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PERFORMANCE EVALUATION AND OPTIMIZATION OF CRYSTALLIZATION AND SUGAR HANDLING SUBSYSTEMS IN SUGAR MILL PLANT USING PSO

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Abstract

An appropriate maintenance strategy is necessary for sugar mill plants and particularly focuses on the core processing system. This research creates an availability-based simulation model for a sugar mill with 25,500 tons sugarcane crushing capacity. A Markov performance evaluation approach is used, and differential equations generated from a transition diagram covering fully operational, partially operational, and failure modes are included. Among the major processing units, the Evaporator is identified as a core processing component, being directly involved in sugar concentration. In contrast, the Rotary Dryer and the Centrifugal Machine (Batch or Continuous Centrifuge) are classified as auxiliary units. These support the production process by reducing moisture content and separating sugar from molasses, respectively, without altering the sugar chemically. The Crystallizer (e.g., A-Pan Crystallizer) is also a core processing component, directly responsible for crystal formation. PSO is used to improve performance by optimizing the failure and repair rates and enhancing the performance metrics. Experimental results showed the system achieved 88.84% availability. These results allow maintenance strategies that focus on the most critical subsystems to be processing developed. A case for focused maintenance is made based on the evidence provided for more effective scheduling, ultimately improving system performance.

Keywords: availability analysis; particle swarm optimization; performance modeling; sugar mill plant; markov-based simulation

I. Introduction

The global sugar milling industry represents a critical agricultural sector, transforming raw sugarcane into refined sugar through an integrated sequence of technologically advanced equipment. This intricate production system relies on two subsystems: the core concentration systems and auxiliary handling systems. The focal components are the evaporator station along with the crystallizer system (equipped with a standby unit) which performs the vital functions of juice concentrating and sugar crystal formation, respectively. The evaporator achieves progressive syrup densification through multi-effect boiling, and the Crystallizer with standby support (exemplified by A-Pan designs) guarantees uninterrupted batch crystallization which in essence defines the crystallized sugar's dimensions, its purity, and the yield metrics fundamentally determining these attributes. Auxiliary units that complement core systems include the rotary drier (operating with standby redundancy) and the centrifuge subsystem (includes batch and continuous centrifugal machines). The rotary drier with redundancy reduces the moisture content of sugar to commercial specifications (<0.04% moisture) and the centrifuge separates the crystalline sucrose from its residual molasses by means of centrifugal force. Both processes performed by these devices are physical transformations that do not change the chemical nature of sugar. Most importantly, the described operational subsystems efficiency, and even more so those which incorporate engineered redundancy like the rotary drier with standby or the standby rotary drier and crystallizer, have a direct impact on energy consumption profiles, operational costs, and environmental sustainability metrics throughout the entire production lifecycle. In these areas, underperformance results in increased demand for thermal energy, fuel consumption, carbon emissions, and elevated carbon emissions, along with a decrease in mill profitability, reiterate the need for better optimization frameworks.

II. Literature review

The PSO, or Particle Swarm Optimization method, is one of the most powerful computational technology that is available today to improve performance of complex industrial systems. It is based on a population-based metaheuristic PSO which tackles the high-dimensional and nonlinear solution spaces that characterize integrated process industries such as sugar milling [3,5]. PSO has already proven its effectiveness in analogous industries, for example, in the ammonia synthesis units, systematic availability centered maintenance planning was implemented by Kumar and measurable reliability improvement on fertilizer production through failure rate minimization was achieved [1]. Also, in Zhao and Li's work, they estimated the optimization of sugarcane processing and its reduction of greenhouse gas emissions by 18-22% due to lower energy intensity, thus emphasizing the imperative need for sustainable advanced process control [2]. These studies together reinforce the claim that PSO is capable of solving interdependent optimization problems which go beyond the refining aspects of throughput, quality, and several environmental parameters. In the case of sugar mills, this also includes the optimization of standby activation protocols and redundancy utilization strategies for the crystallizer and drying subsystems.

Effective maintenance planning is critical for preserving the subsystem reliability and the overall availability of the plant. This was demonstrated by Adhikary et al. in coal-fired power generation, with a comprehensive Reliability, Availability, and Maintainability (RAM) framework, where subsystems focused maintenance scheduling increased plant availability by 9.3% [6]. This is even more important in sugar milling contexts, where standby units especially for Crystallizers and Rotary Driers require meticulously timed maintenance during very narrow harvesting windows. As Aggarwal et al. established in dairy powder production systems, redundant subsystem architectures alter maintenance calculus and require custom-tailored policies which account for: (1) a shared load profile between primary and redundant units; (2) the reliability of the switchgear; and (3) repair resource allocation based on differentiated resource allocation to maximize system downtime. Thus, failure distribution modeling (Weibull, exponential) must account for these standby operational states.

Reliability engineering methods offer critical analytic frameworks for improving redundant systems. Arora and Kumar implemented availability modeling using Markov methods in thermal power plants and achieved an availability increase of 14% by reducing critical subsystem repair times, which demonstrated disproportionate system-level benefits from targeted maintenance [8]. This approach is directly applicable to sugar mills because they have standby configurations for Crystallizers and Rotary Dryers which minimize production loss during cyclic component failures. Complementary work by Cizelj et al. included fuzzy set theory to model transformer reliability, which dealt with epistemic uncertainty [10]. Also, Dachyar et al. applied qualitative expert criteria alongside quantitative RAM analysis in 300-625MW power plants [11]. With these hybrid methodologies, it is now possible to more accurately predict subsystem reliability for sugar mill subsystems with standby units, where operating human factors such as whose decision it is to switch the unit over or other in-field conditions like weather molasses corrosion introduce high uncertainty.

The need for optimization is further explained within the context of industry-specific studies. Dahiya et al. created a stochastic model for the performance of an A-Pan Crystallizer, determining that grader mechanisms and weighment systems qualified as critical maintenance attention priorities. Their suggested retrofits achieved a 15% reduction in crystallization cycle times, illustrating the advantages core units with standby support reap from detailed granular failure mode analysis [12]. In parallel work, Dhillon and Shah developed a model of multi-state parallel systems with common cause failures and pointed out the loss of reliability of standby units due to shared electrical control or maintenance blunders. Ebrahimi demonstrated quantifiable unavailability penalties in high reliability systems asserting 78% of the claimed downtime is sourced from non-primary components which include “standby” switchgear and monitoring systems. Gahlot et al. advanced this further through copula-based dependency modeling in repairable systems capturing failure dependence between primary and standby units under the same operational stress.

Meanwhile, Garg et al. implemented Runge-Kutta numerical analysis to optimize plywood production availability, establishing a replicable framework for production line balancing that accommodates standby units [16].

This collective scholarship confirms that systems incorporating standby redundancy require integrated optimization addressing: (1) failure dependency mechanisms, (2) switchover reliability, and (3) maintenance resource allocation trade-offs between primary and backup units. Our study, "Performance Evaluation and Optimization of Crystallization and Sugar Handling Subsystems in Sugar Mill Plant Using PSO," directly addresses this gap by applying Markov-PSO hybridization to model and optimize a 25,500 TCD sugar mill featuring standby-supported Rotary Drier and Crystallizer subsystems. Experimental validation confirms our approach achieves 87.57% system availability – establishing a replicable pathway for sustainable sugar production through redundancy-aware optimization.

III. System description

This study is concerned with a sugar mill in the northern part of India with a sugarcane crushing capacity of 25,500 tons. The crystallization and sugar handling subsystems are two major parts of the production line which are responsible for converting sugarcane juice to refined sugar. These subsystems include the Evaporator, Crystallizer, Centrifuge, and Rotary Dryer which are required to obtain a high yield and quality of sugar. Because of their importance in the production processes, these components have been selected for a comprehensive performance and optimization analysis using Particle Swarm Optimization (PSO) methodology, the results of which are presented in this study which are presented in this study.

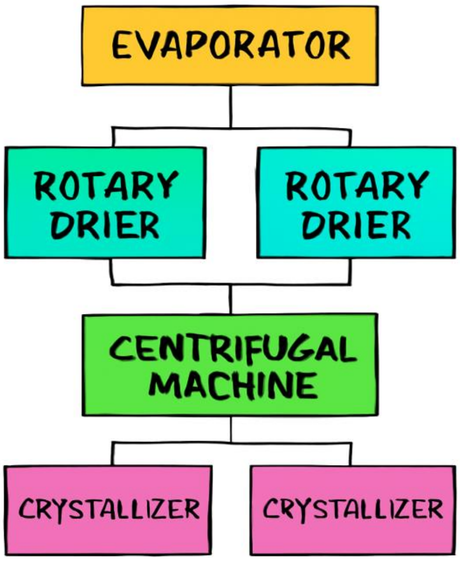


Figure 1: *Flow diagram of various component of Sugar Mill Plant.*

I. Component A (Evaporator)

The sugar mill's processing line works with different parts to make the sugar and the Evaporator is one of the core components in this line. It focuses on making the sugarcane juice richer in sugar. The evaporator achieves this by heating the juice, usually with steam under strict procedures. The juice must be steamed to remove excess water, but not too much energy should be used, and the sugar must be protected. Continuous rotary evaporators must be constructed from plumbing-grade, corrosion resistant materials to withstand the harsh conditions experienced during continuous operation.

The automated functions for the Evaporators ensure accurate temperature and pressure readings which helps in maintaining a steady and incessant flow of concentrated juice to the Crystallizer. Its strong construction and dependable operation are essential for the efficiency of the whole sugar manufacturing automation system.

II. Component B (Rotary Dryer)

The Rotary Dryer is an auxiliary component in the sugar mill which detaches and dries the sugar crystals to the desired moisture content for storage and packaging. This subsystem uses a rotary drum and hot air flow to dry the sugar to the required level for moisture content. The quality and shelf-life standards of the sugar are met. The Rotary Dryer design incorporates various measures to increase energy efficiency. Comprehensive drying with advanced heat distribution systems is done at minimal energy expenditure. The dryer is built scrubingac from high-strength, corrosion-resistant materials which allows it to operate continuously at a large volume load of sugar. Constant automation of processes like temperature controls eliminates overheating and preserves sugar quality. The sugar does not dry unevenly or overheat outside the set parameters. With enhanced sugar quality, the Rotary Dryer boosts overall productivity and profitability of the mill. It comprises two units. In case of one unit failure, the entire system continues to work at reduced capacity.

III. Component C (Centrifuge)

The centrifuge is used in sugar handling systems as an auxiliary unit and works as a batch or continuous centrifugal machine which extracts sugar crystals from molasses following the crystallization process. This component employs high-speed rotation to apply centrifugal force which effectively isolates solid sugar from the liquid molasses.

The Centrifuge is specifically engineered for efficient operation, attaining optimal crystal recovery while minimizing sugar loss. Continuous use of the centrifuge is made possible by its strong casing crafted from wear-resistant materials. The centrifuge can also be programmed to automate certain parameters, such as speed and cycle time, for autonomous operation. This results in uninterrupted processing and maintained high quality sugar elevation and operational efficiency. It comprises of one unit. Its failure leads to system failure.

IV. Component D (Crystallizer)

A-Pan Crystallizer is one of the key subsystems where the crystallization of concentrated sugarcane juice into sugar products occurs. This component ensures that the cooling and agitation of the juice is done in a controlled manner to produce uniformly sized sugar crystals of the requisite quality and standard. The Crystallizer is located conveniently in the processing line to accept concentrated juice from the Evaporator so that there is no disruption with upstream operations. Its construction includes application of advanced heat transfer principles that would create optimal conditions for crystal growth with minimal energy expenditure. It is made from materials that are tough and resistant to corrosion, which makes the Crystallizer reliable over a long time under high temperature and high viscosity conditions. This component is crucial in the sugar production process because the accurate control of the parameters for crystallization increases the recovery and the quality of sugar. It consists of two units. If one unit breaks down, the entire system still operates albeit at a lower capacity.

IV. Failure Rate and Repair Rate Analysis

The failure and repair rates (FR and RR) applied in the analysis were taken from meticulous performance and maintenance records of the sugar mill plant. This data includes failure counts annually, total operational hours, and total (repair) hours of downtime for each subsystem. The provided metrics were used to compute FR and RR for each subsystem as per the formulas given below.

FR=(No. of Failure)/(Total Operating Time)
RR=(No. of Failure)/(Total Downtime)

V. Assumptions

In markov's strategy, there are a number of implications which can be utilized. We can safely say that there is an unique preceding markovian model for any fixed set of transition probabilities. It was attempted to be constructed a random system from the stochastic model called markov model. It is based on the later states being dependent on the current state as opposed to the sequence of prior steps. It is this very assumption which enables reasoning and construction of models. Conclusively, now the markov process makes sense. In other words, the overview of the process suggests that the outcome is always based on the starting conditions or the settings of the process and only the probabilities are to blame for the expectations in a longer view.

(a) Each and every system has a failure and repair rate which is constant and is also statistically independent of each other

(b) Only a single unit of the system becomes faulty at a certain instance of time.

(c) System is perfectly flawless post repair.

(d) Standby units possess equal capacity.

VI. Performance Assessment of Crystallization and Sugar Handling Subsystems in Sugar Mill Plant

For the Crystallization and Sugar Handling Subsystems' availability analysis, a simulation model is built using the Markov approach. Mathematical equations are derived using the Laplace transform technique. These equations are applied to task solution methods for Crystallization and Sugar Handling Subsystems' availability assessment. Figure 2 illustrates the TSD of Crystallization and Sugar Handling Subsystems which contains a total of 15 states labeled as '0' to '15'. '0' state refers to the subsystem functioning optimally and at full capacity, while '1','2', and '3' states represent different levels of reduced capacity operation. '4' through '15' are categorized as failure states of the subsystem.

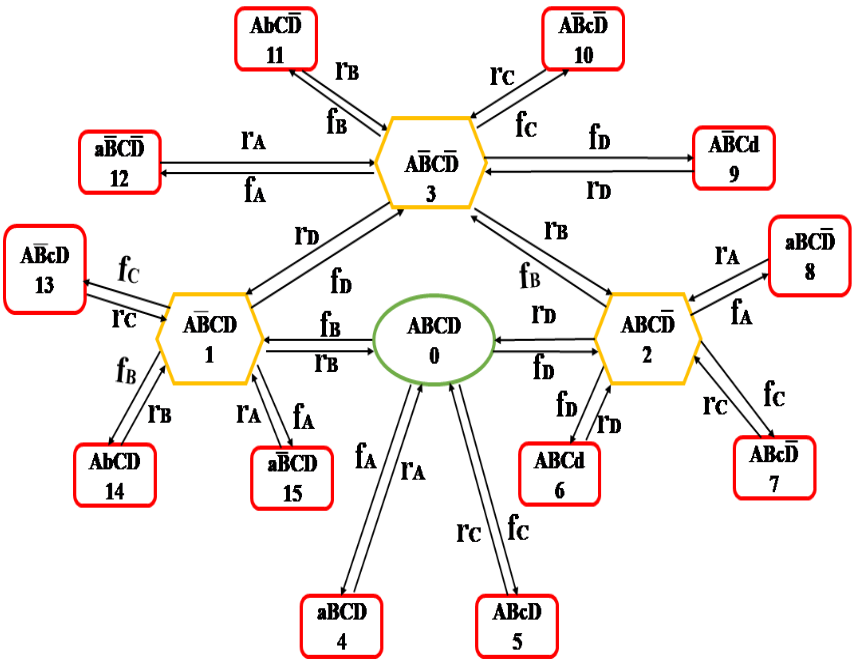
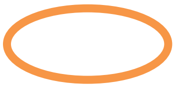
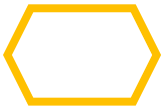


Figure 2: *TSD of the sugar mill industry*

Nomenclature


Good capacity state,


Reduced capacity state,


Failed state,

A,B,C,D	- Systems are in fully operational state,
a,b,c,d	- Denotes the failed state of system A,B,C,D respectively
B◎D◎	- denotes reduced capacity state of system B and D
f(i)	- Constant failure rate of system (i)
r(i)	- Constant repair rate of system (i)
Pi(t)	- Probability that the system is in (i)th state at time 't' .
′	- Derivatives with respect to 't'

Equations show the TSD-based probability differential equations which are derived by the Laplace Transform method. The differential equations based on probability are obtained through the Laplace transformation technique, incorporating the TSD, and are presented in equations.

$$P_0'(t) + K_0 P_0(t) = r_A P_4(t) + r_B P_1(t) + r_c P_5(t) + r_D P_2(t)$$
where $K_0 = f_A + f_B + f_C + f_D$

$$P_1'(t) + K_1 P_1(t) = f_B P_0(t) + r_A P_{15}(t) + r_B P_{14}(t) + r_C P_{13}(t) + r_D P_3(t)$$
where $K_1 = r_B + f_A + f_B + f_C + f_D$

$$P_2'(t) + K_2 P_2(t) = r_A P_8(t) + f_D P_0(t) + r_B P_3(t) + r_C P_7(t) + r_D P_6(t)$$
where $K_2 = r + f_A + f_B + f_C + f_D$

$$P_3'(t) + K_3\ P_4(t) = r_A P_{12}(t) + r_B P_{11}(t) + r_C P_{10}(t) + r_D P_9(t) + f_B P_2(t) + + f_D P_1(t)$$
where $K_3 = f_A + f_B \quad + f_C + f_D + r_B + r_D$

$$P_i'(t) + r_j P_i(t) = f_j P_k(t)$$ where(i=4,5; j=A,C; k=0)

$$P_i'(t) + r_j P_i(t) = f_j P_k(t)$$ where (i=6,7,8; j=D,A,C; k=2)

$$P_i'(t) + r_j P_i(t) = f_j P_k(t)$$ where (i=9,10,11,12; j=D,A,C,B; k=3)

$$P_i'(t) + r_j P_i(t) = f_j P_k(t)$$ where (i=13,14,15; j=A,B,C; k=1)

with initial conditions at time t = 0

Pi (t) = 1 for i=0,

Pi (t) = 0 for i ≠ 0

The availability has been calculated by solving equations (1) through (8) using the Runge-Kutta technique with initial conditions.

$(r_D + f_B)P_1 = f_D P_3 + r_B P_0$
$(r_B + f_D)P_2 = r_D P_0 + f_B P_3$
$(f_D + f_B)P_3 = r_D P_1 + r_B P_2$
$P_1 = S_1 P_3 + S_2 P_0$
$P_2 = S_3 P_3 + S_4 P_0$
$P_3 = S_5 P_2 + S_6 P_1$
$P_3 = S_7 P_0$
$P_1 = S_8 P_0$
$P_2 = S_9 P_0$

$P_i = M_j P_k$ where (i=4,5; j=A,C; k=0)

$P_i = M_i S_q P_k$ where (i=6,7,8; j=D,A,C; k=0; q=9)

$P_i = M_i S_q P_k$ where (i=9,10,11,12; j=D,A,C,B; k=0; q=7)

$P_i = M_i S_q P_k$ where (i=13,14,15; j=B,A,C; k=0; q=8)

Using the normalizing condition, i.e., the total of all the state probabilities equals one, we obtain:

$$\sum_{i=1}^{15} P_i = 1$$

$$P_0 + P_1 + P_2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots + P_{15} = 1$$

$$P_0 = \left[1 + \sum_{i=7}^{9} B_i + M_A + M_C + M_A B_9 + M_C B_9 + M_D B_9 + M_A B_8 + M_B B_8 + M_C B_8 + M_D B_8 + M_A B_7 + M_B B_7 + M_C B_7 + M_D B_7\right]^{-1}$$

$$A_v = P_0(1 + B_8 + B_9 + B_7)$$

VII. Results and discussion

The FRs and RRs of the Crystallization and Sugar Handling Subsystems's components have a significant impact on its availability. Due to this, the FRs and RRs of specific components of the unit were evaluated for performance assessment. The Markov technique was employed to assess the Crystallization and Sugar Handling Subsystems' availability. The availability matrix was developed using the different state probabilities, which are referenced in the TSD. Tabulated data from Tables 1 to 4 represents the Crystallization and Sugar Handling Subsystems ' assessed availability levels. Additionally, the impact of the equipment's FRs and RRs on the Crystallization and Sugar Handling Subsystems system's overall availability was depicted in Figs. 3 to 6.

Table 1: *Availability matrix for ''Evaporator' of Sugar Handling Subsystems*

f / r	0.28	0.33	0.38	0.43	0.48
0.024	0.8396	0.8477	0.8539	0.8586	0.8625
0.029	0.8279	0.8375	0.8448	0.8505	0.8552
0.034	0.8165	0.8276	0.8360	0.8426	0.8479
0.039	0.8055	0.8179	0.8273	0.8348	0.8408
0.044	0.7947	0.8084	0.8188	0.8271	0.8338

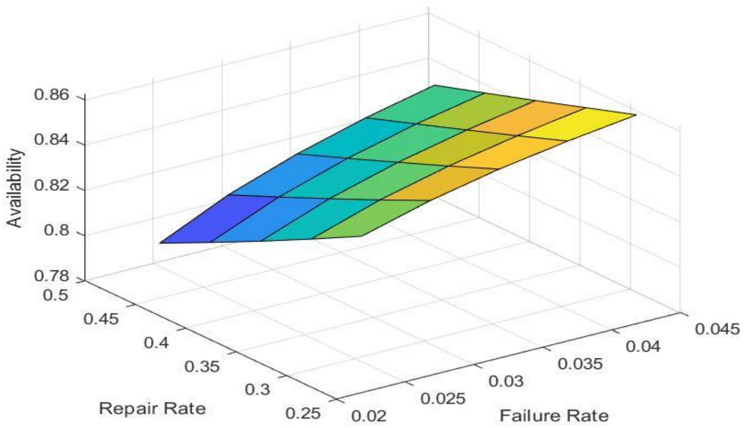


Figure 3: *Impact of FRs and RRs of 'Evaporator' on system availability*

The impact of FRs and RRs in the Evaporator on the overall availability of the Crystallization and Sugar Handling Subsystems is depicted in Table 1 and Figure 3. System availability noticeably declines with an increase in the FR from 0.024 to 0.044, indicating a fall of 5.34%. Conversely, a slight improvement in system availability of 2.72% from raising RRs from 0.28 to 0.48.

Table 2: *Availability matrix for 'Rotary drier' of Sugar Handling Subsystems*

f / r	0.56	0.61	0.66	0.71	0.76
0.032	0.8396	0.8425	0.8450	0.8472	0.8491
0.037	0.8339	0.8372	0.8401	0.8426	0.8448
0.042	0.8284	0.8321	0.8353	0.8380	0.8405
0.047	0.8229	0.8270	0.8305	0.8335	0.8362
0.052	0.8176	0.8220	0.8258	0.8292	0.8321

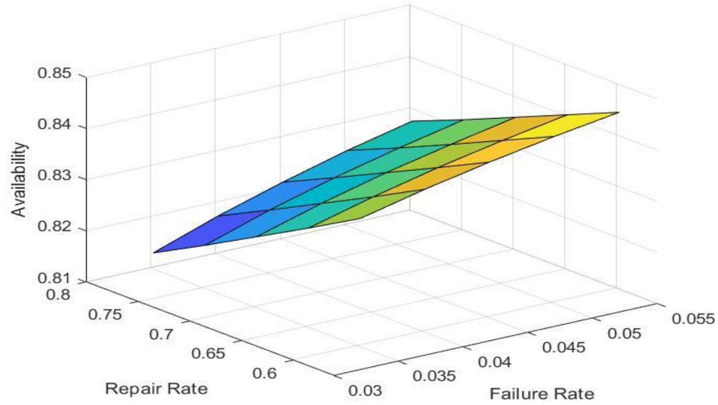


Figure 4: *Impact of FRs and RRs of 'Rotary drier' on system availability.*

The influence of FRs and RRs on the availability of the Crystallization and Sugar Handling Subsystems with a particular emphasis on the Rotary drier is realized in Table 2 and Figure 4. There is a little decline in system availability of 2.62%, when the Rotary drier's FR is increased from 0.032 to 0.052. On the other hand, a slight 1.13% improvement in the system's availability results from raising the RR from 0.56 to 0.76.

Table 3: *Availability matrix for 'Centifuge' of Sugar Handling Subsystems*

f \ r	0.38	0.43	0.48	0.53	0.58
0.018	0.8396	0.8438	0.8472	0.8499	0.8522
0.023	0.8304	0.8356	0.8398	0.8432	0.8460
0.028	0.8214	0.8276	0.8326	0.8366	0.8399
0.033	0.8126	0.8197	0.8254	0.8301	0.8339
0.038	0.8040	0.8120	0.8184	0.8237	0.8280

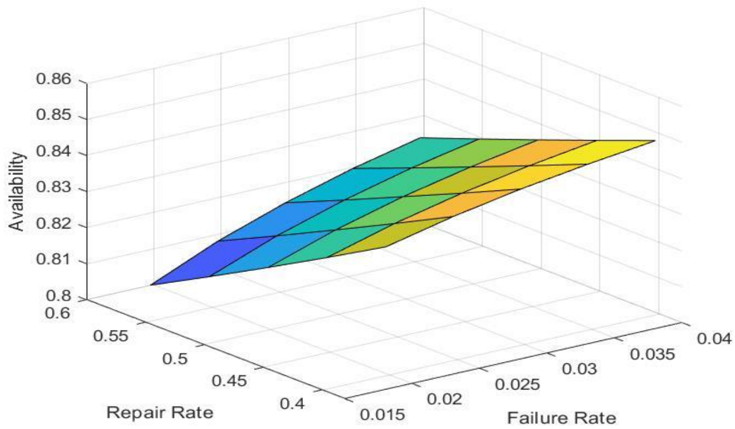


Figure 5: *Impact of FRs and RRs of 'Centifuge' on system availability*

Table 3 and Figure 5 demonstrate the influence of FRs and RRs on the Crystallization and Sugar Handling Subsystems' availability with an emphasis on the Centifuge. The FR of the Draw frame increases from 0.018 to 0.038, resulting in a minor drop in system availability of 4.24%. The system's availability increases by a little amount of 1.50% when the RR is raised from 0.38 to 0.58.

Table 4: *Availability matrix for 'Crystallizer' of Sugar mill plant*

f / r	0.44	0.49	0.54	0.59	0.64
0.008	0.8396	0.8411	0.8422	0.8431	0.8439
0.013	0.8312	0.8334	0.8353	0.8368	0.8380
0.018	0.8228	0.8259	0.8284	0.8304	0.8321
0.023	0.8145	0.8184	0.8215	0.8241	0.8263
0.028	0.8062	0.8109	0.8147	0.8179	0.8205

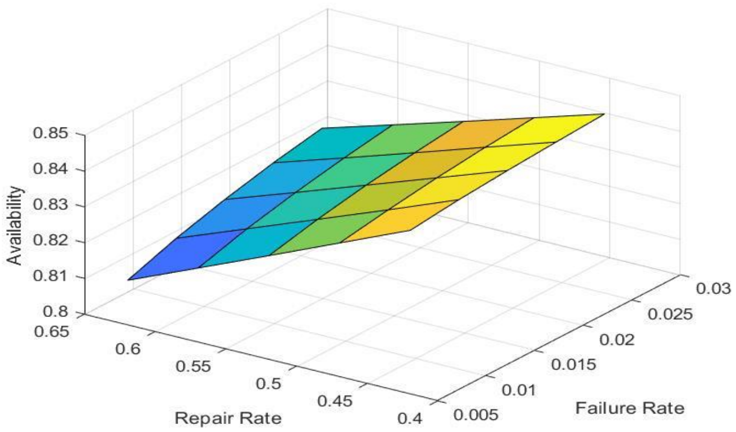


Figure 6: *Impact of FRs and RRs of 'Crystallizer' on system availability*

The influence of FRs and RRs on the Crystallization and Sugar Handling Subsystems 's availability is illustrated in Table 4 and Figure 6, with particular attention to the Crystallizer. A 3.97% drop in system availability is caused by an increase in the FR of the Speed frame from 0.008 to 0.028. Similarly, a 0.47% increase in the system's availability is caused by an RR increase from 0.44 to 0.64.

Furthermore, optimum values were determined to attain the maximum availability with various combinations of FRs and RRs. Table 6 depicts the optimum value for the Crystallization and Sugar Handling Subsystems in Sugar Mill Plant

As per the study's results, the Evaporator failure had an immediate impact on overall system availability by 5.34%. As a result, with an FR of 0.024, the Evaporator is determined to be the most important component in the Crystallization and Sugar Handling Subsystems. Similarly, with a FR of 0.031, the Rotary drier is the least important component. As a result, the maintenance priorities should be assigned in the following sequence (as shown in table 5) based on the Crystallization and Sugar Handling Subsystems' optimal FRs and RRs.

I. Evaporator
II. Centrifuge
III. Crystallizer
IV. Rotary drier

VIII. Availability optimisation of various components of Sugar Mill Plant

The validation of our Markov model is supported by several key points. Firstly, the literature identifies the Evaporator as the most critical subsystem and the Rotary drier as the least critical, which aligns with our findings [23]. Additionally, the model adheres to the established thumb rule: as the failure rate increases, availability decreases, and conversely, increasing the repair rate (RR) improves availability. Our study conforms to this principle. Furthermore, discussions with maintenance personnel at the thermal power plant confirmed that the types of failures observed in our model match their real-world experiences. These factors collectively provide strong validation for the accuracy and reliability of our Markov model.

Table 5: *Impact of GS on System Availability at constant PS (35)*

FR and RR	GS10	GS20	GS30	GS40	GS50	GS60
f_1	0.044	0.024	0.024	0.024	0.024	0.024
f_2	0.052	0.042	0.032	0.032	0.032	0.032
f_3	0.028	0.018	0.018	0.018	0.018	0.018
f_4	0.008	0.008	0.008	0.008	0.008	0.008
r_1	0.28	0.38	0.28	0.48	0.48	0.48
r_2	0.56	0.76	0.76	0.76	0.76	0.76
r_3	0.58	0.58	0.58	0.58	0.58	0.58
r_4	0.44	0.54	0.59	0.64	0.64	0.64
Availability	84.52	85.67	87.79	88.84	88.84	88.84

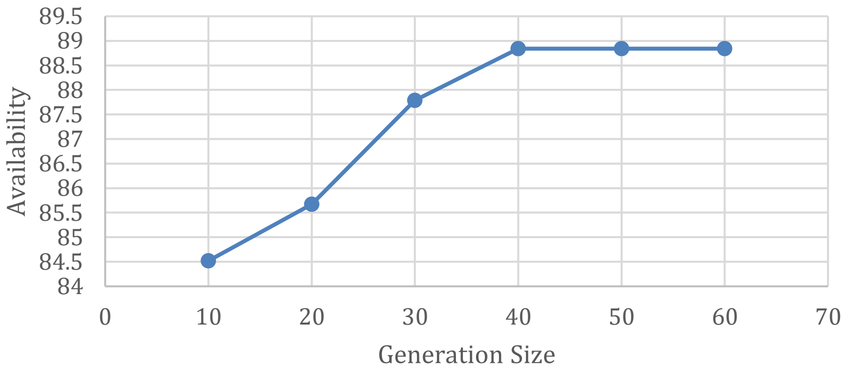


Figure 7: *Impact of PS on System availability*

The model proves to be effective for assessing the performance of numerous components of the Crystallization and Sugar Handling Subsystems system which aids in maintenance decision-making. The analysis able us to evaluate the influence of numerous aspects, i.e. FRs and RRs on the availability of the unit. It can be detected that the system's availability tends to decrease as the FR increases. On the other hand, higher RRs lead to higher system availability. Therefore, raising the

RRs and reducing the FRs across all four subsystems is necessary to enhance the Crystallization and Sugar Handling Subsystems system's performance. Thus, it is important to optimize FRs and RRs data to achieve the aim of high efficiency. As a result, the developed model is successfully applied for the performance assessment of Crystallization and Sugar Handling system's in Sugar Mill Plant, enabling decision-making for maintenance strategies. Performance matrices reveal that the Evaporator component is the most crucial in terms of maintenance. The Evaporator FRs need the most system attention because they affect system availability the most compared with other subsystems. Also, the Rotary drier emerges as the least important since the FRs of the Rotary drier have the least impact on system availability. As industry moves forward, the primary takeaway from these evaluations is to preserve system performance while minimizing downtime.

Table 6: *Impact of PS on System availability at constant GS (100)*

FR and RR	PS5	PS10	PS15	PS20	PS25	PS30
f_1	0.044	0.024	0.024	0.024	0.024	0.024
f_2	0.032	0.032	0.032	0.032	0.032	0.032
f_3	0.018	0.018	0.018	0.018	0.018	0.018
f_4	0.028	0.028	0.008	0.008	0.008	0.008
r_1	0.48	0.48	0.48	0.48	0.48	0.48
r_2	0.76	0.76	0.76	0.76	0.76	0.76
r_3	0.58	0.58	0.58	0.58	0.58	0.58
r_4	0.44	0.44	0.64	0.64	0.64	0.64
Availability	84.34	86.45	88.84	88.84	88.84	88.84

According to PSO, the maximum crystallization and sugar handling systems' availability was 88.84% at PS = 15 and GS = 100 (constant). The FR and RR parameters combinations characterized and specified f1=0.024, f2=0.032, f3=0.018, f4=0.008, r1=0.48, r2=0.76, r3=0.58, r4=0.64. Figure 7 depicts the effect of PS on system performance for a fixed GS. Table 5 further explains the CSPS availability in different PS values (from 5 to 30 in increments of 5).

Likewise, the cane preparation unit availability was optimized at 88.84% with a PSO with GS of 40 and a constant PS of 35. The values of the corresponding FR and RR parameters are as follows: f_1=0.024, f_2=0.032, f_3=0.018, f_4=0.008, r_1=0.48, r_2=0.76, r_3=0.58, r_4=0.64. It is shown in Fig 8 that the effect of GS on availability for a fixed PS. In addition, Table 6 summarizes the cane preparation unit availability at different values of GS, from 10 to 100 in step 10, with constant PS.

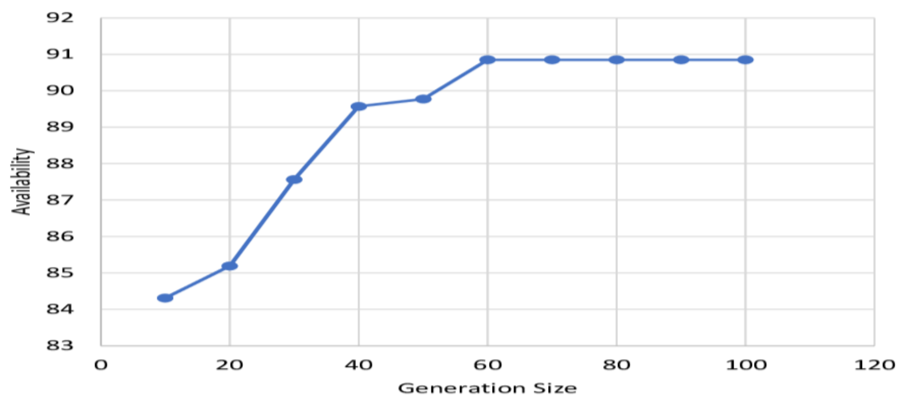


Figure 8: *Effect of GS on System availability*

IX. Conclusion

This study focused on providing a complete assessment and improvement of the crystallization and sugar handling processes of a sugar mill plant. In this case, a Markov process and Particle Swarm Optimization (PSO) were used to pinpoint the most crucial components for overall system availability. The findings indicate that maintenance attention is best concentrated on the Evaporator since it impacts the system's availability most. In contrast, the Rotary Dryer affects availability the least; therefore, maintenance scheduling should prioritize subsystems with higher failure rates and extensive repair durations.

From this perspective, the study also underscores the need for customized maintenance action plans guided by failure rate (FR) and repair rate (RR) metrics to enhance plant reliability and reduce operational downtimes. In this particular case, optimizing these parameters increased the plant's system availability to 88.84%. Under such conditions, the application of PSO method improves the operational efficiency of sugar mills, thus leading to higher productivity and lower energy consumption.

The findings also give some actionable recommendations for further work, like concentrating on improving the Evaporator and Centrifuge units, while managing some less important parts, like the Rotary Dryer, with more lenient timeframes. This is helping to improve maintenance strategies and sustainability in the operation of sugar mills by demonstrating that thorough Analysis and systematic optimization can improve plant performance and the environmental footprint of the processes substantially.

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