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Research Article

Availability Analysis and Performance Modeling of a Milk Pasteurization System using Petri Nets

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Abstract

This paper presents the performance modeling of a refrigeration system in a milk processing plant using Petri nets, providing a quantitative analysis of availability across different operating parameters. The modeling and simulation were carried out using the Petri module of the GRIF software. In this study, an effort was made to apply Reliability, Availability, and Maintainability (RAM) tools, incorporating both quantitative and qualitative approaches to minimize uncertainties related to random failures and plant shutdowns. Additionally, the study seeks to offer guidance for developing cost-effective maintenance strategies, taking into account spare parts management and repair facilities to achieve operational goals.

Keywords: *Performance Evaluation, Petri Nets, Decision Support System, Maintenance Order Priorities, DSS, Performance Analysis*

Introduction

In today's rapidly evolving business environment, the global market must keep pace with technological advancements. As a result, availability, cost-efficiency, safety, and sustainable quality have become the foundational pillars of process industries. For businesses to thrive, highly productive and efficient systems are crucial. To address these demands and enhance profitability, practitioners have adopted Reliability, Availability, and Maintainability (RAM) tools. This paper focuses on industries with complex systems made up of multiple subsystems, where the performance of each subsystem significantly impacts the overall availability of the plant. Analyzing the performance of these subsystems helps managers understand how varying failure and repair rates of a specific subsystem affect the system's overall performance. While increasing repair facilities logically requires additional financial investment, the absence of functioning systems can lead to substantial losses. Tan and Kramer [1] noted that unexpected shutdowns can cause financial losses ranging from $500 to $100,000 per hour.

In recent years, several authors have applied RAM tools for modeling and analyzing the performance of complex systems as part of maintenance management efforts [2-6]. Key RAM tools, such as Fault Tree Analysis (FTA), Reliability Block Diagrams (RBD), Markov models, and Petri nets, are commonly used to model system failures and their interactions.

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Monte Carlo simulations are employed to simulate the life cycle characteristics of a system. Although Markov models are effective tools for performance modeling in areas like concurrency and synchronization, they often suffer from the issue of state space explosions. Petri nets, however, mitigate these limitations and simplify the computational workload required by Markov modeling. In addition to discussing simulation and analytical RAM tools, this paper also examines software tools that expedite computation, offering more efficient solutions.

Petri Nets and Their Applications

Since its introduction in 1962 by Carl Adam Petri in his doctoral thesis at the University of Bonn in West Germany, the Petri nets technique has grown in popularity as a tool for performance modeling systems that exhibit synchronization, concurrency, and randomness. Bipartite directed graphs, or petri nets, are made up of two different kinds of nodes: locations, which are shown as circles, and transitions, which are shown as boxes or bars. Transitions cause tokens, which stand for conditions or resources, to shift between locations; this shift is called "firing." Token distribution between locations at any particular time is called a "marking," and it changes while the net operates.

To better successfully describe and analyze complex systems, a number of adaptations to the basic Petri net framework have been proposed in recent decades. Stochastic Petri nets (SPNs) are one such extension that adds unpredictability by connecting transition firing timings to probabilistic distributions. Generalized stochastic Petri nets (GSPNs), which include immediate (firing with zero delay) and timed transitions, were proposed by Marsan et al. [7]. With the extended stochastic Petri net (ESPN), developed by Dugan et al. [8], this idea was further expanded, supporting time distributions other than the exponential assumption that is often applied to SPNs. Marsan et al. [9] developed deterministic stochastic Petri nets (DSPNs), which provide support for deterministic, exponentially distributed, and instantaneous transitions.

The colored Petri net (CPN) is another important breakthrough that raises the bar by allowing tokens to contain data values. This allows systems to be modeled in which various tokens represent different things. This extension offers more flexibility while maintaining the fundamental ideas of traditional Petri nets.

Petri net applications are quite common. For example, Petri nets were used by Narahari and Vishwanadham [10] to model flexible manufacturing systems (FMSs). Markov models were used by Kumar et al. [12–15] in combination with Petri nets to assess the productivity of sugar, paper, and fertilizer plants. Comparably, Feldmann and Colombo [17] and Desrochers and Al-Jar [16] investigated Petri net applications in flexible production systems and manufacturing, respectively. The plywood production systems of Singh and Garg [18] and the comprehensive evaluation of a paper mill's performance by Sachdeva et al. [19] both used Petri nets for availability analysis.

Petri nets have additionally been used in critical infrastructure modeling. Thangamani [21] used a generalized stochastic Petri net to examine the availability of a lubricating oil system in a combined cycle power plant, while Tavana [20] created a Petri net model for an emergency management system at a nuclear power plant. In a recent study on centrifugal pumps, Selvakumar and Natarajan [14] employed colored Petri nets to evaluate the availability of navigation satellites. Petri nets have also been used for reliability analysis.

Petri nets' adaptability keeps growing in a variety of contexts, including industrial systems, emergency response, and space systems. They offer strong frameworks for assessing performance and dependability.

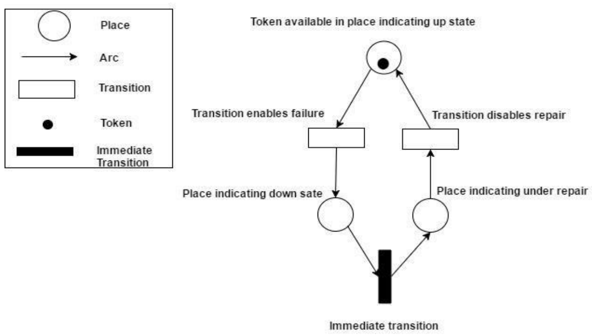

Figure 1. An illustrative Petri net model

System Description

The pasteurizing unit is critical in the milk processing plant, where raw milk is heated to eliminate bacteria and pathogens, ensuring safety and quality. This research focuses on the availability analysis of a pasteurizing system using Petri nets, with a particular emphasis on a high-temperature short time (HTST) pasteurization process. The study examines how sludge formation—resulting from residual milk particles—affects system performance and availability.

The system is comprised of several key subsystems:

1. **Regenerator:** Pre-warms raw milk to approximately 56°C to 68°C using heat from warm pasteurized milk in a counter-current flow across thin steel plates.
2. **Timing Pump:** Regulates flow rate within the HTST system, ensuring that the maximum flow rate meets or exceeds the delivery rate required for maintaining the desired holding time.
3. **Holding Tube:** Maintains milk at the sterilization temperature for the required duration, ensuring temperature variation does not exceed 1°F. The time spent in the holding tube is determined by the pump rate, tube length, and product viscosity.
4. **Indicating Thermometer:** Measures and displays the temperature of the milk after it exits the holding tube, providing critical data for process control.
5. **Vacuum Breaker:** Maintains proper pressure relationships within the system, preventing negative pressure issues and ensuring smooth flow.

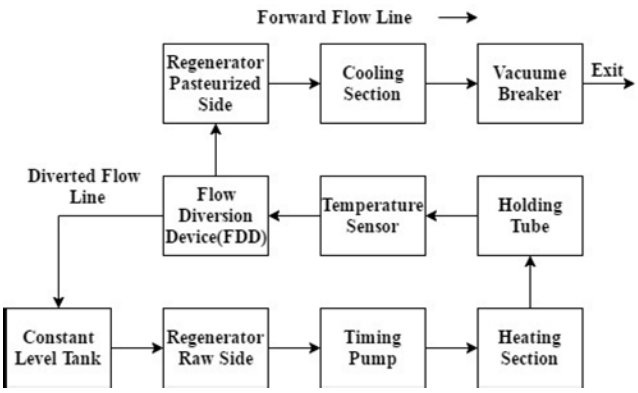

Figure 2. Flow diagram of process design of HTST milk pasteurisation system

Petri Nets Performance Model of the System

In order to do a behavioural study of the pasteurisation system, potential interactions between the system's subsystems are taken into account. The interactions are modelled using SPN. Unsatisfactory repair facilities make it impossible to manage all of the failures at once, forcing malfunctioning subsystems or units to wait for repairs. Because of this, the model includes space for many repair facilities in order to investigate how the availability of these facilities affects system performance. The pasteurisation system is represented by the SPN model in Figure 3, where the locations and transitions have the following meanings.

Places

- **PS_up**: Represents the pasteurizing system in the operational (up) state.
- **PS_dn**: Represents the pasteurizing system in the non-operational (down) state.
- **Prep_avail**: Represents the availability of the repair facility.
- **PRegen_up**: Indicates the regenerator in the operational state.
- **PTim_pump_up**: Indicates the timing pump in the operational state.
- **PHolding_tube_up**: Indicates the holding tube in the operational state.
- **PTemp_sensor_up**: Indicates the temperature sensor in the operational state.
- **PVaccu_up**: Indicates the vacuum breaker in the operational state.
- **PRegn_fail**: Represents the failure state of the regenerator, waiting for repair.
- **PTim_pump_fail**: Represents the failure state of the timing pump, waiting for repair.
- **PHolding_tube_fail**: Represents the failure state of the holding tube, waiting for repair.
- **PTemp_sensor_fail**: Represents the failure state of the temperature sensor, waiting for repair.
- **PVaccu_fail**: Represents the failure state of the vacuum breaker, waiting for repair.

Transitions

- **TRegen_ravail**: Immediate transition indicating the repair availability for the regenerator.
- **TTim_pump_ravail**: Immediate transition indicating the repair availability for the timing pump.
- **Tholding_tube_ravail**: Immediate transition indicating the repair availability for the holding tube.
- **Ttemp_sensor_ravail**: Immediate transition indicating the repair availability for the temperature sensor.
- **Tvaccum_ravail**: Immediate transition indicating the repair availability for the vacuum breaker.
- **Tsystemup**: Immediate transition indicating that the system is operational.
- **Tsysdown**: Immediate transition indicating that the system is down.

Guard Functions

- **[g1]**: ((#Regn_fail > 0 or #Tim_pump_fail > 1 or #Holding_tube_fail > 0 or #Temp_sensor_fail > 0 or #Vaccu_fail > 0) or (#Regn_fail > 0 and #Tim_pump_fail > 1 and #Holding_tube_fail > 0 and #Temp_sensor_fail > 0 and #Vaccu_fail > 0)) enables the transition **Tsysdown**.
- **[g2]**: ((#Regn_up > 0 or #Tim_pump_up > 0 or #Holding_tube_up > 0 or #Temp_sensor_up > 0 or #Vaccu_up > 0) or (#Regn_up > 0 and #Tim_pump_up > 0 and #Holding_tube_up > 0 and #Temp_sensor_up > 0 and #Vaccu_up > 0)) disables the transition **Tsystemup**.

The following assumptions are made for modeling and analyzing the refrigeration system:

- Failure and repair times follow an **exponential distribution**.
- **Failure and repair rates** are considered **statistically independent**.
- After repair, the unit is restored to an **"as good as new"** condition.
- The **standby units** have the **same nature and capacity** as the active units.
- The **switchover time** between active and standby units is assumed to be **negligible**.
- **No repair delays** are considered except for the availability of repair personnel.
- The **First Come, First Serve (FCFS)** rule is applied for repair prioritization.
- The system can operate in a **reduced capacity mode** if necessary.

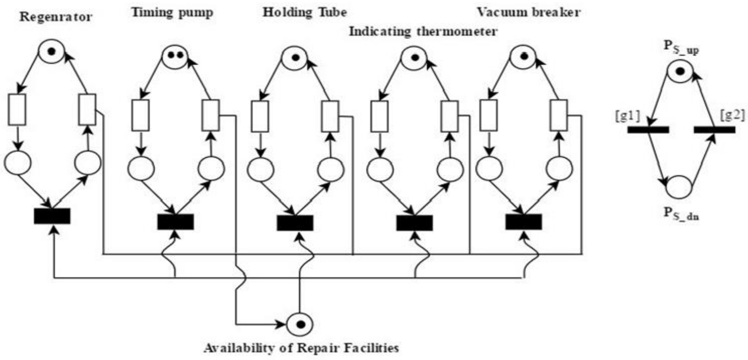

Figure 3. Petri net model of HTST milk pasteurisation system

There is just one repair facility for the current model. When a transition linked to the failure event fires, the token from the subsystem's up state location is removed, and a new token is added to the subsystem's wait for repair location. The token is moved to the under repair place and removed from the wait for repair place and repair facilities available place if it is present at the repair facilities available place. This triggers the instant enabled transition. The token is moved from the system up location to the system down place whenever more than one subsystem fails at the same time. Equipped with matching guard functions [g1] and [g2], related immediate transitions are enabled and disabled accordingly. When every subsystem is operational and has a token at its up location, the place Ps_up contains the token. The token from place Ps_up travels to place Ps_dn and the guard [g1] activates the transition Tsysdown as soon as any one subsystem fails. After this unit's repair is finished, the token is moved back to position Ps_up and the transition Tsystemup is enabled by guard [g2]. The system's availability under the specified 95% confidence level is shown by the value of place Ps_up.

Performance Analysis

The availability of a milk plant's pasteurisation system has been assessed in relation to its performance. A PN model of the milk pasteurisation process has been created in order to do this. Figure 3 illustrates this. The maintenance logbook of the VITA milk facility in Ambala, India, was consulted to gather failure and repair data for the major components involved with this system. Because the majority of the system components are mechanical, the exponential distribution of failure and repair data has been assumed in this study. Table 1 displays the specifics of the repair and failure statistics that are currently available for each of the main subsystems. GRIF-predicates Petri module (2018), a licensed PN software package, was used to obtain the availability matrix of the various subsystems. The results are shown in Tables 2 through 6. Programming was completed taking into account a number of factors and their appropriate specified values. Using the aforementioned tools, the MOCA RP computation and simulation were conducted for 10,000 hours and several replications, ranging from 10 to 21,000. Figures 4, 5, 6, 7, and 8 depict the impact of failure and repair rates on the availability of the system.

Figure 4 illustrates how the regenerator significantly affects the system's availability. The system availability is decreased by 8.65% when the failure rate rises from 0.00015 to 0.00019 and the repair rate falls from 0.400 to 0.200. A comparable result of the vacuum breaker decreasing system availability by 8.29% has been noted. Though less than the previous two (4.68%), the difference in failure and maintenance data on holding tubes also has a substantial impact. The availability of the system is hardly affected by the fluctuations in the timing pump and indicating thermometer failure and repair rates (by 1.2% and 0.87%, respectively).

Table 1 Exponential failure and repair data of milk pasteurising system

Name od Subsystem	Failure Rate	Repair Rate
Regenerator	1.5E-4	3.0E-1
Timing pump	4.0E-3	4.0E-2
Holding tube	4.0E-3	4.5E-1
Indicating thermometers	4.5E-4	3.0E-1
Vacuum breaker	2.0E-3	4.0E-2

Figure 9 shows the effect of increasing the number of repair facilities. Four repairmen is when the system's availability stabilises, indicating that adding more repair facilities does not appreciably increase availability. This result emphasises how crucial it is to strike a balance between financial considerations and the provision of sufficient repair facilities. The research does a good job of highlighting the essential subsystems' maintenance priorities.

Table 2 Availability matrix showing the effect of variation in failure ($\lambda 1$) and repair ($\mu 1$) rates of 'regenerator' subsystem on system availability

$\mu 1$ / $\lambda 1$	*0.2000*	*0.2500*	*0.3000*	*0.3500*	*0.4000*	*Constant parameters*
0.00015	0.9391	0.9545	0.9565	0.9600	0.9615	$\lambda 2 = 0.004, \mu 2 = 0.040$
0.00016	0.9333	0.9429	0.9474	0.9500	0.9524	$\lambda 3 = 0.004, \mu 3 = 0.450$
0.00017	0.9286	0.9412	0.9444	0.9474	0.9500	$\lambda 4 = 0.00045, \mu 4 = 0.300$
0.00018	0.8800	0.9032	0.9062	0.9143	0.9268	$\lambda 5 = 0.002, \mu 5 = 0.040$
0.00019	0.8750	0.9000	0.9048	0.9130	0.9259	

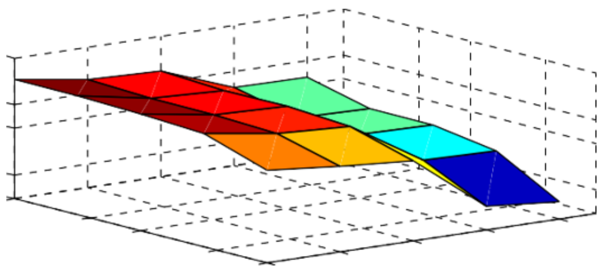

Figure 4 Effect of failure and repair rates of regenerator on system availability (see online version for colours)

Table 3 Availability matrix showing the effect of variation in failure ($\lambda 2$) and repair ($\mu 2$) rates of 'timing pump' subsystem on system availability

$\mu 2$ / $\lambda 2$	*0.0200*	*0.0300*	*0.0400*	*0.0500*	*0.0600*	*Constant parameters*
0.003	0.9524	0.9633	0.9657	0.9643	0.9655	$\lambda 1 = 0.00015$, $\mu 1 = 0.300$
0.004	0.9522	0.9524	0.9545	0.9600	0.9630	$\lambda 3 = 0.004$, $\mu 3 = 0.450$
0.005	0.9515	0.9525	0.9544	0.9599	0.9629	$\lambda 4 = 0.00045$, $\mu 4 = 0.300$
0.006	0.9500	0.9524	0.9543	0.9588	0.9627	$\lambda 5 = 0.002$, $\mu 5 = 0.040$
0.007	0.9459	0.9520	0.9535	0.9578	0.9619	

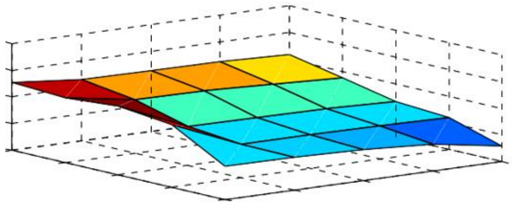

Figure 5 Effect of failure and repair rates of timing pump on system availability (see online version for colours)

Table 4 Availability matrix showing the effect of variation in failure ($\lambda 3$) and repair ($\mu 3$) rates of 'holding tube' subsystem on system availability

$\mu 3$ / $\lambda 3$	*0.2000*	*0.2500*	*0.3000*	*0.3500*	*0.4000*	*Constant parameters*
0.004	0.9369	0.9381	0.9510	0.9512	0.9519	$\lambda 1 = 0.00015$, $\mu 1 = 0.300$
0.005	0.9186	0.9271	0.9333	0.9347	0.9357	$\lambda 2 = 0.004$, $\mu 2 = 0.040$
0.006	0.9183	0.9270	0.9323	0.9333	0.9350	$\lambda 4 = 0.00045$, $\mu 4 = 0.300$
0.007	0.9160	0.9226	0.9308	0.9323	0.9345	$\lambda 5 = 0.002$, $\mu 5 = 0.040$
0.008	0.9051	0.9054	0.9209	0.9300	0.9333	

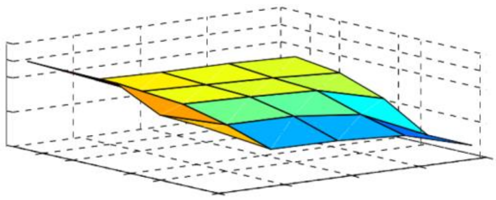

Figure 6 Effect of failure and repair rates of holding tube on system availability (see online version for colours)

Table 5 Availability matrix showing the effect of variation in failure (λ4) and repair (μ4) rates of 'indicating thermometer' subsystem on system availability

$\mu 4$ / $\lambda 4$	*0.1000*	*0.2000*	*0.3000*	*0.4000*	*0.5000*	*Constant parameters*
0.00045	0.9391	0.9429	0.9437	0.9450	0.9455	$\lambda 1 = 0.00015$, $\mu 1 = 0.300$
0.00050	0.9378	0.9377	0.9380	0.9383	0.9440	$\lambda 2 = 0.004$, $\mu 2 = 0.040$
0.00055	0.9360	0.9365	0.9377	0.9379	0.9388	$\lambda 3 = 0.004$, $\mu 3 = 0.450$
0.00060	0.9341	0.9349	0.9356	0.9365	0.9387	$\lambda 5 = 0.002$, $\mu 5 = 0.040$
0.00065	0.9320	0.9340	0.9350	0.9360	0.9378	

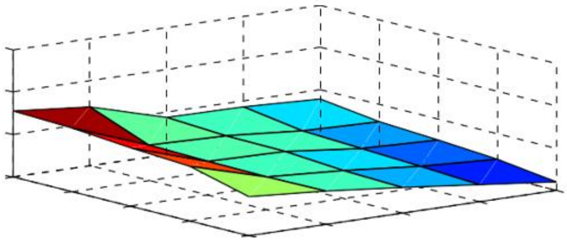

Figure 7 Effect of failure and repair rates of indicating thermometer on system availability (see online version for colours)

Table 6 Availability matrix showing the effect of variation in failure ($\lambda 5$) and repair ($\mu 5$) rates of 'vacuum breaker' subsystem on system availability

$\mu 5$ / $\lambda 5$	*0.0200*	*0.0300*	*0.0400*	*0.0500*	*0.0600*	*Constant parameters*
0.001	0.9391	0.9474	0.9482	0.9509	0.9529	$\lambda 1 = 0.00015$, $\mu 1 = 0.300$
0.002	0.9143	0.9371	0.9480	0.9457	0.9464	$\lambda 2 = 0.004$, $\mu 2 = 0.040$
0.003	0.8971	0.9231	0.9331	0.9355	0.9410	$\lambda 3 = 0.004$, $\mu 3 = 0.450$
0.004	0.8743	0.9091	0.9123	0.9163	0.9286	$\lambda 4 = 0.00045$, $\mu 4 = 0.300$
0.005	0.8700	0.9031	0.9094	0.9157	0.9186	

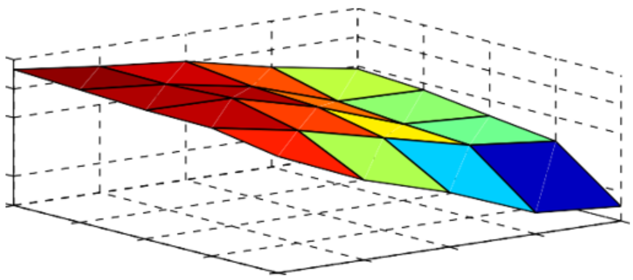

Figure 8 Effect of failure and repair rates of vacuum breaker on system availability (see online version for colours)

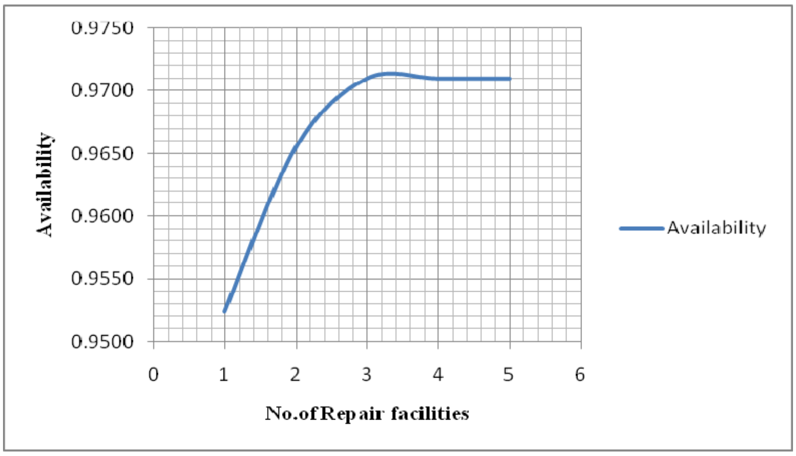

Figure 9 Effect of the number of repair facilities on system's availability (see online version for colours)

Conclusion

A thorough examination of the system has shown that the vacuum breaker and regenerator are crucial subsystems that require the management's full attention. It is challenging to examine the heat transfer surfaces in the regenerator unit without damaging the machinery. Higher heat and caustic (acidic) cleaning solutions can harm old gaskets. Liquid leakage and fluid mixing are prevented by moulded gaskets surrounding plate edges and ports. Weep holes are drilled into the raw milk side deflector plates to enable free draining of the regenerator in the event of a shutdown. The heating partition must have all of its surface regions thoroughly cleaned and sanitised. Determining the optimal allocation of resources will be aided by analysing the impact of repair facility availability on system performance. With this in mind, the managers who are in charge can organise and implement appropriate maintenance procedures and approaches. The management of human resources, the availability of resources, and the adherence to maintenance planning protocols make complex industrial systems maintenance extremely difficult. The paper's findings give practicing engineers guidance on how to schedule inspections and guarantee maintenance priorities for crucial units and subsystems, which can aid in organising the several tasks associated with strategic maintenance procedures. This strategy also creates a trade-off between the cost of a scarcity brought on by the plant's unscheduled shutdown and the investment in repair facilities and spare components. We observe that process networks (PNs) are an effective tool for process industry performance modelling and analysis because they eliminate the laborious computing work necessary for Markov modelling. The current study has demonstrated that enhancing the upkeep and financial success of milk facilities and their products may be achieved through performance analysis of the pasteurisation system.

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