA and PSO algorithms for performance optimization. Kumar and Aggarwal [11] developed a Petri nets model for performance evaluation of computer program execution in distributed processing system and suggested the two reliability measures to determine the probability of computer program execution. Haiyue et al. [12] proposed general procedure of modeling for reliability evaluation of a critical system and demonstrated through an example to show the effectiveness of proposed approach. Haverkort and Niemegeers [13] proposed a performability modeling technique especially for the system which can be partially operable. Through this framework, they have suggested a few general rules for performability modeling software tools in terms of their adaptability and output. Holliday and Vernon [14] analyzed the performance of computer system through the Petri nets modeling method and showed the capability of PN model for parallel system to obtain an accurate estimation of system performance. Leveson and Stolzy [15] described the application of Petri nets model in software development process. They explored the possibility for the software reliability analysis for its properties i.e., safety and fault-tolerance to determine the criticality of functions in certain conditions. Lindemann [16] proposed an improved randomization technique for DSPN model to determine the steady-state solution process. This technique is easy to implement and provides comparatively stable numerical solution. Liu and Chiou [17] suggested that in reliability engineering, Petri nets model is more efficient than fault trees for system failure analysis and to describe the relation between events and conditions. Molloy [18] analyzed the system performance using Petri nets and Markov process with the exponential transition rate. They have also suggested that Petri nets model is much simpler for its specification as compared to Markovian analysis. The discrete-time PN model provides improved human interface and better specification mechanism. Sachdeva et al. [19, 20] analyzed the behavior pattern of pulping and screening system in a paper plant for reducing overall operation and repair costs. They proposed the Petri Nets-based methodology to compute the reliability parameters using Mante Carlo simulation of the Petri Nets model and the effect of parameters on system availability have also been discussed.

It is observed in the literature that the researchers have successfully investigated various industrial systems using Petri nets modeling method, the present deals with the performance analysis of a complex manufacturing system using the Petri nets modeling method to reflect the real system behavior using the uncertain data. The obtained results will be highly beneficial in future maintenance planning for the different sub-systems.

2. System description

The dished end (DE) manufacturing system is part of container manufacturing process. The dished ends are manufactured in this system to install on the ends of a shell. This process completes the manufacturing of heavy-duty containers mainly used to store the chemicals. The schematic process flow diagram of the DE manufacturing system is shown in Figure 1 [10].

- **Sub-system A:** It is a gas cutting machine used to cut the circular pieces for the manufacturing of dished ends.
- **Sub-system B:** It is a hydraulic power press used to obtain the required curvature in the dished end.
- **Sub-system C:** These are two submerged arc welding machines installed in parallel and it is used to join the dished end with the shell.
• *Sub-system D*: It is another hydraulic power press machine that is used to bend the ends of the container to improve strength. This process is known as chiming process.
• *Sub-system E*: It is a stress-relieving furnace used to process the finished container.

Figure 1. Schematic process flow diagram of DE manufacturing system

2.1. Assumptions:
• Failure and repair rates for each sub-system are constant and statistically independent.
• Performance-wise a repaired unit is as good as new.
• The sub-systems/units never degraded with time.
• Sufficient maintenance facilities are available for each component. So, there is no waiting time to get the repair facility.
• All the units are initially operating and are in the working state.
• The system may work as the reduced capacity state.

2.2. Notations:

![Diagram with various states and transitions]

- ‘Places’ represents the system state
- ‘Timed Transition’ associated with failure and repair rate of the sub-system
- ‘Immediate Transition’ have their own guard function
- ‘Token’ represents the current condition and state of the sub-system
- ‘Arc’ the direction of arc from places to transition and transition to places are known as input and output arcs.
3. Performance Analysis

3.1. Performance Modeling:
The Petri Nets model of the DE manufacturing system is shown in figure 2. In this model, the black dots (Tokens) are used to indicate the state and availability of the system/sub-systems and repair facility respectively. The number of tokens at a place represents the number of sub-systems and the number of repair facilities. The various places with token represent the current state of the system and availability of repair facility whereas various transitions are responsible for the movement of token from one place to another. The direction of the arc represents direction of movement. In this model, two types of transitions are used i.e., timed transition and immediate transition. The timed transitions are associated with the failure and repair rates of the sub-systems and follow the exponential distribution whereas immediate transitions have their own guard function [19]. The places and transitions for various stations have the following meaning:

![Petri Nets model of DE manufacturing system](image)

**Figure 2.** Petri Nets model of DE manufacturing system

3.2. Places:
The following places have been used in the Petri nets model.

- \( P_{Sup} \) represents the system is in working state.
- \( P_{Sfull} \) represents the system is in full capacity working state.
- \( P_{Sred} \) represents the system is in reduced state.
- \( P_{Sdn} \) represents the system is in failed state.
- \( P_{Aup}, P_{Bup}, P_{Cup}, P_{Dup} \) and \( P_{Eup} \) represent the working states of sub-systems i.e. CNC Gas Cutting Machine (A), Dished Ends Fabricating Machine (B), C.S. Saw Welding Machine (C) and Chiming Process (D) respectively.
3.4. Guard Functions:
The guard functions of various immediate transitions associated with the Petri Nets model of the DE manufacturing system are as follows:

- $P_{Adn}$, $P_{Bdn}$, $P_{Cdn}$, $P_{Ddn}$ and $P_{Edn}$ represent the failed states of sub-systems i.e. CNC Gas Cutting Machine (A), Dished Ends Fabricating Machine (B), C.S. Saw Welding Machine (C) and Chiming Process (D) respectively.
- $P_{Arep}$, $P_{Brep}$, $P_{Crep}$, $P_{Drep}$ and $P_{Erep}$ represent the sub-systems i.e. CNC Gas Cutting Machine (A), Dished Ends Fabricating Machine (B), C.S. Saw Welding Machine (C) and Chiming Process (D) respectively are under repair.
- $P_{rep}$ represents the repair facility.

3.3. Transitions:
The following transitions have been used in the Petri nets model.

- $T_{Adfail}$, $T_{Bfail}$, $T_{Cfail}$, $T_{Dfail}$ and $T_{Efail}$ are the timed transitions associated with the failure rates ($\lambda _1=0.0047$, $\lambda _2=0.003$, $\lambda _3=0.0067$, $\lambda _4=0.0035$ and $\lambda _5=0.0045$) of CNC Gas Cutting Machine (A), Dished Ends Fabricating Machine (B), C.S. Saw Welding Machine (C) and Chiming Process (D) respectively.
- $T_{Arep}$, $T_{Brep}$, $T_{Crep}$, $T_{Drep}$ and $T_{Erep}$ are the timed transitions associated with the repair rates ($\mu _1=0.055$, $\mu _2=0.041$, $\mu _3=0.079$, $\mu _4=0.45$, and $\mu _5=0.35$) of CNC Gas Cutting Machine (A), Dished Ends Fabricating Machine (B), C.S. Saw Welding Machine (C) and Chiming Process (D) respectively.
- $T_{Adirec}$, $T_{Bdirec}$, $T_{Cdirec}$, $T_{Ddirec}$ and $T_{Edirec}$ are the immediate transitions activated without delay if its guard function is satisfied and move the token from $P_{Adn}$, $P_{Bdn}$, $P_{Cdn}$, $P_{Ddn}$ and $P_{Edn}$ to $P_{Arep}$, $P_{Brep}$, $P_{Crep}$, $P_{Drep}$ and $P_{Erep}$ respectively.
- $T_{Srep}$, $T_{Sfull}$, $T_{Sdn}$, and $T_{Srep}$ are also the immediate transitions activated without delay if its guard function is satisfied and move the token from $P_{Sfull}$, $P_{Srep}$ and $P_{Sdn}$ to $P_{Srep}$, $P_{Sfull}$, $P_{Sdn}$ and $P_{Srep}$ respectively.
4. Computational Results

4.1. Performance analysis of the System:

The system performance has been analysed by varying the input parameters of DE system as shown in table 1 [10]. Under this analysis the input parameters have been varied one by one in a given range by fixing other parameters at the same time. The effect of varying the different parameters on system availability is shown in figure 3.

Table 1. Ranges of failure and repair rate parameters for DE manufacturing system

| Sub-System | Ranges of failure rate parameters | Ranges of repair rate parameters |
|------------|-----------------------------------|---------------------------------|
| A          | 0.0047-0.0107                     | 0.055 - 0.115                   |
| B          | 0.003 - 0.009                     | 0.041 - 0.101                   |
| C          | 0.0067 - 0.0157                   | 0.079 - 0.169                   |
| D          | 0.0035 - 0.0095                   | 0.45 - 1.05                     |
| E          | 0.0045 - 0.0105                   | 0.35 - 0.95                     |
| C'         | 0.0066 - 0.0156                   | 0.067 - 0.157                   |

The behavior of the system is obtained in terms of effect on the system availability with the alteration in parameters of different sub-systems. At first, the above Petri Nets model is modelled in the Petri Module of GRIF2018.15-x32 Simulation Package with the use of the above places, transitions and guard functions. This module uses the MOCA-Computation engine based on the Monte-Carlo simulation. In this analysis, the Moeca-computation time is taken as 10000 hours at the confidence range of 90% [5]. The maintenance data for the various sub-systems is gathered from the industry. This data is further translated into the parameterized for the sub-systems A, B, C, D and E respectively. The system availability is found to be 81.3% substituting the above failure and repair rate parameters in the timed transitions of each sub-system. Further, the system behavior pattern is studied by varying the various parameters of different sub-systems one by one within a constrained range (Figure 3), keeping the other sub-systems with constant parameters.

Table 2 shows the performance assessment of the system in terms of percentage decrement and increment in steady-state availability of DE manufacturing system [9]. It can be observed that the system availability is highly influenced by sub-system (B) and least influenced by sub-system (D) as compared to other sub-systems.

Table 2. Performance Assessment of DE manufacturing system

| Sub-System | Ranges of failure rates | Decrease in availability | Ranges of repair rates | Increase in availability | Repair priority |
|------------|-------------------------|--------------------------|------------------------|--------------------------|-----------------|
| A          | 0.0047-0.0107           | 8.74%                    | 0.055 - 0.115          | 3.76%                    | II              |
| B          | 0.003 - 0.009           | 10.26%                   | 0.041 - 0.101          | 2.98%                    | I               |
| C          | 0.0067 - 0.0157         | 4.3%                     | 0.079 - 0.169          | 1.7%                     | III             |
| D          | 0.0035 - 0.0095         | 2.46%                    | 0.45 - 1.05            | 0.84%                    | IV              |
| E          | 0.0045 - 0.0105         | 2.96%                    | 0.35 - 0.95            | 0.7%                     | V               |
Figure 3. Effect of failure and repair rate parameters of various sub-systems on the availability of DE manufacturing system

In the Petri Nets simulation model, the system availability can be analyzed against the number of repair facilities. Figure 4 shows the effect of repair facilities on system availability. The system availability is increased by 1.92% and 2.86% when the repair facilities increased from one repairman to two and three number of repair facilities respectively. Further increment in repair facilities doesn’t increase the system availability. So, it may be suggested to the maintenance personnel for increasing the repair facilities with acceptable maintenance cost.
8

Figure 4. Effect of the number of repair facilities on the availability of DE manufacturing system

5. Conclusions
The present paper shows the effectiveness of the proposed simulation method for performance analysis of complex manufacturing system. The behavioral pattern of sub-systems depicts the actual system performance in actual running conditions. The analysis has been carried out using the failure and repair rate for various sub-systems in the parameterized form. In this analysis, we can identify the sub-systems which highly affects the system performance. The sub-system B is the most critical component of the system. The findings of this study can be utilized by the maintenance personnel to make a separate maintenance policy for different sub-systems. The system performance can be improved by increasing the repair facilities within acceptable production costs.

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