Availability Analysis of Shoe Manufacturing Unit Using Petri Nets

Ankur Bahl, Satnam Singh, and Jaiinderpreet Singh

Abstract Today industries are under immense pressure to achieve production targets and high payback ratios for survival. This can only be accomplished by assuring the highest levels of system availability. Availability analysis is helpful to accomplish minimum failures objective or to enhance the mean time between failures to meet the production targets. The paper proposes Petri net-based modelling of a shoe manufacturing unit to compute the availability of various machines of the unit. The industrial system consists of four machines/subsystems namely sewing machine, skiving machine, moulding machine, and toe puffing machine. The dynamic nature of the system is studied through the MC simulation. The effect of failure and repair times on system availability have been analysed and discussed. The results can be presented to the maintenance personnel which; in turn; will help them to study the dynamic behavior of the plant and to decide maintenance priorities.

Keywords Petri nets · Availability · Simulation · Maintenance

1 Introduction

In the present era of modern technology, it is required to build highly complex systems to achieve production targets. To achieve production targets, it is desired by the plant managers that these systems should not fail. But during the operation of the plant, the failure of subsystems may occur due to many reasons such as wear and tear of the equipment or some faults related to sensing devices. Also, faulty operating procedures adopted by equipment operators may sometimes lead to unavoidable failures. Failure is an unavoidable phenomenon. Hence it is desired to increase the system availability. Availability of the system can be enhanced either by redundancy or by increasing the reliability of the components. The increase in availability is achieved if the components are more reliable and more effective maintenance measures are being adopted. As availability is a function of both reliability and maintainability so

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they are used to assess the plant performance. In broader terms, the availability of the system is measured as the proportion of uptime to the total time the system is in service. Various tools and techniques have been discussed by various authors for the availability analysis of complex systems in the literature. Zhang et al. [1] used six sigma and Gauss–Legendre quadrature formula for carrying out the reliability analysis of a complex system. Byun et al. [2] discussed a matrix-based system reliability method to identify the intricate dependence between the various component failure for reliability analysis.

Few researchers [3] discussed the RAM analysis of tunnel boring machines using Markov chains. The effect of failure and rates of various components of the machine on the RAM analysis was analysed. Agrawal et al. [4] carried the reliability analysis of the dragline using FMEA and Bathtub curve. Pandey et al. [5] presented the reliability analysis of the butter oil processing unit using Markov chains considering the constant FRRs of the components. Garg et al. [6] used a Supplementary Variable Technique for carrying out the long-run steady-state availability analysis of the yarn plant. Khorshidi et al. [7] studied the reliability analysis of complex large systems using the FMEA technique. Murthy et al. [8] performed the reliability analysis using a Markov model of the phase measurement unit considering the transient system states. Imakhlaf et al. [9] discussed the reliability analysis of the non-coherent systems using binary decision diagrams. Choi et al. [10] proposed the fault tree model to analyse the reliability and availability of seabed storage tanks. A four-step procedure of data collection and modelling the system for the reliability assessment was proposed. Modgil et al. [11] used Markov-based approach to carry out performance modelling of a shoe manufacturing unit. Ahmed et al. [12] presented the availability analysis of gas sweetening plant. Though the fault tree, decision tree, and reliability block diagrams have been used by various researchers for the availability analysis, but it is difficult to form them for large complex systems.

Many researchers have used the Markov chains and Supplementary Variable Technique for the reliability analysis of the complex systems. These techniques are helpful in calculation of long-run availability but they are difficult to formulate. Moreover, they involve complex differential equations to calculate the availability of the system which needs more computational efforts. It is hard to produce state transition diagrams for complex systems. These traditional tools and techniques do not address problems like complex parallelism, process dependency, and resource constraints. These problems are well addressed by Petri nets; which is an effective modelling tool to represent complex systems. Petri net is a graphical tool; is used as communication visual aid and being a mathematical tool; helps to study the dynamic behaviour of the system by setting up the governing equation to the model.

Many authors have discussed the various applications of Petri nets in different fields. Bahl et al. [13] discussed the use of Petri nets in the availability analysis of a distillery plant. Sachdeva et al. [14] presented the application of stochastic Petri nets to study the behaviour of the feeding system of a paper plant. Patel and Joshi [15] carried out the analysis of manufacturing systems using Petri nets. Liu et al. [16] presented the use of DSPN for the performance analysis of a subsea low preventer unit. Kaakai et al. [17] presented the application of hybrid Petri nets in the design of new stations for the transit of passengers which help the authorities about the safety and security parameters. Khan et al. [18] discussed the applications of Petri nets in deciding the control strategies to reduce the railway. Fecarotti et al. [19] carried out the performance modelling of fuel cell systems using stochastic Petri nets.

Inspired by the great modelling work done by various researchers; an attempt has been made in this paper; to use the Petri net as a modelling tool to study the dynamic behaviour of the shoe manufacturing unit. The detailed analysis of the effect of failure and repair times of various units of the shoe manufacturing unit on the overall system availability has been performed.

2 Petri Nets

Algebraically the Petri nets are represented by 5- tuple

$$PN = \{P, T, A, W, M_0\}$$

P is the finite set of places $\{P_1, P_2, \ldots, P_n\}$.

T is the finite set of transitions $\{T_1, T_2, \ldots, T_n\}$.

A is a set of directed arcs.

W is a weight function that takes values 1, 2, 3, …

M_0 is the initial marking.

A marking M can be represented by vector M = {m1, m2, …, mi} where mi represents the number of tokens in the place Pi.

Whereas graphically the PN are represented by the circles representing the places, rectangles representing the transitions, arrows representing the arc. There are two arcs input arcs (places to transition) and output arc (transition to places). The dynamic behaviour of the system is depicted by the movement of the token from place to place. The elements of the Petri net are represented in Table 1.

3 System Description

The shoe manufacturing plant has four different machines, namely sewing machine, skiving machine, moulding machine, and toe puffing machine. The process of shoe manufacturing starts with input raw material in the form of leather and polymer sheets of various sizes and shapes are which are fed to the sewing and skiving machine. In a sewing machine, the leather sheets of different shapes and sizes are stitched together. In a skiving machine, the polymer sheets are trimmed to the desired shape and size. Both the leather and polymer sheets are then glued together manually by skilled workers and sent to the moulding machine where the heat is provided to them and pressure is applied to make a strong bond between them. After this tip of the shoe is attached to the shoe upper mould by the toe upper puffing machine. The final product

Table 1 Elements of Petri net

PLACE	Place represents the conditions of an event
TRANSITION	Transitions represent the event of a system. Its firing leads to change in the state of a system
IMMEDIATE TRANSITION	This transition is associated with zero delays
ARC	Arc represents the relation between place and transition
TOKEN	Tokens used to represent the current state of the system. Place holding token represents the working state of the system

is sent for quality check and ready for dispatch. There is one unit of each sewing and skiving machine. The failure of any of these machines leads to failure of the system and production comes to halt. There are two units of each moulding machine and toe puffing machine. The failure of any one unit of these machines reduces the plant capacity but does not brings the whole system to halt. The schematic diagram of the system is shown in Fig. 1.

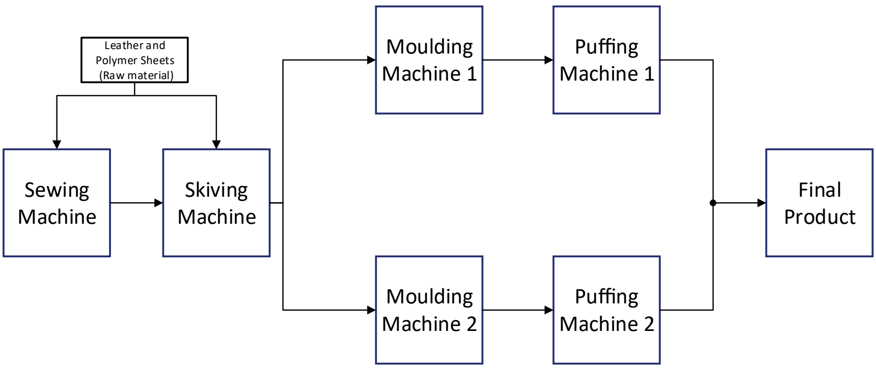


Fig. 1 Schematic flow diagram of a shoe manufacturing plant

3.1 Assumptions for the Modelling

1. A crew of Six repairmen is available.
2. The repair of fault is addressed without delay.
3. Concurrent failure can happen in the system.
4. Failure and repair rates are independent of each other
5. The priority policy of FCFS is considered.
6. After repair, the system state is restored to the original.

4 Petri Net-Based System Modelling

To carry out the performance analysis of a shoe manufacturing plant, the interactions among various units of the system are considered. Petri nets are applied to model the interaction between them. If the failures occur simultaneously in the various units of the systems, then repair is done on the first come first serve basis and it also depends upon several repair facilities available at the time of failure. Figure 2 shows the Petri net model representing the above system. Table 2 represents the description of the Petri net model.

4.1 Representation of Dynamic Behaviour of the System

Figure 2 shows the butter oil processing system in the upstate. The presence of tokens in places 1, 4, 7, 11, 13, and 16 make the transitions Tr1, Tr4, Tr7, Tr10, Tr13, Tr16 enabled. As soon as the stochastic delay of transition Tr1 is achieved the transition fires lead to movement of a token from place 1 to place 2. Place 2 representing the waiting for the repair condition of the unit. The token in place 2 enables the immediate transition which moves the token to place 3 which represents the unit is under repair. The transition Tr2 gets enabled with the presence of token in place 3. As the stochastic delay becomes equal to repair rate the transition Tr2 fires which put the token from place 3 to place 1. Similarly, all the units will behave, and depending upon the different guard conditions the tokens from Place System_up_State move to System_down_state. When anyone unit of a clarifier or the filling unit fails the system will run at reduced capacity which is represented by a token in system_reduced_capacity place.

4.2 Performance Analysis of the System

The performance analysis of the shoe manufacturing plant is done using the MC simulation of the PN model using the GRIF2020 Petri net module. The simulation evaluates the plant availability. It runs for 10,000 replications for 1 year at a 95% confidence level. The system performance analysis is evaluated by considering the effect of variation of Failure and repair rates of the various units the plant availability. Also, the system is evaluated in terms of the plant working at reduced capacity. The data-related failure and repair times of all units of the system are shown in Table 3.

The effect of variation of failure and repair times on the availability of the plant is shown in Table 4. As shown in a table with an increase in failure times and a decrease in repair times of various machines the system availability increases by 5%, 9.5%, 2.3%, and 2% for a sewing machine, skiving machine, moulding machine, and toe

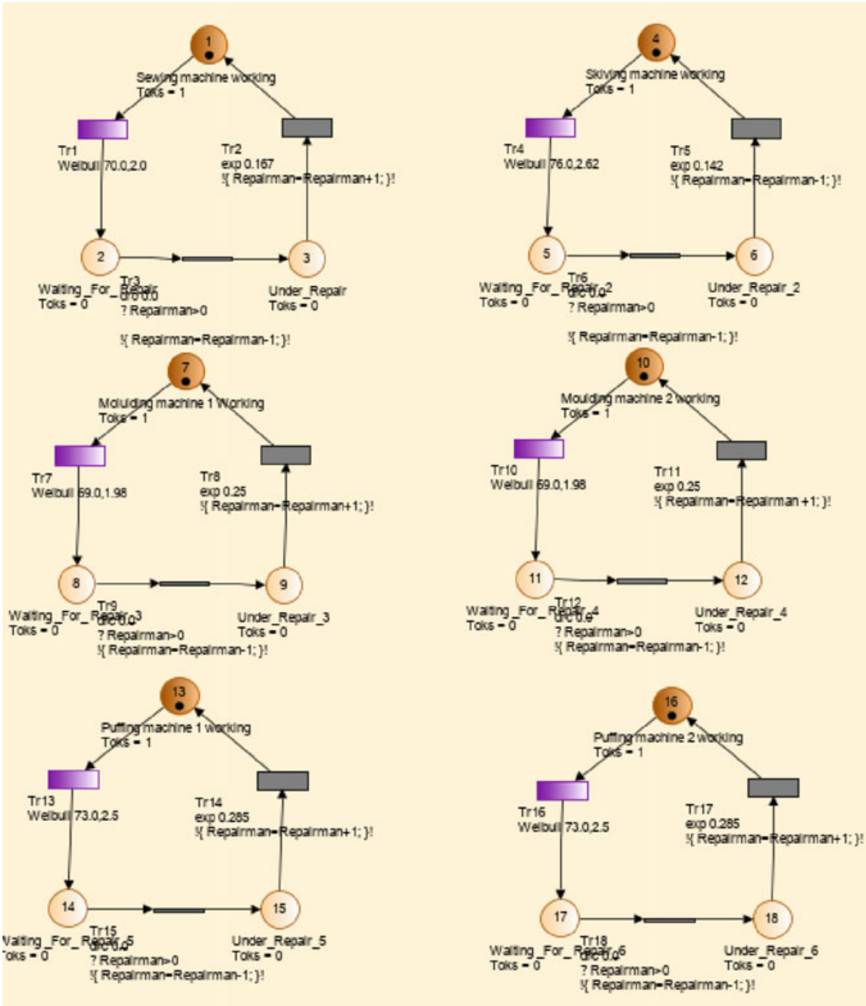
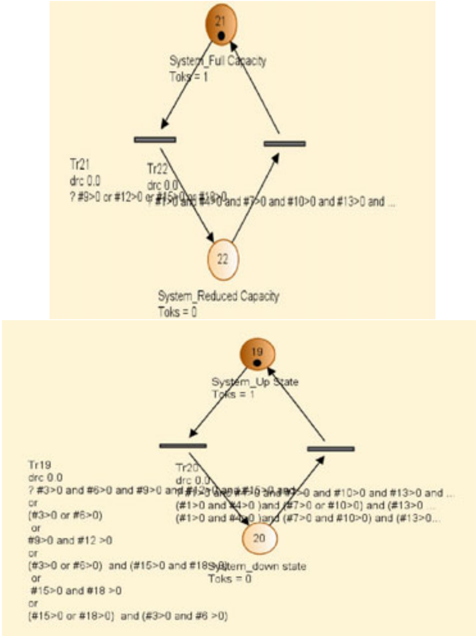


Fig. 2 Petri net model of shoe manufacturing plant

Fig. 2 (continued)



puffing machine respectively. This shows that the impact of the failure of the skiving machine on the system is highest as compared to other machines. Therefore, plant engineers need to pay more attention to it.

5 Conclusion

The Petri nets have been observed as an influential tool to study and analyse the dynamic behaviour of complex systems. In this paper, the Petri net-based model for the shoe manufacturing unit has been developed to find the system availability. The PN modelling helps the decision-makers to understand the interaction about the various units of the system. The Weibull and exponential distributions are considered for failure and repair times of all the four machines. Upon critical examination of the analysis of the failure and repair times, it is revealed that the skiving machine has a significant impact on system availability. However, other machines such as moulding and toe puffing machines have a lesser impact on system availability. The performance analysis helps the plant managers to pay attention to the critical subunits of systems. Also, it helps them make decisions related to the maintenance priority and spare part inventory management for achieving the long-term availability of the plant. Apart from these recompenses, the performance analysis can also be used by plant managers for exploring cost–benefit analysis and replacement-related decisions.

Table 2 Description of the places and transitions

Places	*Description*
Sewing machine working, Skiving machine working, moulding machine1 working, moulding machine2 working, puffing machine 1 working and puffing machine 2 working	Places represent the working states of various machines
Waiting_For_Repair_1 andWaiting_For_Repair_2	Places represent the sewing and the skiving machine has failed and is waiting for repair
Waiting_For_Repair_3 and Waiting_For_Repair_4	Places represent the moulding machine has failed and is waiting for repair
Waiting_For_Repair_5 and Waiting_For_Repair_6	Places represent the puffing machine has failed and is waiting for repair
Under_Repair_1 and Under_Repair_2	Places represent the sewing and skiving machine has gone under repair
Under_Repair_3 and Under_Repair_4	Places represent the moulding machine has gone under repair
Under_Repair_5 and Under_Repair_6	Places represent the puffing machine has gone under repair
System_Full_ Capacity	Place represents that all the units are working
System_Reduced_Capacity	Place represents that some of the units are not in working and the system is running with reduced capacity
System_Up_State	Place represent that the system is in a working state
System_Down_State	Place represents that the system is in the downstate or the system is not available
Transition	*Description*
Tr1, Tr4, Tr7, Tr10, Tr13, Tr16	Represents the timed transitions associated with stochastic delay all the units and firing of these transitions lead to failure of the corresponding unit. The scholastic delays are related to the failure rates of the units
Tr2, Tr5, Tr8, Tr11, Tr14, Tr17	Represents the timed transitions associated with stochastic delay all the units and firing of these transitions lead to repair of the corresponding unit. The scholastic delays are related to repair rates of the units

Table 3 Failure and repair data for various units of shoe manufacturing plant

Machines	Failure data (Weibull distribution)			Repair data (Exponential distribution)
	Scale factor (θ)	Shape factor(β)	MTBF (h)	MTTR (h)
Sewing machine	70	2.0	63	6
Skiving machine	76	2.62	74	7
Moulding machine	69	1.98	65	4
Puffing machine	73	2.5	79	3.5

Table 4 Effect of failure and repair times on the system availability

Units	Variation of failure times (repair times)	System availability
Sewing machine	55–90	0.90–0.86
	(7–4)	(0.7–0.84)
Skiving machine	60–90	0.92–0.84
	(9–6)	(0.81–0.89)
Moulding machine	45–80	0.88–0.86
	(5–3)	(0.86–0.88)
Puffing machine	50–85	0.87–0.85
	(4–1)	(0.87–0.89)

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