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Performance Modelling and Analysis of Veneer Layup System of Plywood Manufacturing Plant Using Petri Nets Technique

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SUMMARY

This work presents performance modelling and analysis of the Veneer Layup System for a plywood manufacturing plant using the Petri Nets framework. The Petri Nets – based simulation modelling helps to evaluate the availability of the sub-system over a long period by running the plant in a virtual manner. The main factor that makes it more effective among various popular simulation methods is the ability to deal with real working conditions. The results obtained through the analysis can be utilized to identify these sub-systems that highly affect the system performance. Separate maintenance planning for each sub-system can reduce the production loss due to the unavailability of any sub-system for performing its intended task.

KEY WORDS: *availability; performance; Petri Nets; modelling tool.*

1. INTRODUCTION

Petri Nets technique offers a valuable tool for modelling and analysing the performance of various systems. With ongoing research advancements and the development of new software tools, Petri Nets are likely to remain a powerful technique for performance evaluation in various fields. Petri Nets (PNs) are a simulation modelling tool that has been extensively used to model and analyse a large and complex class of real-time Safety-Critical Systems (SCS). These systems include the Control System, Nuclear Power Plant (NPP), Manufacturing System, Patient-Monitoring System, Space Aircraft System and many more. Failure of such SCS causes severe loss of human lives, finances and environmental resources. PNs have various important properties, such as liveness, safety, boundedness, well-formedness, soundness, and termination.

However, it is not easy to analyse a system modelled with PNs when the reachable states and the number of tokens in places increase. In such circumstances, the complexity of the system increases exponentially. Furthermore, the time and space complexity of the system analysis increases. An extensive and complex system modelled with PNs is subjected to the state explosion problem. Petri Nets were invented by Carl Adam Petri in 1962. A part of his research

work, Carl Adam Petri used them to model the functionality or behaviour of a system. Petri Nets were first used in Computer Systems and Computer Networks and were later applied to Manufacturing System, Production Systems, Scheduling Systems and Controllers of model behaviour. There are also several other applications of PNs. Certain efficient pieces of software based on this technique, such as the Petri Nets module of the Graphical Interface for Reliability Forecasting, are now commercially available.

The paper is intended to demonstrate the superiority of the PNs approach over the Markov modelling technique in many aspects. This technique considerably reduces the tedious computational efforts that are usually required as in the case of the Markov Method. Simulations using Petri Nets are very flexible and provide accurate predictions of the system performance measures. Whereas the Markov approach generally considers one failure at a time and the failure pattern is normally assumed to be exponential, PNs based techniques can handle more than one failure with different types of real time dependent failure models. This modelling technique is also currently being extensively applied to the field of availability analysis. PNs based deadlock prevention policies for Flexible Manufacturing Systems have been compared and surveyed for complex system [1]. Multi - objective Genetic Algorithms (GA) have been used with Petri Nets and Bayesian Model Averaging (BMA) for robust manufacturing system design [2]. An automated synthesis of hybrid Petri Nets models has been discussed for robotic cells in the aircraft industry. Aircraft manufacturers are increasingly utilizing robotic cells for efficient production. To optimize these complex systems, the research investigated the automation of the development of hybrid Petri Nets models [3]. The task of testing communication in distributed control system was described with the help of Coloured Petri Nets [4]. The widespread use of Internet of Things technology through Coloured Petri Nets (CPN) simulation has been reported for Production-Logistics Systems [5].

Coloured Petri Nets (CPNs) have been discussed as a technology that can be combined with Internet of Things technologies to establish an active sensing system for real-time, multi-source manufacturing information [6]. A key objective of applying discrete-event modelling is to design a suitable control system for plants. This control system plays an important role in ensuring the plant's outputs consistently meet the predetermined specifications [7]. Petri Nets have been proposed for Flexible Manufacturing System in large-scale discrete-event systems [8]. The performability of the veneer layup system in a plywood manufacturing plant has been described in terms of its availability [9]. A graphical and mathematical modelling tool based on Petri Nets has been discussed for deadlock analysis in automated manufacturing system [10]. A new Place-Transition Control method was developed in the Flexible Manufacturing Unit and analysed using Petri Nets [11]. The most relevant challenges and opportunities related to the use of Petri Nets as a modelling technique for manufacturing systems were analysed [12]. The modelling and availability analysis of a Container Manufacturing Industry (CMI) using the PNs technique was described and various availability levels were attained by changing numerous operating parameters that affect the overall availability of the system [13].

A modelling and analysis methodology was prepared for evaluating the performance of a coal handling system with the help of Petri Nets [14]. The analysis and maintenance decisions of a wood industrial subsystem were discussed with the help of Stochastic Petri Nets modelling [15]. The methodologies for modelling, specification and control synthesis in the regulation control framework were represented [16]. The performability of a veneer-cutting system in a plywood manufacturing industry was evaluated using a Markov approach. Recent studies have also applied Petri Nets for maintenance decision-making and subsystem prioritization in industrial systems. However, most of the reported studies have focused either on conventional availability

analysis of specific subsystems or on different industrial configurations [17]. Limited research has addressed the integrated reliability, availability, and maintainability (RAM) analysis of plywood manufacturing systems using Petri Net-based approaches. The application of Stochastic Petri Nets to capture the complex failure, operational, and maintenance behaviour of such systems also remains relatively unexplored. Moreover, comprehensive Petri Net-based frameworks that simultaneously consider maintenance requirements, system uncertainties, operational constraints, and performance optimization are still scarce. These gaps highlight the need for a more integrated approach to improve the performance and productivity of plywood manufacturing systems.

2. MODELLING TOOLS

The Petri Nets modelling tool facilitates the creation of models using places, transitions, and arcs to represent system states, events, and their relationships. It enables the assignment of performance attributes such as rates or probabilities to transitions, allowing for the modelling of system behaviour over time. Users can simulate the PNs to observe dynamic behaviour and analyse performance metrics like throughput and response time. Fault Tree Analysis (FTA) analyses system failure causes hierarchically, Reliability Block Diagrams (RBDs) visualize system reliability through component interconnections, the Markov method assesses system state transitions probabilistically, and Petri Nets model system behaviour and synchronization through directed graphs. These tools offer diverse perspectives for improving system reliability and performance.

i. **Fault Tree:** Fault trees in modelling tools serve as blueprints for potential failures that might impact a system's efficiency. Through the tool, users illustrate how these failures interconnect and gauge their probability and consequence. This aids in ranking which issues need immediate attention. Continuously updating the plan as insights are gathered, one can test out remedies to enhance overall performance.

ii. **Reliability Block Diagrams:** Reliability Block Diagrams (RBDs) in modelling tools offers a visual means of evaluating the reliability performance of intricate systems by segmenting them into individual components or blocks and illustrating their interconnections. Each block denotes a system component, and the linkages between them depict how these components interact in terms of performance reliability.

iii. **Markov Method:** The Markov method, within the context of modelling tools, refers to mathematical techniques used to analyse systems that undergo state transitions over time in a probabilistic manner. This model enables the prediction of future states and system behaviour based on its current state and transition probabilities. Markov methods are widely used to analyse and predict the behaviour of dynamic systems in various fields, including engineering, manufacturing units, process industries, electronics and computer science applications.

iv. **Petri Nets:** A Petri Net is a formal language or graphical tool for modelling systems with concurrency, commonly used in today's multi-threaded systems to represent parallel processes. In this system, concurrent operations occur simultaneously. It is represented as a bipartite graph, with nodes known as "Places" representing conditions, and "Transitions" representing events or activities. As shown in Figure 1, places and transitions are connected by directed arcs, which exist only between a place and a transition or vice versa. Tokens circulate within the system between places, representing the flow of information or

resources. In Petri Nets, "upstate" and "downstate" describe the conditions of places within the system, indicating whether a place contains at least one token (upstate) or is empty (downstate), representing the presence or absence of a resource, respectively. Incorporating a repairman into a Petri Nets model involves representing various states of machinery or equipment as places, with transitions depicting events like breakdowns or maintenance tasks.

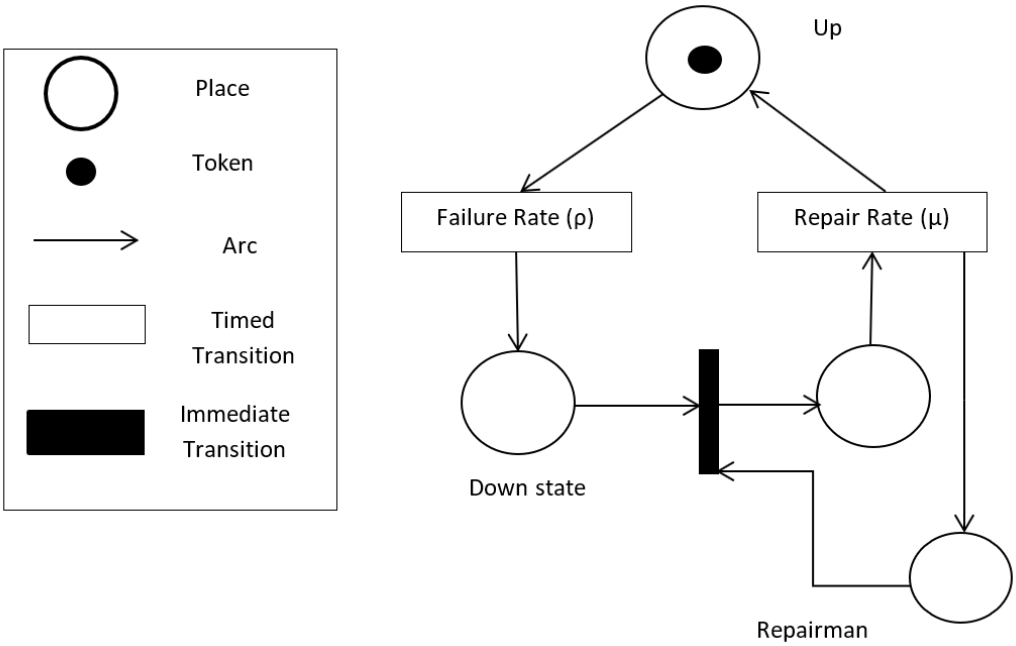


Fig. 1 *The Petri Nets Model of a system*

A token may shift from a location signifying working equipment to a different location reflecting the repairman's availability. When a machine breaks down and enters a downstate, it indicates the need for a repairman. The machine returns to an upstate once the repair is finished, suggesting that its functionality has been restored, and the token moves directly to the repairman's availability location, indicating that he is prepared for the next maintenance task.

2.1 EXTENSIONS OF PETRI NETS

Petri Nets have been extended to include Event Graphs, emphasizing event occurrences; Deterministic Timed Petri Nets for deterministic timing; Stochastic Timed Petri Nets for probabilistic analysis; Colour Petri Nets for detailed state modelling; and Hybrid Nets, combining different types for versatile system modelling.

2.1.1 Event Graph (Marked Graph, Decision - free): Each place has exactly one input transition and exactly one output transition. An event graph serves as a graphical tool aimed at analysing and visualizing the behaviour inherent in a Petri Nets model.

2.1.2 Deterministic Timed Petri Nets: Deterministic time delays are associated with transitions. Deterministic Timed Petri Nets are a type of Petri Net in which transitions occur at specific, predetermined times. Unlike other types of Petri Nets in which transitions may occur randomly or based on certain conditions, in Deterministic Timed Petri Nets, the timing of transitions is fixed and deterministic.

2.1.3 Stochastic Timed Petri Nets: Stochastic time delays are associated with transitions. Stochastic Petri Net is a timed transition PNs with atomic firing and all transition delays are exponentially distributed. Stochastic Timed Petri Nets are a variation of Petri Nets that integrate probabilistic timing into their modelling framework.

2.1.4 Colour Petri Nets: Colour Petri Net is an extension of traditional Petri Nets that allows tokens to carry additional information, known as colours. In Colour Petri Nets, tokens are not just markers of state, but can also represent different types, attributes, or conditions of entities within the system.

2.1.5 Hybrid Petri Nets: In Hybrid Petri Nets transitions can represent discrete events that occur instantaneously, while places can contain continuous variables that change continuously over time. This hybrid approach enables the modelling of systems with mixed dynamics, such as cyber-physical systems, where discrete events interact with continuous processes.

3. SYSTEM DESCRIPTION

The plywood industry typically involves a nine-step production process. These steps include log collection, debarking, steaming blocks, peeling blocks and veneer cutting, drying veneers, gluing and lay-up, pressing in hot and cold presses, trimming, and super finishing and grade stamping as shown in Figure 2.

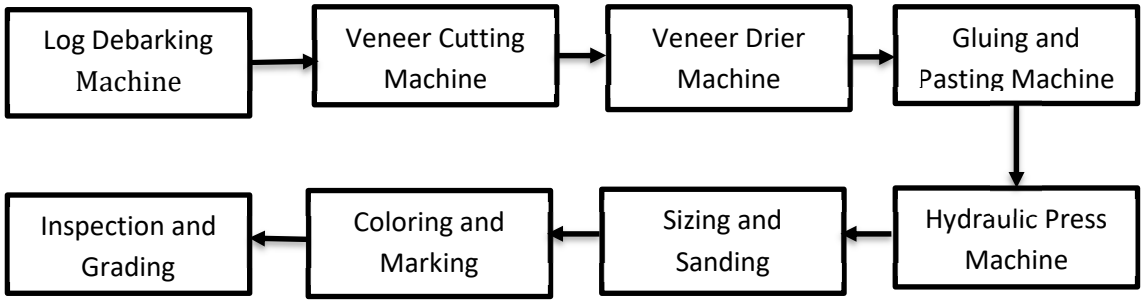


Fig. 2 *Flow Diagram of plywood manufacturing process*

Veneer production, which constitutes around 37 to 42% of the total plant output, is an important aspect of the plywood industry. The base materials commonly used in this industry, particularly in the Ganga basin of Northern India, are poplar and eucalyptus wood. Optimization of the veneer production subsystem is vital for efficiency and quality with factors such as log quality, debarking efficiency, drying methods, adhesive application and pressing conditions taken into consideration. Regional considerations such as wood availability, climate conditions affecting drying processes, and market demand for various plywood grades and finishes also influence production strategies. The system consists of the following subsystems:

3.1 Log Debarking Machine The log debarking machine removes bark from logs prior to their conversion into plywood sheets, ensuring clean logs free from defects and contaminants. This enhances the quality of resulting veneer or chips and prolongs the operational lifespan of subsequent machinery.

3.2 Veneer Lathe Plywood manufacturing wouldn't be possible without a Veneer Lathe Machine. This workhorse takes thick logs and whittles them down into thin sheets of wood called veneer. Think of it as a giant vegetable peeler for logs, but instead of removing a thin layer of skin, it creates wide, smooth sheets. The lathe uses sharp blades or a spinning drum to

precisely shave off these consistent layers, making sure each piece of veneer is exactly the same thickness.

3.3 Veneer Drier The veneer dryer serves as a specialized component within a plywood manufacturing plant, aimed at removing moisture from recently cut veneer sheets to attain the desired moisture content for subsequent processing and storage. Employing controlled heat and airflow, it safeguards against defects such as warping or cracking. Various techniques, including hot air circulation or infrared radiation, may be employed depending on the dryer's configuration. Efficient moisture removal is essential for producing high-quality plywood sheets with uniform thickness and strength.

3.4 Glue Spreaders and Lay-up In plywood manufacturing, glue spreaders and lay-up are important steps. First, the veneer surfaces are prepared, coated with adhesive. The veneer sheets are then stacked with their grain orientations perpendicular to each other and pressed to activate the adhesive. After curing, the plywood is trimmed and finished to achieve the required dimensions and a smooth surface. This process results in strong plywood sheets suitable for use in construction and furniture manufacturing. In plywood production, veneer sheets are prepared from logs, sorted, graded, and cleaned to ensure proper adhesion. Efficient adhesive application and proper lay-up are essential for achieving the required quality and strength of the final plywood product.

4. PETRI NETS MODELLING OF THE SYSTEM

Petri Nets, a graphical and mathematical modelling tool, provide a comprehensive framework for understanding and optimizing complex systems like the plywood production process. Within this modelling paradigm, places signify various states or locations within the production line, while transitions represent events or actions that occur during manufacturing, such as material preparation, cutting, gluing, pressing, and finishing. Tokens, which circulate within the PNs, symbolize the presence of materials or workpieces at different stages of production. By structuring the Veneer Lay-up System using Petri Nets, it becomes possible to simulate diverse production scenarios, pinpoint potential bottlenecks, optimize resource allocation and scheduling to enhance overall productivity and throughput. Furthermore, Petri Nets facilitate dynamic analysis, allowing for the evaluation of the system's response to changes in production demand, machine breakdowns, maintenance activities or other disruptions. This detailed and adaptable modelling approach empowers plywood manufacturers to make informed decisions, improve efficiency and design resilient production processes tailored to their specific needs and challenges.

4.1 Places

- PUp_State (P_{15}) represents the system in upstate.
- PDown_State (P_{17}) represents the system in down state.
- PSys_Fulcap (P_{14}) represents the system operating at full capacity.
- PSys_Redcap (P_{16}) represents the system operating at reduced capacity.
- Rep_avail (P_{13}) represents the availability of the repair facility.
- PLogDebarkingMach_up (P_1), PVeneerLathe_up (P_4), PVeneerDrier_up (P_7) and PG. Sp. &Layup_up (P_{10}) represent the operating state of the Log Debarking Machine, Veneer Lathe, Veneer Drier and Glue Spreader and Layup, respectively.

- PLog Debarking Mach_dn (P_2), PVeneerLathe_dn (P_5), PVeneerDrier_dn (P_8) and PG. Sp. &Layup_dn (P_{11}) represent the downstate of the Log Debarking Machine, Veneer Lathe, Veneer Drier and Glue Spreader and Layup, respectively.
- PLogDebarkingMach_rep (P_3), PVeneerLathe_rep (P_6), PVeneerDrier_rep (P_9) and PG. Sp. &Layup_rep (P_{12}) represent the repair state of the Log Debarking Machine, Veneer Lathe, Veneer Drier and Glue Spreader and Layup, respectively.

4.2 Transitions

- TLog Debarking Mach._fail, TVeneerLathe_fail, TVeneerDrier_failand TG. Sp. &Layup_fail are timed transitions and are associated with failure rates ($\rho 1$, $\rho 2$, $\rho 3$ and $\rho 4$) of the Log Debarking Machine, Veneer Lathe, Veneer Drier and Glue Spreader and Layup, respectively.
- TLog Debarking Mach._rep, TVeneer Lathe_ rep, TVeneer Drier_ rep and TG. Sp. & Layup_ rep are timed transitions and are associated with repair rates ($\mu 1$, $\mu 2$, $\mu 3$ and $\mu 4$) of the Log Debarking Machine, Veneer Lathe, Veneer Drier and Glue Spreader and Layup, respectively. TLog Debarking Mach.rep_avail ($T9$), TVeneer Lathe rep_avail ($T10$), TVeneer Drier rep_avail ($T11$) and TG. Sp. & Layup rep_avail ($T12$) are immediate transitions. These are associated with the availability of the repair facility for the Log Debarking Machine, Veneer Lathe, Veneer Drier and Glue Spreader and Layup, respectively.
- TSys_red ($T13$), TSys_full ($T14$), TSys_fail ($T15$) and TSys_up ($T16$) are also immediate transition. These are associated with the system operating at reduced capacity, at full capacity, in a failed state and in an upstate and respectively.

4.3 Programmed Guard Functions

The PNs model is based on a computer program developed for guard functions associated with various transitions. These are:

- [G1] = (#2>0 and #13>0) disables the transition TRep.avail_Log Debarking Machine.
- [G2] = (#5>0 and #13>0) disables the transition TRep.avail_Veneer Lathe.
- [G3] = (#8>0 and #13>0) disables the transition TRep.avail_Veneer Drier.
- [G4] = (#11>0 and #13>0) disables the transition TRep.avail_Glue Spreader and Lay-up.
- [G5] = ((#4>0 and #4<3)or(#7>0and#7<2))or((#4>0and#4<3)and(#7>0and#7<2)) enables the transition TSys_red.
- [G6] = (#1>0and#4>2and#7>1and#10>0) disables the transitions TSys_full.
- [G7] = (#1<1or#4<1or#7<1or#10<1) enables the transitions TSys_fail.
- [G8] = (#1>0and#4>0and#7>0and#10>0) disables the transitions TSys_rep.

The following assumptions have been made for modelling and analysis of the systems:

- The exponential distribution is used for the repair rate, while the Weibull distribution is used for the failure rate.
- Failure rates and repair rates are statistically independent.
- The repaired unit is equivalent in quality to a new one.
- The standby units have the same characteristics and capacity as the active units.
- The transition time between active and standby units is minimal.
- Repair commencement experiences no delay apart from repairman unavailability.
- Repair priority is determined on a first-come, first-served basis.

The system can also operate in a reduced-capacity mode.

4.4 Failure Rate (λ): Failure Rate is defined as the number of failures occurring in a system per unit of operating time. It indicates the frequency at which a system or component is expected to fail during its normal operating period.

$$\lambda = \frac{\text{Number of Failures}}{\text{Total Operating Time}} \qquad \lambda = \frac{1}{MTBF}$$

4.5 Repair Rate (μ): Repair Rate is defined as the number of repairs completed per unit of repair time. It represents the rate at which a failed component or system is restored to its operational state.

$$\mu = \frac{\text{Number of Repairs}}{\text{Total Operating Time}} \qquad \mu = \frac{1}{MTTR}$$

4.6 Mean Time Between Failures (MTBF): MTBF is defined as the average operating time between two consecutive failures. It is an important measure of system reliability, with a higher MTBF indicating better reliability and longer operational performance.

$$\text{MTBF} = \frac{\text{Total Operating Time}}{\text{Number of Failures}}$$

4.7 Mean Time To Repair (MTTR): MTTR is the average time required to repair the system or machine after a failure. It indicates the efficiency of the maintenance process in restoring the system to its normal operating condition.

$$MTTR = \frac{\text{Total Repair Time}}{\text{Number of Repairs}}$$

The developed Petri Nets model with a single repair facility is presented in Figure 3. Computer programming and simulation were used to analyse the performance of the system. This was carried out using the licensed GRIF software package and its Petri module. The failure and repair rates of the Plywood Vaneer System are shown in Table 1.

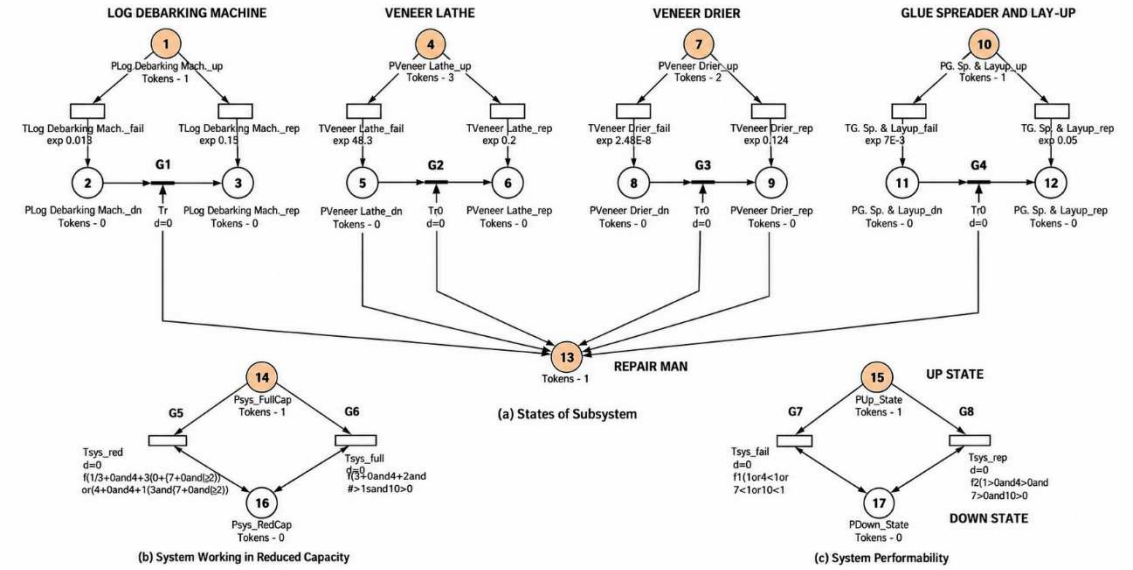


Fig. 3 *Transition Diagram of Petri Nets Model for plywood manufacturing process*

Table 1 *Failure and repair rates of Veneer System*

Sub-System's Name	*Mean Failure Rate (ρ_i)*	*Mean Repair Rate (μ_i)*
Log Debarking Machine (A)	*0.013 (ρ_1)*	*0.15 (μ_1)*
Veneer Lathe (B)	*0.004 (ρ_2)*	*0.2 (μ_2)*
Veneer Drier (C)	*0.0024 (ρ_3)*	*0.126 (μ_3)*
Gluing Spreader and Lay-up (D)	*0.005 (ρ_4)*	*0.19 (μ_4)*

5. RESULTS AND DISCUSSION

The system performance has been analysed by varying the input parameters of the Veneer Lay-up System. The performance analysis is carried out to understand its long-term performance in terms of availability. The modelling and simulation were carried out using a licensed software package, with the Petri Nets module and various parameters, places, transitions, guard function and their appropriate predefined values. The simulation was run for 1000 hours, with approximately 21000 replications at a confidence level of 96%, using the above-mentioned software. The maintenance data for the various subsystems were collected from the industry.

Table 2 *Effect of variation in the failure and repair rates of the Log Debarking Machine subsystem on system performability (%)*

Failure Rates (ρ_1)	*Repair Rates of Log Debarking Machine (μ_1)*					*Constant Parameters*
	0.05	*0.15*	*0.25*	*0.35*	*0.45*	
0.003	*0.913*	*0.951*	*0.958*	*0.964*	*0.965*	$\rho_2 = 0.004$, $\mu_2 = 0.2$, $\rho_3 = 0.0024$, $\mu_3 = 0.126$, $\rho_4 = 0.005$, $\mu_4 = 0.19$
0.013	*0.776*	*0.883*	*0.924*	*0.934*	*0.938*	
0.023	*0.663*	*0.831*	*0.883*	*0.905*	*0.912*	
0.033	*0.574*	*0.783*	*0.848*	*0.882*	*0.902*	
0.043	*0.484*	*0.745*	*0.818*	*0.869*	*0.885*	

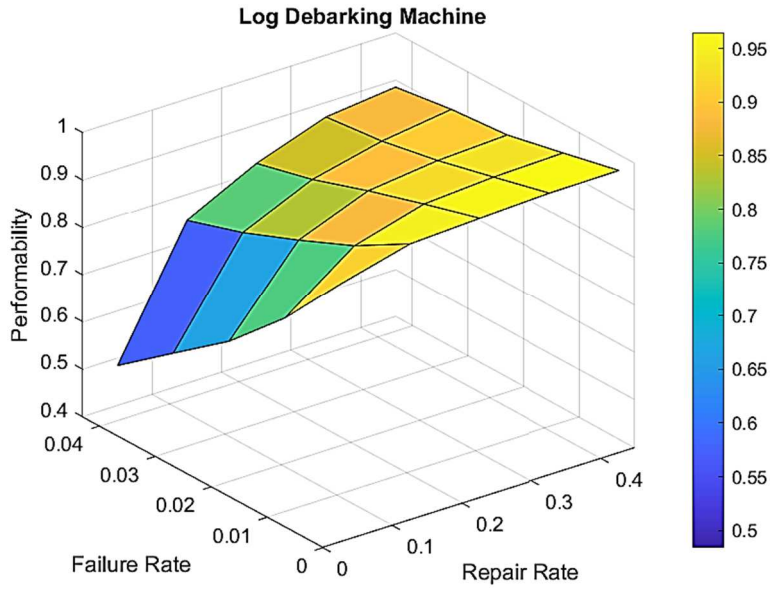


Fig. 4 *Effect of failure and repair rate parameters of the Log Debarking Machine subsystem on system performability*

To conduct the performance analysis, the parameters of the other subsystem remain constant, while the failure and repair rates (ρ and μ respectively) of a particular subsystem are varied within a permissible range.

Table 2 and Figure 4 show variations in the failure and repair rates of the log debarking machine, which have a significant impact on the performability of the system. An increase in failure rate from 0.003 to 0.043 decreases the performability from 0.913 to 0.484, whereas an increase in the repair rate from 0.05 to 0.45 increases the system performability from 0.913 to 0.965, i.e., the performability increased by 49.84%.

Figure 5 and Table 3 show that variations in the failure and repair rates of the Veneer Lathe have a significant impact on the availability of the system. An increase in the failure rate of the Veneer Lathe from 0.002 to 0.006 and a reduction in the repair rate from 0.3 to 0.1 reduce the system availability by up to 5.5%.

Table 3 *Effect variation in the failure and repair rates of Veneer Lathe Subsystem on system performability (%)*

Failure Rates (ρ_2)	***Repair Rates of Veneer Lathe (μ_2)***					***Constant Parameters***
	0.1	*0.15*	*0.2*	*0.25*	*0.3*	
0.002	*0.867*	*0.878*	*0.890*	*0.893*	*0.898*	$\rho_1 = 0.013$, $\mu_1 = 0.15$, $\rho_3 = 0.0024$, $\mu_3 = 0.126$, $\rho_4 = 0.005$, $\mu_4 = 0.19$
0.003	*0.865*	*0.872*	*0.886*	*0.889*	*0.892*	
0.004	*0.863*	*0.870*	*0.883*	*0.885*	*0.888*	
0.005	*0.860*	*0.868*	*0.876*	*0.879*	*0.881*	
0.006	*0.856*	*0.862*	*0.871*	*0.875*	*0.877*	

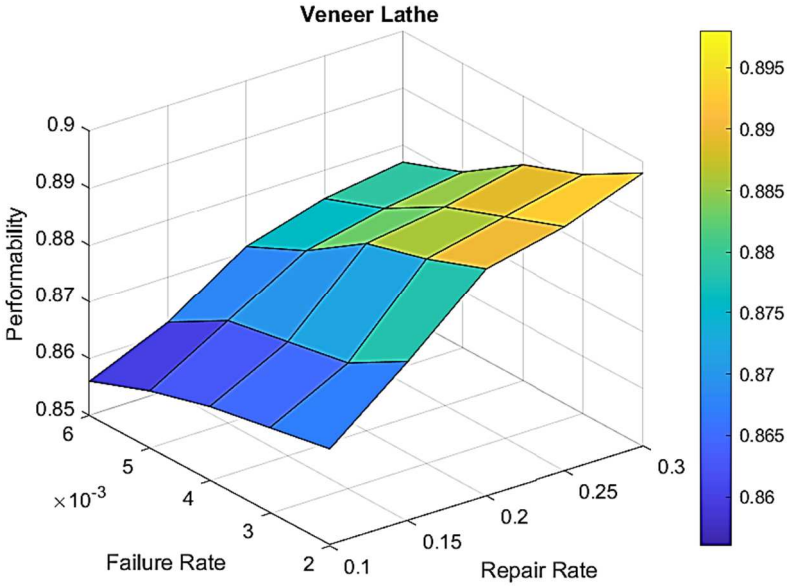


Fig. 5 *Effect of failure and repair rate parameters of Veneer Lathe subsystem on system performability*

Figure 6 and Table 4 illustrate that variations in the failure and repair rates of the Veneer Drier have a moderate impact on the system availability. An increases in the failure rates of the veneer drier from 0.0012 to 0.0036 decreases the system performability from 0.892 to 0.870. In contrast, an increases in the repair rate of the Veneer Drier from 0.106 to 0.146 increases the system performability from 0.892 to 0.911, i.e., by 4.3%.

Table 4 *Effect variation in the failure and repair rates for Veneer Drier Subsystem on system performability (%)*

Failure Rates (ρ_3)	***Repair Rates of Veneer Drier (μ_3)***					***Constant Parameters***
	0.106	*0.116*	*0.126*	*0.136*	*0.146*	
0.0012	*0.892*	*0.897*	*0.901*	*0.908*	*0.911*	$\rho_1 = 0.013$, $\mu_1 = 0.15$, $\rho_2 = 0.004$, $\mu_2 = 0.2$, $\rho_4 = 0.005$, $\mu_4 = 0.19$
0.0018	*0.881*	*0.885*	*0.887*	*0.889*	*0.890*	
0.0024	*0.879*	*0.880*	*0.883*	*0.885*	*0.886*	
0.0030	*0.872*	*0.878*	*0.881*	*0.882*	*0.884*	
0.0036	*0.870*	*0.875*	*0.873*	*0.878*	*0.880*	

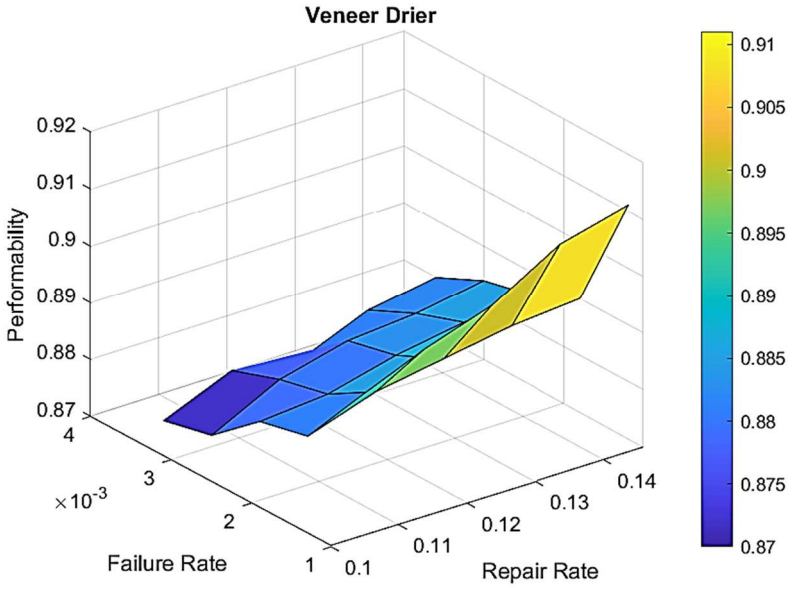


Fig. 6 *Effect of Failure and Repair Rate parameters of the Veneer Drier subsystem on system performability*

Table 5 and Figure 7 illustrate that variations in the failure and repair rates of the Gluing Spreader and Lay-up subsystem have a significant impact on the system availability. An increase in the failure rates of the Gluing Spreader and Lay-up subsystem from 0.001 to 0.009 decreases the system performability from 0.892 to 0.768, whereas an increase in the repair rate from 0.05 to 0.33 increases the system performability from 0.892 to 0.919, i.e., by 16.43%.

Table 5 *Effect variation in the failure and repair rates of the Gluing Spreader and lay-up subsystem on system performability (%)*

Failure Rates	***Repair Rates of Gluing Spreader and Lay-up***					***Constant Parameters***
	0.05	*0.12*	*0.19*	*0.26*	*0.33*	
0.001	*0.892*	*0.895*	*0.898*	*0.918*	*0.919*	$\rho_1 = 0.013$, $\mu_1 = 0.15$, $\rho_2 = 0.004$, $\mu_2 = 0.2$, $\rho_3 = 0.0024$, $\mu_3 = 0.126$
0.003	*0.858*	*0.871*	*0.890*	*0.901*	*0.912*	
0.005	*0.844*	*0.869*	*0.883*	*0.889*	*0.890*	
0.007	*0.795*	*0.866*	*0.873*	*0.879*	*0.887*	
0.009	*0.768*	*0.844*	*0.856*	*0.860*	*0.883*	

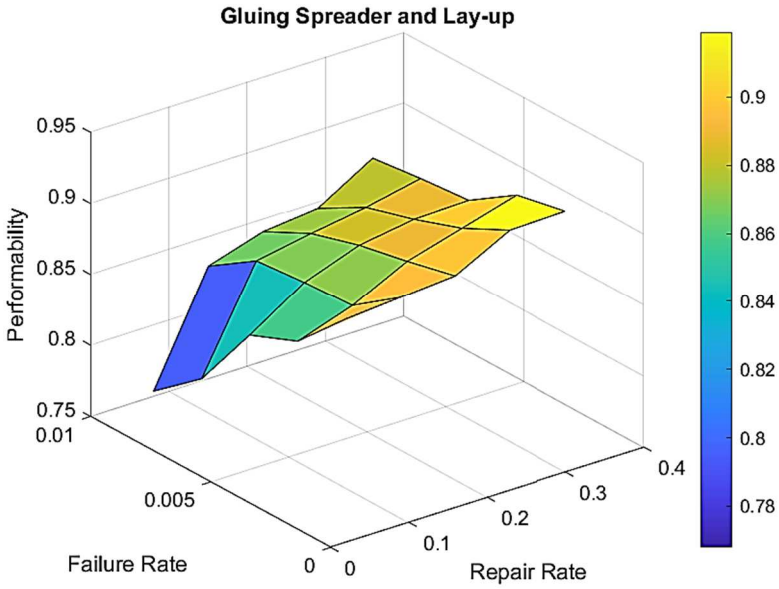


Fig. 7 *Effect of failure and repair rate parameters of the Gluing Spreader and lay-up subsystem on system performability*

Table 6 and Figure 8 clearly depict that an increase in the number of repair facilities from one to five increases the system's availability by 1.43%. With the help of the above-mentioned subsystems, the Log Debarking Machine showes the highest variation in the system performability, i.e., 49.84%, whereas the Veneer Drier showes the lowest variation, i.e., 4.50%. The Gluing Spreader and Lay-up and Veneer Lathe subsystems show performance variations of 16.43% and 4.68%, respectively.

Table 6 *Effect of repair facilities on system availability (%)*

No. of Repair Facilities	*Availability (%)*
1	*88.3*
2	*89.5*
3	*90.8*
4	*90.8*
5	*90.8*

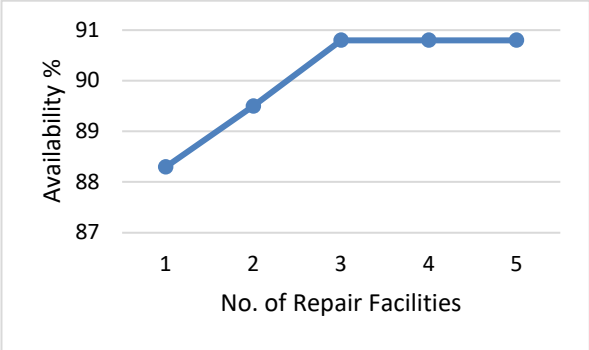


Fig. 8 *Effect of failure and repair rates of the repair facilities on system availability (%)*

6. CONCLUSIONS AND FUTURE RESEARCH

The study presents a Petri Nets-based framework for performance modelling and availability analysis of the Veneer Layup System in a plywood manufacturing plant. The proposed approach identifies critical subsystems and evaluates the effects of failure and repair characteristics on overall system availability. It can support maintenance planning by identifying maintenance-sensitive subsystems and guiding suitable preventive and corrective actions. However, the study is limited to data from a single plant and assumes statistically independent failure and repair processes. Economic factors such as maintenance costs, production losses, and spare-parts availability are not considered.

Future research may focus on integrating optimization techniques such as Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Biogeography-Based Optimization (BBO), and Teaching-Learning-Based Optimization (TLBO) for determining optimal maintenance policies. The proposed methodology can be extended to other manufacturing and process industries with similar operational characteristics, such as the Cement Manufacturing Industry, Thermal Power Plant Industry, Steel Manufacturing Industry, Paper and Pulp Industry, Sugar Manufacturing Industry, Textile Manufacturing Industry, Automobile Manufacturing Industry, Chemical and Process Industry, thereby further enhancing system availability and operational efficiency.

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