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Performance Modeling and Analysis of Refrigeration System of a Milk Processing Plant using Petri Nets

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Abstract

This paper described the performance modeling of the refrigeration system of a milk processing plant using Petri nets and obtained a quantitative analysis in terms of availability under varying operating parameters. For the modeling and simulation of the system, a Petri module of GRIF software was used. In the current study, an effort was made to use reliability, availability, and maintainability (RAM) tools, which can be quantitative or qualitative methods and software that reduce the uncertainties involved in random failures and consequent shutdowns of the plant. Finally, an attempt was made to provide a specific direction for determining maintenance strategies to meet operational objectives economically considering spare parts and repair facilities.

Keywords: availability; Petri nets; performance modeling; RAM tools

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1. Introduction

In the present-day business scenarios, the global market must follow the footprints of rapid changes in technology. As a result, availability, cost, safety, and sustainable quality have become the four pillars of process industries. Highly productive and efficient systems have become an essential requirement for the survival of businesses. In view of this, practitioners have implemented RAM tools to meet the above requirements and improve revenues. This paper mainly deals with industries that have systems comprised of many subsystems, whose individual performances affect the total availability of the plant. The analysis of performance measures of the subsystems helps the practicing manager understand the effect of varying the failure and repair rates of a particular subsystem on the overall performance of the system. Logically, an increase in the number of repair facilities increases the financial investment. However, its non-functioning may lead to heavy costs. Tan and Kramer [1] observed that the financial loss resulting from an unexpected shutdown may range from $500-$100,000 per hour. In recent years, many authors have applied RAM tools for the modeling and performance analysis of complex systems as a part of maintenance management [2-6]. Fault tree analysis (FTA), reliability block diagrams (RBD), Markov models, and Petri nets are some important analytical RAM tools used to model failure interactions in a system. Monte Carlo simulation is used to exhibit and simulate the life cycle characteristics of the system. Markov models are also a very useful performance modeling tool used in concurrency, synchronization, and failures, but the significant drawback of the Markov method is state space explosions. The use of Petri nets eliminates the shortcomings and reduces the tedious computational efforts required in the case of Markov modeling. Apart from discussing simulation and analytical RAM tools, we also consider software tools that are generally much faster in computations.

2. Petri Nets and Their Applications

The Petri nets technique was proposed by Carl Adams Petri in his doctoral thesis in 1962 at the University of Bonn, West Germany and has now emerged as a dominant performance modeling tool for systems that exhibit concurrency, randomness, and synchronization. Petri nets are bipartite directed graphs whose nodes are divided into two disjoint sets called places

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(represented by circles) and transitions (represented by boxes or bars). A typical illustration of the Petri net model is shown in Figure 1. Tokens are stored in places and move from one place to another along arcs through transitions. Marking is an assignment of tokens to places, and these may change during the execution of a Petri net.

In the last three decades, several extensions to the classical Petri nets as well as their applications focused on the modeling and analysis of complex systems have been made. If the transition firing times are stochastically timed, the Petri net is called a stochastic Petri net (SPN). Marsan et al. [7] described generalized stochastic Petri nets (GSPN) belonging to two different classes, namely immediate and timed transitions. Immediate transitions (drawn as bars) are assumed to fire in zero time once enabled. Dugan et al. [8] defined the extended stochastic Petri net (ESPN), which reduces the restrictions of the exponential assumption of times to occurrence in the application of SPNs and GSPNs, even though in practice there is a wide range of circumstances where it is necessary to model a phenomenon whose time to occurrence is not exponentially distributed. By applying ESPN, it is possible to use general firing time distributions. Marsan et al. [9] presented deterministic stochastic Petri nets (DSPNs), which allow for the definition of immediate, exponentially distributed, and deterministically timed transitions. A recent extension of Petri nets is colored Petri nets (CPNs), which preserve useful properties of Petri nets and at the same time extend initial formalism to allow for the distinction between tokens and have a data value attached to them.

Narahari and Vishwanadham [10] presented a Petri nets approach for modeling and analyzing flexible manufacturing systems (FMSs). Dekker and Groenendijk [11] discussed various availability assessment methods and their typical applications in industrial practices. Kumar et al. [12-15] used Markov modeling for analyzing and evaluating the performance of paper, fertilizer, and sugar plants. Desrochers and Al-Jar [16] described applications of Petri nets in manufacturing systems. Feldmann and Colombo [17] applied a high-level Petri nets technique named colored Petri nets for the modeling and analysis of flexible production systems. Singh and Garg [18] performed the availability analysis of plywood manufacturing systems under the assumption of exponential failure and repair rates. Sachdeva et al. [3, 19] performed a detailed analysis of a paper mill using Petri nets to evaluate the performance regarding the availability plant. Tavana [20] applied Petri nets for dynamic process modeling of an emergency management system at a nuclear power plant. Thangamani [21] dealt with the availability analysis of a lube oil system in a combined cycle power plant using a generalized stochastic Petri net, and the Monte Carlo simulation approach was used for further analysis. Selvakumar and Natarajan [14] performed a reliability analysis of centrifugal pumps using the FMECA and FEM techniques. Negi et al. [21] applied the belief universal generating function for the reliability evaluation of non-repairable *k*-out-of-*n* systems. Zheng et al. [22] performed a modeling and availability analysis of navigation satellites based on colored Petri nets (CPN), considering both failures and performance status. More recently, Angel [2] presented an analytical model using stochastic Petri nets to develop an intelligent emergency evacuation system in buildings for accidental fire occurrences.

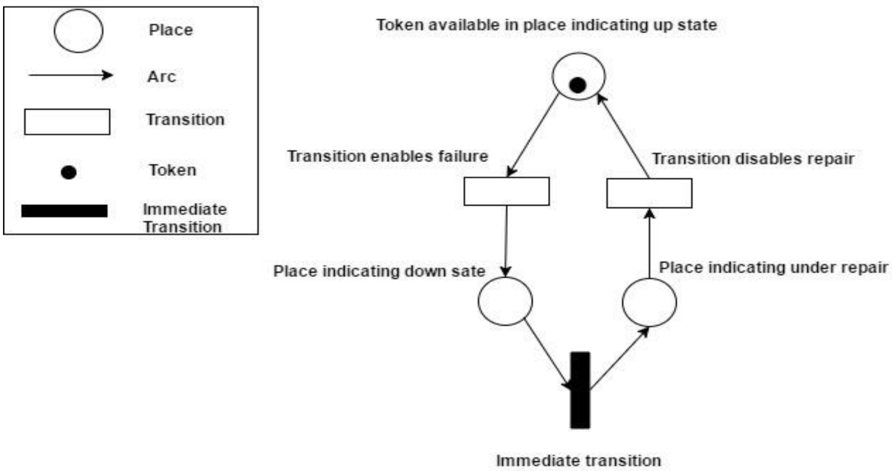


Figure 1. An illustrative Petri net model

3. System Description

A milk processing plant has many interconnected functional systems, such as milk pasteurization, milk filling, refrigeration, inspection and quality control, and milk food making. One of the most important systems of the plant is the refrigeration system, which is the subject of discussion in this paper. Refrigeration is an essential requirement in a dairy plant for the preservation of milk and its products (stored below 5^{o}C), the preservation of its nutritional value, and the prevention of the growth of microbes. Figure 2 shows a schematic diagram of a refrigeration system of a milk plant where the refrigeration effect, in the form of chilled water or low pressure/temperature vapour, is generated. Here, high pressure and low-temperature liquid refrigerant (usually ammonia) are expanded to obtain low-temperature chilled mediums.

Furthermore, these chilled mediums are utilized for chilling milk in heat exchangers, pasteurization, cold storage, and deep fridges of all types. The refrigerant, after absorbing heat, returns to the compressors, where its heat value is enhanced to discard into the atmosphere through the condenser. The decisions of the selection of the system, its subsystems, and performance modeling technique are based on practical experience, analytical considerations, and literature search. Some of the major units that can be considered as a subsystem are:

Heat Exchanger (1): It extracts heat from the warm milk and transfers it to chilled water through the convection process. Its failure leads to the failure of the entire refrigeration system.

Compressor (2): The purpose of the compressor is to draw low-pressure refrigerant vapour from the evaporator and compress it so that the vapour can be condensed back into a liquid by cooling with air or water. It is one of the main functional parts of the refrigeration system and is provided in redundancy. The failure of one compressor reduces the processing capacity of the system.

Centrifugal Pumps (3): There are three pumps, namely A, B, and C, which are provided in series for performing intended functions. They are used to circulate and deliver water/brine or milk. They are made up of cast steel and designed to work at full load. They are comprised of pump seals, shaft, bearings, casing, and a fluid driver. The pumps are also provided with standby units. The failure of any of the pumps results in the system working in reduced capacity mode.

Accumulator (4): The purpose of the accumulator is to save power consumption by accumulating a sufficient amount of cold water/brine that is needed to cool milk. It has two parallel chambers walls isolated from all sides that divide it into a warm water side and a cold water side.

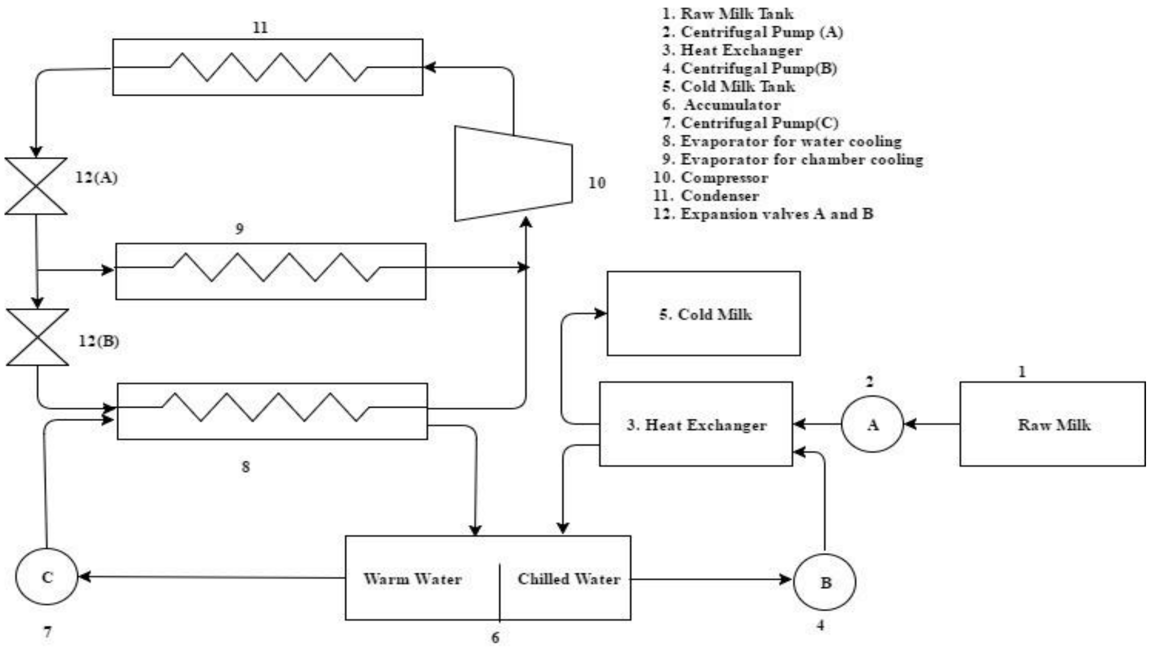


Figure 2. Flow diagram of the refrigeration system

4. Petri Nets Performance Model of the System

Stochastic Petri nets have been used to model the interactions among various subsystems. The failures and repair data were obtained from the maintenance logbook of the plant in consultation with supervisors. In the present state, only a single repair facility is available; as a result, all the failures cannot be handled at a time, and failed subsystems must wait and queue for the repair. Therefore, a place for a number of repair facilities is provided in the model to study the effect of availability of repair facilities on system performance. Furthermore, the existing model was also programmed with the study of the effect of system performance in reduced capacity mode concurrently. Figure 3 shows the Petri net model of the refrigeration system of the Vita Milk Processing Plant in Ambala Haryana, India.

The places and transitions used in this model have the following meanings:

Places:

- P_{Sys_up} represents the refrigeration system in upstate.
- $P_{Sysfull\_cap}$ represents the refrigeration system at full capacity.
- P_{Sysred_cap} represents the refrigeration system at a reduced capacity.
- P_{Sys_dn} represents the refrigeration system in downstate.
- P_{Rep_avail} represents the availability of the repair facility.
- P_{Hex_up}, P_{Comp_up}, P_{Pump_up}, and P_{Accum_up} represent the working states of the heat exchanger (1), compressor (2), centrifugal pumps (3), and accumulator (4), respectively.
- P_{Hex_dn}, P_{Comp_dn}, P_{Pump_dn}, and P_{Accum_dn} represent the down states of the heat exchanger (1), compressor (2), centrifugal pumps (3), and accumulator (4), respectively.
- P_{Hex_rep}, P_{Comp_rep}, P_{Pump_rep}, and P_{Accum_rep} represent the repair states of the heat exchanger (1), compressor (2), centrifugal pumps (3), and accumulator (4), respectively.

Transitions:

- T_{Hex_fail}, T_{Comp_fail}, T_{pump_fail}, and T_{Accum_fail} are timed transitions and associated with failure rates (λ_1, λ_2, λ_3, and λ_4) of the heat exchanger (1), compressor (2), centrifugal pumps (3), and accumulator (4), respectively.
- T_{Hex_rep}, T_{Comp_rep}, T_{pump_rep}, and T_{Accum_rep} are timed transitions and associated with repair rates (μ_1, μ_2, μ_3, and μ_4) of the heat exchanger (1), compressor (2), centrifugal pumps (3), and accumulator (4), respectively.
- T_{Hexrep_avail}, $T_{Comprep\_avail}$, $T_{pumprep\_avail}$, and $T_{Accumrep\_avail}$ are immediate transitions and associated with the heat exchanger (1), compressor (2), centrifugal pumps (3), and accumulator (4), respectively.
- T_{Sys_red}, T_{Sys_full}, T_{Sys_fail}, and T_{Sys_up} are immediate transitions fired with no delay as soon as these are enabled, and they are associated with the system working at either full capacity or reduced capacity.

Guard functions:

The guard functions associated with the various transitions shown in Figure 3 are described below:

- [g1]=((#8>0or#9>0)or(#8>0and#9>0)or(#10>0or#11>0)or(#10>0and#11>0))and((#2>0and#2<3)or(#3>0and#3<2)) disables the transition t_{sys_red}.
- [g2]=(#1>0and#2>2and#3>1and#4>0) enables the transition T_{sys_full}.
- [g3]=((#6>0or#7>0)or(#8>1and#9>0)or(#10>0and#11>0)or(#13>0or#12>0)) disables the transition T_{Sys_fail}.
- [g4]= (#1and#2and#3and#4) enables the transition T_{Sys_up}.

The following assumptions are considered for the modeling and analysis of the system:

- The exponential distribution is used to represent failure time and repair time.
- Failure and repair rates are statistically independent.
- The repaired unit is equally good as new.
- The nature and capacity of the standby units are the same as those of the active units.
- The switchover time from active to standby units and vice versa is negligible.
- There is no delay in repair, except the availability of repairmen is considered.
- The repair priority is based on first come first serve (FCFS).
- The system may work in the reduced capacity mode.

Table 1. Failure and repair data of refrigeration system

Name of subsystem	Mean failure rate (λ_i)/hr	Mean repair rate (μ_i)/hr
Heat exchanger (1)	8.425×10^{-4}	1.5×10^{-1}
Compressor (2)	4.000×10^{-4}	2×10^{-1}
Centrifugal pump (3)	4.5×10^{-2}	2×10^{-1}
Accumulator (4)	3.30×10^{-5}	4.5×10^{-2}

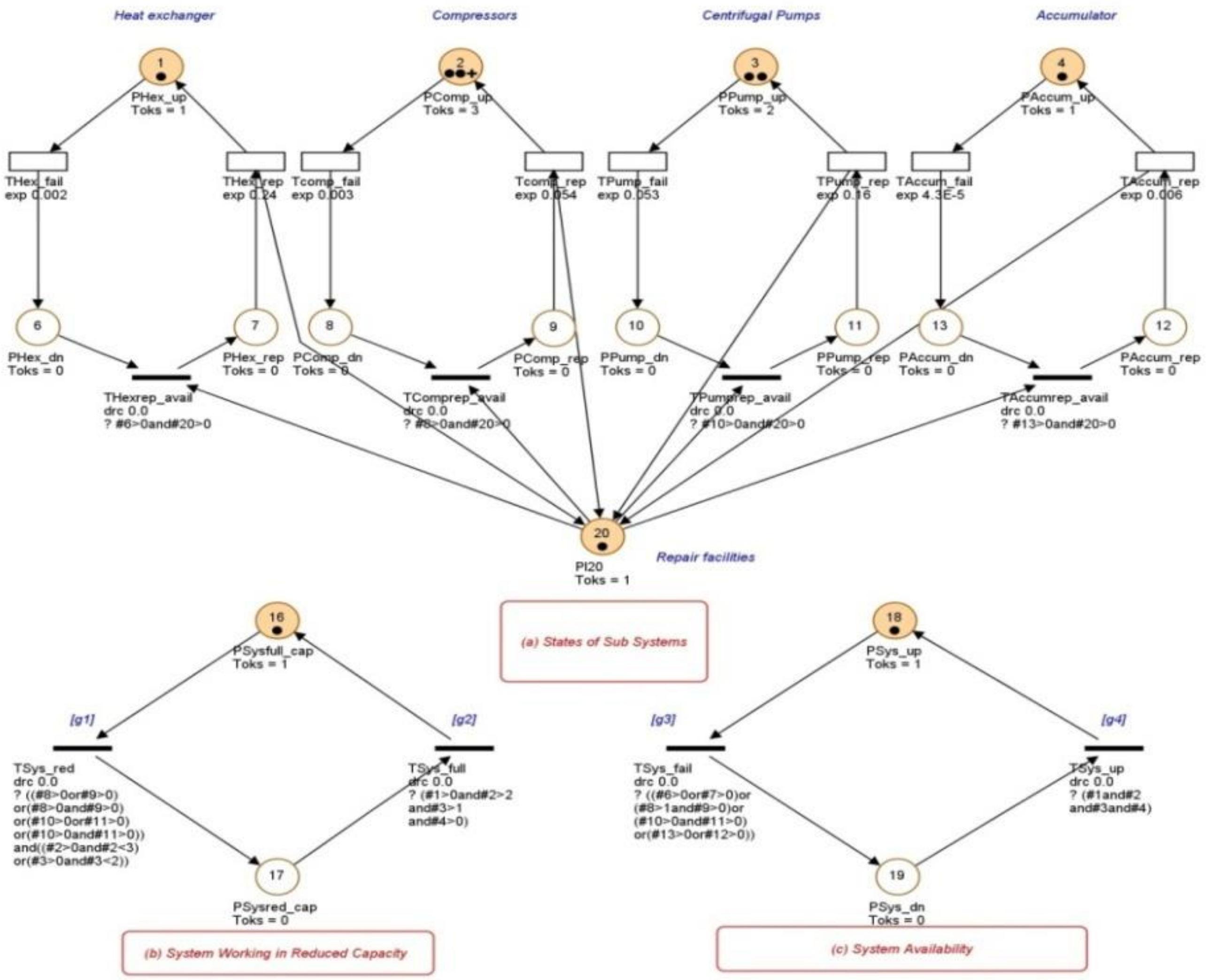


Figure 3. Petri net performance model of the refrigeration system

5. Performance Analysis

The long-run availability of the system is analyzed using the Petri net technique. The programming is performed with a licensed Petri Nets software package GRIF-predicates Petri module (2018) considering various parameters and their suitable predefined values. The MOCA R computation along with simulation is run for 10,000 hours and for many histories ranging from 10-21,000 by using the above software. The performance analysis is carried out by varying the failure and repair rates of each subsystem within a possible range while keeping the other subsystem parameters constant. The maximum availability of the system is found to be 95.53%, with a 95% confidence limit. According to this analysis, the availability matrix of the various subsystems is obtained, as presented in Tables 2 to 5. The programming considers various parameters and their suitable predefined values. The impact on availability within confined ranges of failure and repair rate parameters of various subsystems are discussed thereafter.

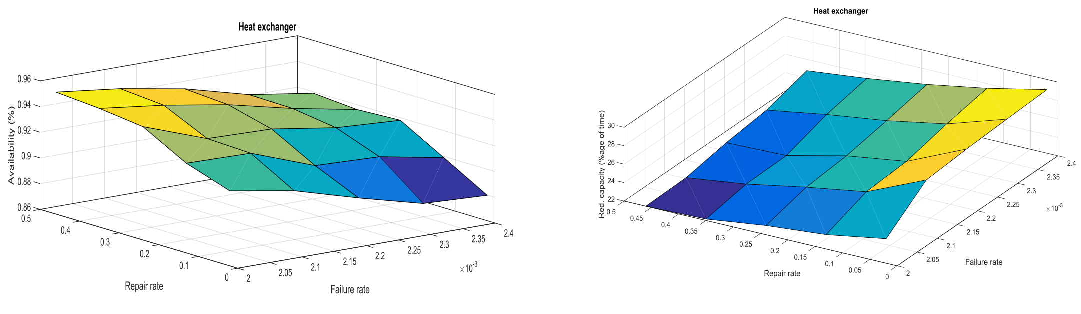
Table 2(a). Impact of failure and repair rates of heat exchanger on availability of system

λ_1 \ μ_1	0.02	0.13	0.24	0.35	0.46	Constant parameters
0.0020	0.9084	0.9298	0.9482	0.9523	0.9549	λ_2=0.0030, μ_2=0.055 λ_3=0.0550, μ_3=0.160 λ_4=0.000043, μ_4=0.006
0.0021	0.8997	0.9288	0.9301	0.9460	0.9488	
0.0022	0.8753	0.9104	0.9288	0.9376	0.9399	
0.0023	0.8522	0.9085	0.9210	0.9259	0.9266	
0.0024	0.8478	0.8990	0.9180	0.9163	0.9189	

Table 2(b). Impact of failure and repair rates of heat exchanger in reduced capacity (percentage of time) of system

λ_1 \ μ_1	0.02	0.13	0.24	0.35	0.46	Constant parameters
0.0020	24.660	23.558	23.000	22.158	22.006	λ_2=0.0030, μ_2=0.055 λ_3=0.0550, μ_3=0.160 λ_4=0.000043, μ_4=0.006
0.0021	25.356	25.227	24.175	22.967	22.115	
0.0022	26.428	25.538	24.594	23.077	22.925	
0.0023	28.683	26.623	25.423	24.546	23.479	
0.0024	28.902	27.500	26.373	25.477	24.772	

Figure 4(a) and Table 2(a) show a significant impact on the availability of the system with the variation in failure and repair rates of the heat exchanger. An increase in failure rate of the heat exchanger from 0.0020 to 0.0024 and a reduction in repair rate from 0.46 to 0.02 reduce the system availability by up to 10.71%. The same variations in failure and repair rates of the heat exchanger also have a similar impact on the system working at reduced capacity 6.896% of the time, as shown in Figure 4(b) and Table 2(b).



(a) (b)

Figure 4. Effect of failure and repair rates of heat exchanger (a) on availability (b) on reduced capacity

Figure 5(a) and Table 3(a) show that a significant impact is observed on the availability of the system with the variation in failure and repair rates of the compressor. An increase in failure rate from 0.0020 to 0.0040 and a reduction in repair rate from 0.095 to 0.015 reduce the system availability by up to 5.17%. The same variations in failure and repair rates of the compressor have a greater impact on the system working at reduced capacity 11.95% of the time, as shown in Figure 5(b) and Table 3(b).

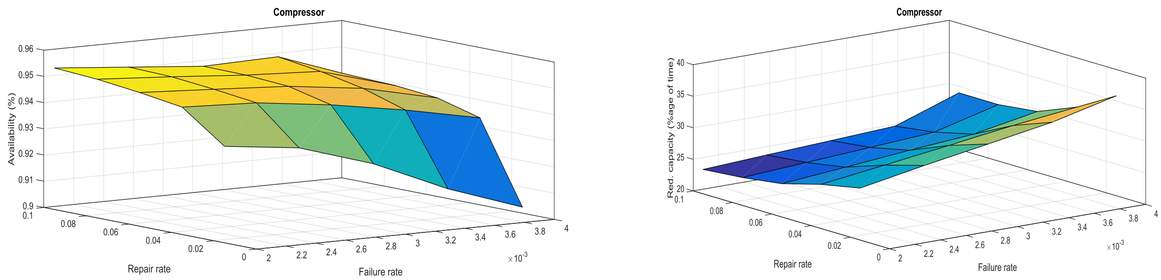
Table 3(a). Impact of variations in failure and repair rates of compressor on availability of system

λ_2 \ μ_2	0.015	0.035	0.055	0.075	0.095	Constant parameters
0.0020	0.9368	0.9486	0.9510	0.9529	0.9540	λ_1=0.0020, μ_1=0.460 λ_3=0.045, μ_3=0.200 λ_4=0.000033, μ_4=0.045
0.0025	0.9334	0.9484	0.9494	0.9510	0.9515	
0.0030	0.9245	0.9458	0.9488	0.9477	0.9490	
0.0035	0.9121	0.9460	0.9491	0.9494	0.9497	
0.0040	0.9023	0.9332	0.9376	0.9392	0.9397	

Table 3(b). Impact of variations in failure and repair rates of compressor in reduced capacity (percentage of time) of system

λ_2 \ μ_2	0.015	0.035	0.055	0.075	0.095	Constant parameters
0.0020	28.233	26.991	25.267	24.412	23.863	λ_1=0.0020, μ_1=0.460 λ_3=0.045, μ_3=0.200 λ_4=0.000033, μ_4=0.045
0.0025	30.048	28.295	26.129	25.038	24.410	
0.0030	31.707	29.644	27.048	25.667	24.918	
0.0035	33.399	31.042	27.844	26.334	25.450	
0.0040	35.813	32.206	29.680	28.937	28.969	

Figure 6(a) and Table 4(a) show that there is a high impact on the availability of the system with the variation in failure and repair rates of a centrifugal pump. An increase in failure rate of the centrifugal pump from 0.0450 to 0.0650 and a reduction in repair rate from 0.20 to 0.12 reduce the system availability by up to 12.47%. The same variations in failure and repair rates of the centrifugal pump also have a greater impact on the system working at reduced capacity 21.911% of the time, as shown in Figure 6(b) and Table 4(b).



(a) (b)

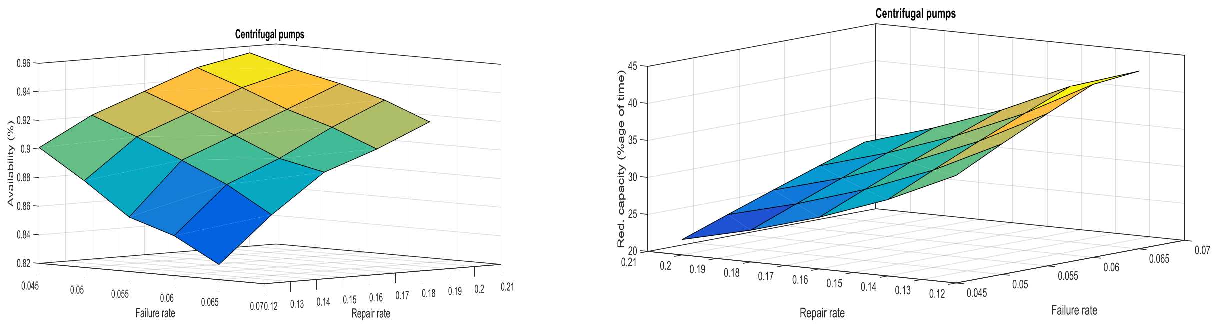
Figure 5. Effect of failure and repair rates of the compressor (a) on availability (b) on reduced capacity

Table 4(a). Impact of variations in failure and repair rates of centrifugal pump on availability of system

λ_3 \ μ_3	0.12	0.14	0.16	0.18	0.20	Constant parameters
0.0450	0.9010	0.9207	0.9344	0.9480	0.9553	λ_1=0.0020, μ_1=0.460 λ_2=0.0004, μ_2=0.200 λ_4=0.000043, μ_4=0.006
0.0500	0.8807	0.9084	0.9225	0.9368	0.9465	
0.0550	0.8581	0.8949	0.9095	0.9245	0.9395	
0.0600	0.8479	0.8808	0.8960	0.9148	0.9308	
0.0650	0.8306	0.8624	0.8892	0.9024	0.9184	

Table 4(b). Impact of variations in failure and repair rates of centrifugal pump at reduced capacity (percentage of time) of system

λ_3 \ μ_3	0.12	0.14	0.16	0.18	0.20	Constant parameters
0.0450	34.525	30.310	26.982	24.293	22.084	λ_1=0.0020, μ_1=0.460 λ_2=0.0004, μ_2=0.200 λ_4=0.000043, μ_4=0.006
0.0500	37.625	33.147	29.583	26.691	24.299	
0.0550	40.566	35.890	32.115	29.030	26.460	
0.0600	43.364	38.487	34.543	31.280	28.570	
0.0650	43.995	40.994	36.854	33.475	30.626	



(a) (b)

Figure 6. Effect of failure and repair rates of centrifugal pump (a) on availability (b) on reduced capacity

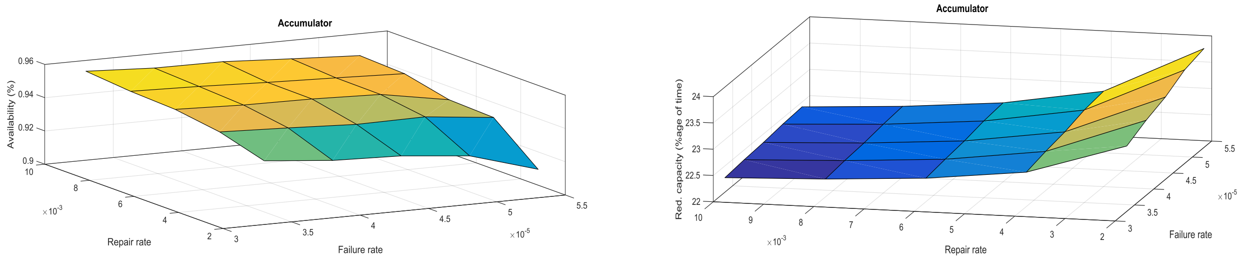
Figure 7(a) and Table 5(a) show that a low impact is observed on the availability of the system with the variation in failure and repair rates of the accumulator. An increase in failure rate from 0.000033 to 0.000053 and reduction in repair rate from 0.010 to 0.002 reduce the system availability by up to 2.4%. The same variations in failure and repair rates have the least impact on the system working at reduced capacity 1.61% of the time, as shown in Figure 7(b) and Table 5(b).

Table 5(a). Impact of variations in failure and repair rates of accumulator on availability of system

λ_4 \ μ_4	0.002	0.004	0.006	0.008	0.010	Constant parameters
0.000033	0.9383	0.9460	0.9499	0.9501	0.9535	λ_1=0.0020, μ_1=0.460 λ_2=0.0004, μ_2=0.200 λ_3=0.0550, μ_3=0.160
0.000038	0.9345	0.9444	0.9485	0.9500	0.9514	
0.000043	0.9332	0.9425	0.9481	0.9484	0.9512	
0.000048	0.9271	0.9430	0.9468	0.9471	0.9489	
0.000053	0.9292	0.9386	0.9396	0.9456	0.9468	

Table 5(b). Impact of variations in failure and repair rates of accumulator at reduced capacity (percentage of time) of system

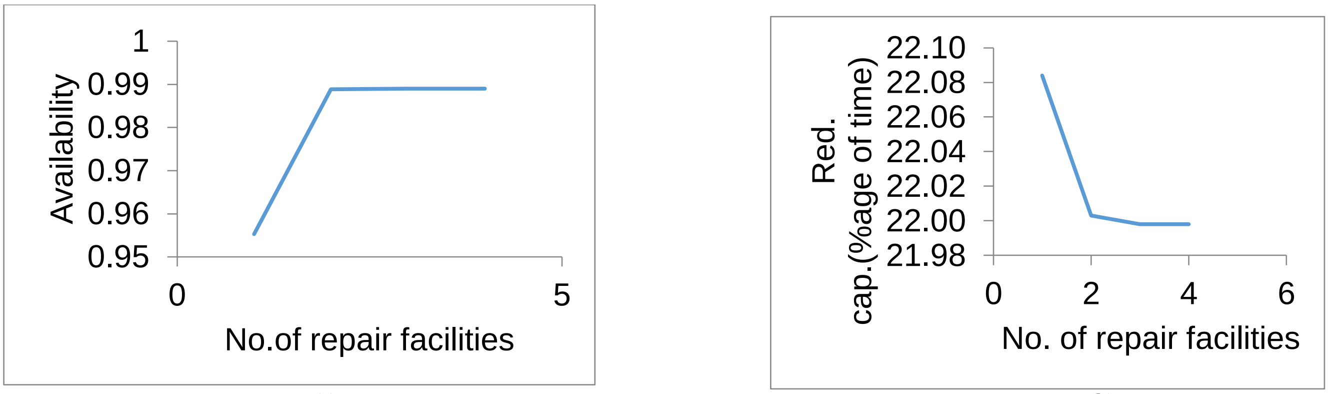
λ_4 \ μ_4	0.002	0.004	0.006	0.008	0.010	Constant parameters
0.000033	23.243	22.654	22.448	22.341	22.276	λ_1=0.0020, μ_1=0.460 λ_2=0.0004, μ_2=0.200 λ_3=0.0550, μ_3=0.160
0.000038	23.428	22.745	22.505	22.388	22.314	
0.000043	23.567	22.814	22.550	22.419	22.339	
0.000048	23.781	22.924	22.625	22.472	22.383	
0.000053	23.882	22.978	22.667	22.509	22.408	



(a) (b)

Figure 7. Effect of failure and repair rates of accumulator (a) on availability (b) on reduced capacity

Figures 8 and Table 6 show the impact of an increase in repair facilities on the system's performance. The availability stabilized, i.e., no further enhancement was observed when there were three repairmen in the system, which indicates how adequate repair facilities can be provided with the least cost.



(a) (b)

Figure 8. Effect of number of repair facilities (a) on availability (b) on reduced capacity

Table 6. Impact of repair facilities on availability and system working at reduced capacity (percentage of time)

No. of repair facilities	Availability	System working at reduced capacity (percentage of time)
1	0.9553	22.084
2	0.9889	22.003
3	0.9890	21.998
4	0.9890	21.998

6. Conclusions

The detailed research studies carried out here highlighted that the centrifugal pumps are the most critical subsystems that need utmost attention when selecting maintenance strategies. In centrifugal pumps, failure mainly occurs due to the failure of pump seals and bearings. The analysis of the effect of repair facilities on the system's availability will help in deciding the maintenance resource allocation. It has also been perceived that the use of Petri nets eliminates the shortcomings and reduces the tedious computational efforts required in the case of Markov modeling. The selection of an appropriate RAM tool has a direct impact on the operational and maintenance costs.

The findings of this paper may contribute some guidelines for practitioners through an understanding of the system's behaviour so that they can opt for suitable maintenance inspection plans and ensure the maintenance priorities. The obtained outcomes demonstrate the usefulness of the RAM tools that can also be used by process engineers to learn how to apply these techniques concurrently in all phases of the plant life, so as to reduce the operation and maintenance costs, enhance the production volume, and achieve the quality requirements of food safety standards.

References

1. J. S. Tan and M. A. Kramer, "A General Framework for Preventive Maintenance Optimization in Chemical Process Operations," *Computers and Chemical Engineering*, Vol. 21, pp.1451-1469, 1997
2. A. S. Angel and R. Jayaparvathy, "Performance Modeling of an Intelligent Emergency Evacuation System in Buildings on Accidental Fire Occurrence," *Safety Science*, Vol. 12, pp. 196-205, 2019
3. A. Sachdeva, D. Kumar, and P. Kumar, "Reliability Analysis of the Pulping System using Petri Nets," *International Journal of Quality and Reliability Management*, Vol. 25, No. 8, pp. 860-877, 2008
4. C. Haitang, L. Peiwen, and S. Xueke, "Reliability Analysis of the CAM on the Drive Gear Plate of D Type Knotter," *International Journal of Performability Engineering*, Vol. 15, No. 1, pp. 23-34, 2019
5. J. Selvakumar and K. Natarajan, "Reliability Analysis of Centrifugal Pump Through FMECA and FEM," *International Journal of Performability Engineering*, Vol. 13, No. 2, pp. 119-128, 2017
6. S. Negi, J. Namita, and S. B. Singh, "Reliability Assessment of Non-Repairable k-out-of-n System using Belief Universal Generating Function," *International Journal of Performability Engineering*, Vol. 14, No. 5, pp. 831-840, 2018
7. M. A. Marsan, G. Conte, and G. Balbo, "A Class of Generalized Stochastic Petri Nets for the Performance Evaluation of Multiprocessor Systems," *ACM Transactions on Computer Systems*, Vol. 2, No. 2, pp. 93-122, 1984
8. B. J. Dugan, S. K. Trivedi, R. Geist, and V. Nicola, "Extended Stochastic Petri Nets: Application and Analysis," Extended Stochastic Petri Nets: Applications and Analysis, pp. 507-519, 1984
9. M .A. Marsan and G. Chiola, "On Petri Net with Deterministic and Exponentially Distributed Firing Time G. Rozenberg (ed.)," Advances in Petri nets Lecture Notes in Computer Science, pp. 132-145, 1987
10. Y. Narahari and N. Vishwanadham, "A Petri Net Approach to the Modeling and Analysis of Flexible Manufacturing Systems," *Annal of Operations Research*, Vol. 3, No. 8, pp. 449-472, 1985
11. R. Dekker and W. Groenendijk, "Availability Assessment Methods and Their Application in Practice," *Microelectronics Reliability*, Vol. 35, No. 9-10, pp. 1257-1274, 1995
12. D. Kumar, I. P. Singh, and J. Singh, "Reliability Analysis of the Feeding System in the Paper Industry," *Microelectronics Reliability*, Vol. 28, No. 2, pp. 213-215, 1988
13. D. Kumar, J. Singh, and P. C. Pandey, "Maintenance Planning for the Pumping System in the Paper Industry," *Reliability Engineering and System Safety*, Vol. 25, No. 4, pp. 293-302, 1989
14. D. Kumar, P. C. Pandey, and J. Singh, "Process Design for a Crystallization System in the Urea Fertilizer Industry," *Microelectronics Reliability*, Vol. 31, pp. 855-859, 1991
15. D. Kumar, J. Singh, and P. C. Pandey, "Availability Analysis of Crystallization System in the Sugar Industry under Common Cause Failure," *IEEE Transactions on Reliability*, Vol. 41, No. 1, pp. 85-91, 1992
16. A. A. Desrochers and R. Y. Al-Jaar, "Applications of Petri Nets in Manufacturing Systems," IEEE Press, New York, 1995
17. K. Feldmann and A. W. Colombo, "Material Flow and Control Sequence Specification of Flexible Production Systems using Coloured Petri Nets," *International Journal of Advanced Manufacturing Technology*, Vol. 14, pp. 760, 1998
18. J. Singh and S. Garg, "Availability Analysis of Core Veneer Manufacturing System in Plywood Industry," in *Proceedings of International Conference on Reliability and Safety Engineering*, pp. 497-508, 2005
19. A. Sachdeva, P. Kumar, and D. Kumar, "Behavioral and Performance Analysis of Feeding System using Stochastic Reward Nets," *International Journal of Advanced Manufacturing Technology*, Vol. 45, pp. 156-169, 2009
20. M. Tavana, "Dynamic Process Modeling using Petri Nets with Applications to Nuclear Power Plant Emergency Management," *International Journal of Simulation and Process Modeling*, Vol. 4, No. 2, pp. 130-138, 2008
21. G. Thangamani, "Generalized Stochastic Petri Nets for Reliability Analysis of Lube Oil System with Common-Cause Failures," *American Journal of Computational and Applied Mathematics*, Vol. 2, No. 4, pp. 152-158, 2012
22. H. S. Li, H. Zheng, H. T. Zhao, and Z. X. Zheng, "Research on the Availability Analysis Method of Navigation Satellite based on Petri Nets," in *Proceedings of China Satellite Navigation Conference*, pp. 127-136, 2018