OPTIMIZATION AND PERFORMANCE EVALUATION OF SUGAR MILL PLANT MICRO COMPONENTS USING PSO

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Abstract

Sugar mill plants, especially their core processing units, are highly dependent on a well-organized and efficient maintenance strategy for reliable operation. In this study, an availability-based simulation model was developed for a 25,500 TCD sugar mill. This model is based on a Markov-based performance evaluation framework, which uses differential equations to form state-transition diagrams representing transitions between fully operational, partially operational, and failure states. A comparative analysis of the subcomponents studied concluded that a centrifugal pump failure has minimal impact on overall system availability, while a clarification unit failure has the most significant impact. To improve system reliability and performance, the Particle Swarm Optimization (PSO) method was applied to optimize failure and repair rates. The experimental results obtained show that the overall availability of the system after applying the proposed optimization strategy is achieved at 88.57%, which shows effectiveness and practical utility of the model.

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

I. Introduction

The processing systems and millhouse equipment are considered prime units in the sugar mill industry converting raw sugarcane into refined sugar. These units comprise centrifugal pumps, juice heaters, boiler feedwater pumps, and clarifiers, which play a vital role in maintaining efficiency and consistency of production [1]. The centrifugal pumps ensure that the required amount of fluid is circulated throughout the processing cycle to ensure a continuous supply of material in a seamless manner. The efficiency of the grinding process has a great bearing on the juice yield from sugarcane. The obtained juice after grinding is heated to the required temperature by a juice heater and then transported by a boiler feed water pump to the clarifier [2]. Heating up and clarification of the juice properly increases its energy efficiency, enhances juice extraction, and improves the quality of sugar produced. This reduces production wastage significantly, thereby reducing overall costs by manifold [3]. Advanced and energy-efficient equipment not only help in sustaining the quality of refined sugar as per industry standards but also reduce operating costs so that the production sustainable and economically viable. Besides, there would be efficient juice extraction and reduced thermal-fluid waste, thus making production more environment-friendly and sustainable. Reliable

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and durable millhouse equipment helps to ensure continuous mill operation during peak seasons of harvest so that demand in the market is met to maintain a stable and profitable supply chain [4]. Herein, these processes enhance productivity, sustainability and profitability by the satisfaction of these vital objectives in maximizing the functions of the sugar industry, Economical and efficient sustenance of the sugar industry is possible due to these technologies [5].Adhikary et al. (2010) applied a reliability, availability and maintainability framework for general industries; however, a maintenance strategy deployment planning is more advantageous for the process industry. They formulated a subsystem architecture and developed a performance model for a skimmed milk powder processing plant based on exponential repair and failure distributions. In my research, heuristic approaches were performed to determine the optimal maintenance planning policies for the plant [7].

II. Literature review

The Markov type availability assessment was performed on the power and steam generation systems by Arora and Kumar (1997), and they constructed a mathematical model for it. The steam generation system's performance (in terms of availability) improved by 14% when the repair time for its three subsystems was cut from 100 to 50 hours. The power generation system comprised of four subsystems demonstrated 6% improved availability with a repair time reduction from 200 to 50 hours [8]. The Markov approach to evaluate the availability of steam and power generation systems was modeled mathematically by Arora and Kumar (1997). Cutting the repair time of subsystems led to even more improvement of availability of the system by 14%. In the same way, Cizelj et al. (2001) developed a model to evaluate the availability of high-voltage transformers using numerical methods and implemented fuzzy set theory to enhance the reliability of the components. Based on expert opinion and qualitative parameters, Dachyar et al. (2018) devised a maintenance strategy for thermal power plants with coal operation and capacity of 300 to 625 megawatts. The A-Pan crystallization process in sugar manufacturing was modeled mathematically by Dahiya et al. (2019). The grader (C) and weighment and bagging (D) subsystems were ranked as the highest maintenance subsystems The authors recommended retrofitting these subsystems in order to improve system overall performance [12]. Dhillon and Shah (2007) looked into multi state parallel systems considering human error and failure mechanisms to develop appropriate maintenance strategies [13]. Ebrahimi (2003) described the enhanced system unavailability in high-reliability systems and the components which provide such unreliability need to be improved in terms of function time without failure [14]. Gahlot et al. (2018) studied series-configured repairable systems with partial CAP and full CAP, where the failure rates Weibull distributed, including copula-based analysis of dependence structures among system components [15]. Garg et al. (2010) developed a reliability model for the plywood production line and assessed the system availability using the Runge-Kutta method [16].

III. System description

This research is being carried out in a sugar mill located in the northern part of India, which has the capacity of crushing 25,500 tons of sugarcane. The juice preparation subsystem of the sugar cane milling system has several subsystems within the plant and is one of the most important components as shown in figure 1. That is precisely why we have chosen it for an availability analysis which the results are offered in this research.

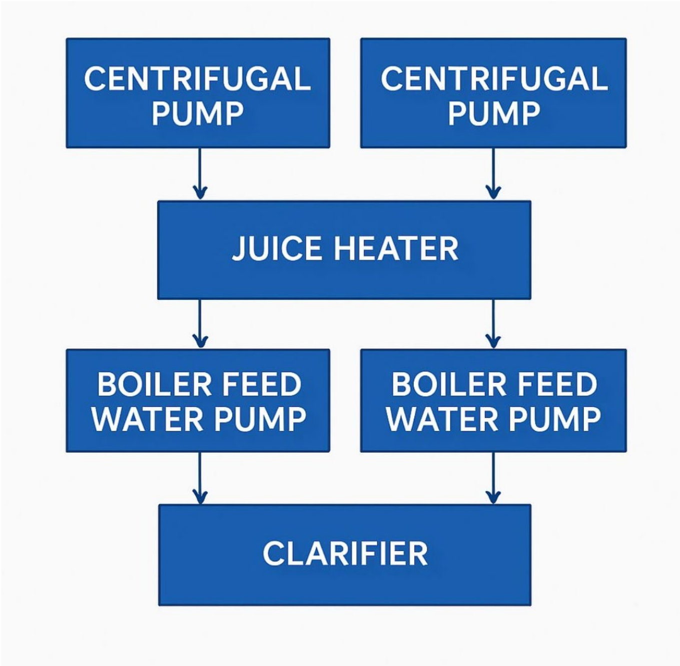


Figure 1: *Illustrative diagram of juice preparation unit.*

I. Centrifugal Pump

The first process of juice preparation is accomplished using a centrifugal pump. It acts as a fluid moving apparatus which brings sugarcane juice from one processing stage to another. Efficient centrifugal pumps handle large volumes of juice, and they greatly smoothen the flow into subsequent processing stages. For greater operational ease, this process can be fully automated which helps maintain a steady supply of juice. Centrally, the objective of a centrifugal pump is to relocate the juice from the place where it is collected initially. It is made up of a primary pump and several other auxiliary parts which are manufactured using quality materials with high resistance to wear as well as high strength. The centrifugal pump includes a standby unit. Unit failure is not attributed to the centrifugal pump.

II. Juice heater

After transferring the sugarcane juice, it is subjected to heating processes. The heater increases the temperature of the juice for processing and improving extraction efficiency. In most cases, it is placed along the section of the juice line so that the head of the juice is optimally heated. The design of the heater allows the receipt of sufficient heat without loss of effectiveness. The juice heater serves primarily as a temperature regulating device so that the clarifier is properly supplied with steam for heating. Made from best grade materials, its resistance to corrosion is superb. The juice heater prevents any delays during the processing and uniformity needed during heating will increase the quality of the juice during extraction. The juice heater does not include a standby unit. Unit failure is attributed to the juice heater.

III. Boiler feed water pump

Water under the required working conditions is delivered smoothly to the juice heater through a boiler feed water pump. Since operations on juice are being processed, the pump works in such a way that water can be supplied in the right amount for proper temperature within the heater. The pump controls flow and guarantees the operation of the juice heater efficiently without wastage. Well-catered water supply has to be maintained towards the juice heater to enhance efficiency and quality during processing. The boiler feed water pump consists of standby units. The boiler feed water pump does not cause unit failure.

IV. Clarifier

The clarifier serves as a particular apparatus within the sugar industry that clarifies sugarcane juice. The sugarcane juice contains certain impurities and the clarifier attempts to separate solids and different forms of contaminants emanating from the sugarcane. This leads to an improved quality of juice which can be processed even further. Clarified juice helps in maximizing the quantity of sugar that can be extracted from sugarcane. The complete line for processing sugar cane juice is made up of the following: centrifugal pump, juice heater, boiler feed water pump, and clarifier. These components ensure the effective preparation and purification of juice. The clarifier does not have a standby unit. Unit failure is caused by the clarifier.

IV. Assumptions

The Markov assumption has several important implications that can be used in system analysis and modeling. It is straightforward to assume that a unique predictable Markovian structure exists for the system, based on a fixed set of transition probabilities. A Markov model is a stochastic model used to understand the behavior of a random system in which future states depend only on the current state, not on the sequence of previous states. This assumption provides a strong foundation for model construction and analysis. As a result, the form of a Markov process is unambiguous—that is, the behavior of the process is completely governed by the initial conditions and their associated transition probabilities. Expected outcomes in the long run depend on these probabilities. The following assumptions are adopted in this study:

(a) The failure and repair rates of each subsystem are constant and assumed to be statistically independent of each other.

(b) Only one unit is assumed to be out of order at any given time.

(c) Assuming the system is "as good as new" upon completion of repairs, it is assumed to function flawlessly.

(d) All standby units are assumed to have the same capacity and performance characteristics.

V. Performance Evaluation

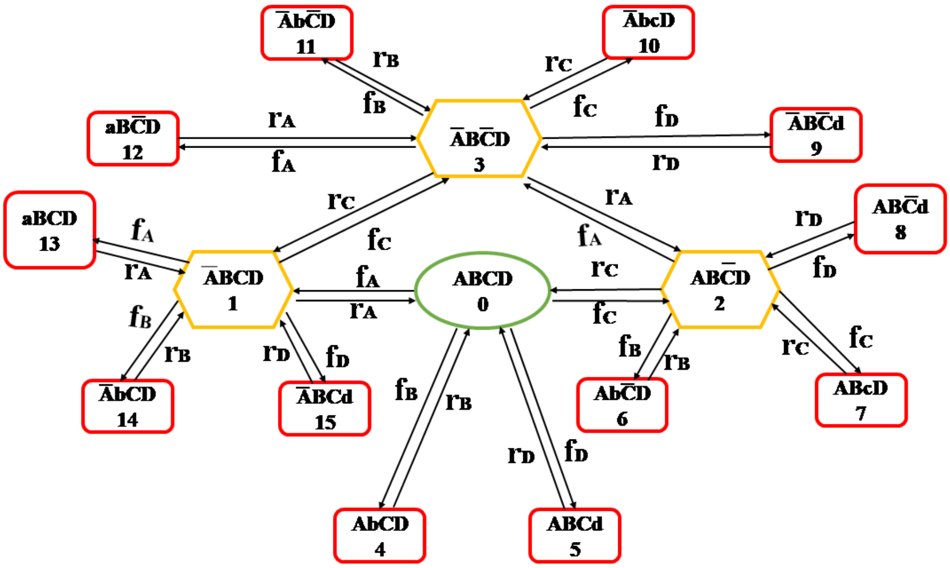
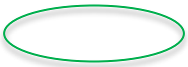


Figure 2: *TSD of the sugar mill industry*

Nomenclature



Full-capacity operating state,

Reduced capacity state,

Failed state

A,B,C,D	- Components operating in a healthy or fully functional condition.
a,b,c,d	- Represents the failed state of components A, B, C, and D, respectively
$\bar{A}\bar{C}$	- Indicates that components A and C are functioning in a reduced-capacity or degraded state
f(i)	- Mean fixed FR
r(i)	- Mean fixed RR
Pi(t)	- Probability that at time 't', the system is in its state.
′	- Derivatives concerning 't'

The probability-based differential equations, formulated via Laplace transformation and the TSD shown in figure 2, are shown in the following equations:

$$P_0'(t) + (f_A + f_B + f_C + f_D)P_0(t) = r_A P_1(t) + r_B P_4(t) + r_D P_5(t) + r_C P_2(t)$$
$$P_1'(t) + (r_A + f_A + f_B + f_C + f_D)P_1(t) = f_A P_0(t) + r_A P_{13}(t) + r_B P_{14}(t) + r_C P_3(t) + r_D P_{15}(t)$$

$P_2'(t) + (r_C + f_A + f_B + f_C + f_D)P_2(t) = f_C P_0(t) + r_A P_3(t) + r_B P_6(t) + r_C P_7(t) + r_D P_8(t)$
$P_3'(t) + (f_A + f_B + f_C + f_D + r_A + r_C)P_4(t) = r_A P_{12}(t) + r_B P_{11}(t) + r_C P_{10}(t) + r_D P_9(t) + f_A P_2(t) + f_C P_1(t)$
$P_4'(t) + r_B P_4(t) = f_B P_0(t)$
$P_5'(t) + r_D P_5(t) = f_D P_0(t)$
$P_6'(t) + r_B P_6(t) = f_B P_2(t)$
$P_7'(t) + r_C P_7(t) = f_C P_2(t)$
$P_8'(t) + r_D P_8(t) = f_D P_2(t)$
$P_9'(t) + r_D P_9(t) = f_D P_3(t)$
$P_{10}'(t) + r_C P_{10}(t) = f_C P_3(t)$
$P_{11}'(t) + r_B P_{11}(t) = f_B P_3(t)$
$P_{12}'(t) + r_A P_{12}(t) = f_A P_3(t)$
$P_{13}'(t) + r_A P_{13}(t) = f_A P_1(t)$
$P_{14}'(t) + r_B P_{14}(t) = f_B P_1(t)$
$P_{15}'(t) + \mathrm{r} P_{15}(t) = f_D P_1(t)$

with initial conditions at time t = 0
Pi (t) = 1 for i=0,
Pi (t) = 0 for i ≠ 0
System availability was determined by solving equations (1)–(8) using the Runge-Kutta method, applying the specified initial conditions.
$(f_C + r_B)P_1 = f_A P_0 + r_C P_3$
$(f_A + r_C)P_2 = f_C P_0 + r_A P_3$
$(r_A + r_C)P_3 = f_C P_1 + f_A P_2$

$P_1 = S_1 P_0 + S_2 P_3$
$P_2 = S_3 P_0 + S_4 P_3$
$P_3 = S_5 P_2 + S_6 P_1$
$P_1 = S_8 P_0$
$P_2 = S_9 P_0$
$P_3 = S_7 P_0$
$P_4 = M_B P_0$
$P_5 = M_D P_0$
$P_6 = M_B S_9 P_0$
$P_7 = M_C S_9 P_0$
$P_8 = M_D S_9 P_0$
$P_9 = M_D S_7 P_0$
$P_{10} = M_C S_7 P_0$
$P_{11} = M_B S_7 P_0$
$P_{12} = M_A S_7 P_0$
$P_{13} = M_A S_8 P_0$
$P_{14} = M_B S_8 P_0$
$P_{15} = M_D S_8 P_0$

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

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

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

$$P_0(1 + S_8 + S_9 + S_7 + M_B + M_D + M_B S_9 + M_C S_9 + M_D S_9 + M_D S_7 + M_C S_7 + M_B S_7 + M_A S_7 + M_A S_8 + M_B S_8 + M_D S_8) = 1$$

$$P_0 = \frac{1}{1 + S_8 + S_9 + S_7 + M_B + M_D + M_B S_9 + M_C S_9 + M_D S_9 + M_D S_7 + M_C S_7 + M_B S_7 + M_A S_7 + M_A S_8 + M_B S_8 + M_D S_8}$$

$$A_v = P_0 + P_1 + P_2 + P_3$$
$$A_v = P_0(1 + S_8 + S_9 + S_7)$$

$$A_v = \left(\frac{1}{1 + S_8 + S_9 + S_7 + M_B + M_D + M_B S_9 + M_C S_9 + M_D S_9 + M_D S_7 + M_C S_7 + M_B S_7 + M_A S_7 + M_A S_8 + M_B S_8 + M_D S_8} \right) (1 + S_8 + S_9 + S_7)$$

VI. Results and discussion

The ultimate availability concerning the scope of juice preparation was reviewed using the Markov method. A TSD generated an availability matrix encompassing various state probabilities. Probabilities were computed, and results from Fig. 3 to 6 reflect the relation between FR and RR of the equipment and the overall availability of the juice preparation unit.

Table 1: *Availability matrix for 'Centrifugal Pump' of sugar mill plant*

f / r	0.0015	0.0020	0.0025	0.0030	0.0035
.018	.8059	.8044	.8022	.7992	.7955
.023	.8068	.8059	.8044	.8022	.7995
.028	.8073	.8068	.8057	.8041	.8019
.033	.8077	.8074	.8066	.8053	.8036
.038	.8079	.8078	.8072	.8062	.8048

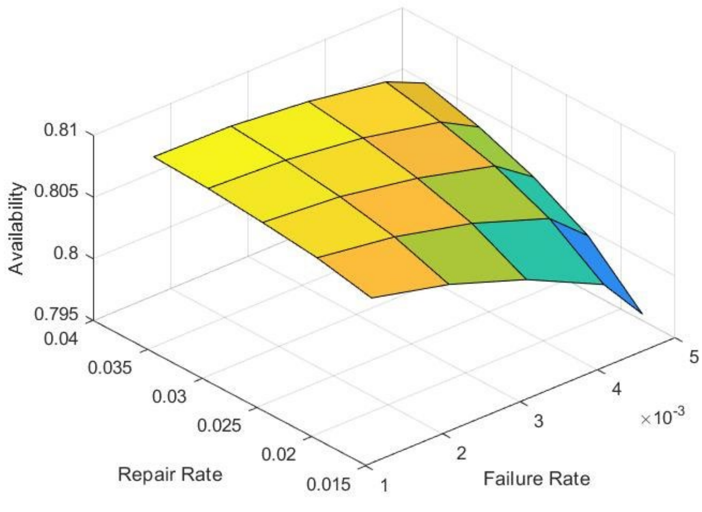


Figure 3: *System Availability vs. Centrifugal Pump FRs and RRs*

Examining the centrifugal pump's FRs and RRs From Table 1 and Fig 3, it is evident how these variables impact the total sum of juice preparation unit availability. System availability drops when the FR rises, but this increase has limitations; in FRs of 0.0015 cut back system dependency, but with a higher FR cap of 0.0050, the system faced an 1.29 % drop yield on dependency. Increasing RR from 0.018 to 0.038 leads to improved unavailability curve performance by slightly aiding dependency by 0.25% but not significantly.

Table 2: *Availability matrix for 'Juice Heater' of sugar mill plant*

f / r	.0020	.0025	.0030	.0035	.0040
.040	.8059	.7939	.7807	.7687	.7571
.050	.8150	.8040	.7934	.7831	.7730
.060	.8216	.8121	.8027	.7936	.7847
.070	.8266	.8182	.8099	.8018	.7938
.080	.8306	.8230	.8155	.8082	.8010

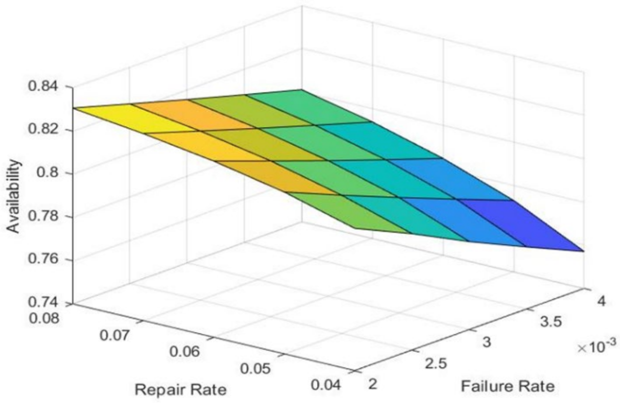


Figure 4: *System Availability vs. Juice Heater FRs and RRs.*

In the case of the juice heater, Table 2 and Fig. 4 capture the interplay of FRs and RRs with respect to the equipment availability from system FR availability perspective. System availability drops by 6.05% when the juice heater FR is increased from 0.0020 to 0.0040. System availability improves by 3.06% when the RR is elevated from 0.040 to 0.080.

Table 3: *Availability matrix for 'Boiler Feed Water Pump' of 'Sugar mill plant'*

f / r	.0025	.0030	.0035	.0040	.0045
.011	.8059	.7935	.7796	.7643	.7480
.016	.8210	.8145	.8071	.7988	.7837
.021	.8271	.8232	.8186	.8134	.8077
.026	.8302	.8275	.8244	.8209	.8170
.031	.8319	.8300	.8278	.8253	.8224

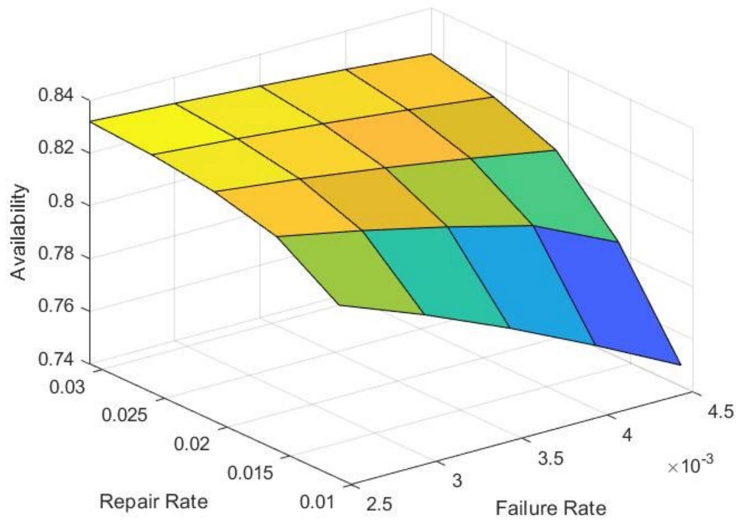


Figure 5: *System Availability vs. Boiler Feed Water Pump FRs and RRs*

The influence of FRs and RRs on the boiler feed-water pump with respect to juice preparation unit availability is illustrated in Table 3 and Fig. 5. An increase in the boiler feed water pump's FR from 0.0025 to 0.0045 causes a reduction in system availability by 7.18%. The availability of the system increases by 3.23% when the RR is increased from 0.011 to 0.031.

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

f / r	.0030	.0035	.0040	.0045	.0050
.027	.8059	.7940	.7825	.7713	.7605
.032	.8173	.8070	.7970	.7872	.7776
.037	.8259	.8168	.8078	.7991	.7906
.042	.8325	.8243	.8168	.8085	.8008
.047	.8378	.8304	.8231	.8160	.8090

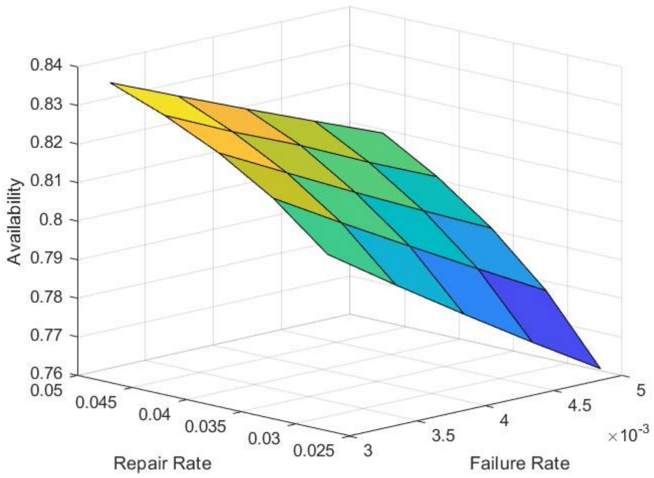


Figure 6: *System Availability vs. Clarifier FRs and RRs*

With relation to the clarifier, table 4 and figure 6 describe the effect of FRs and RRs on the juice preparation unit availability. Raising the clarifier's FR from 0.0030 to 0.0050 causes system availability to fall by 5.63%. Moreover, rising the RR from 0.027 to 0.047 wrings a further 3.96% gain in system availability.

The clarifier failure caused a reduction on system availability by 2.62%, which indicates that the clarifier is the most critical component in the juice preparation unit with a failure rate (FR) of 0.0020. The centrifugal pump was noted as having the lowest FR of 0.0015. Clearly, the identified FRs and RRs for the juice preparation unit need to set the maintenance priorities.

I. Clarifier
II. Juice Heater
III. Boiler Feed Water Pump
IV. Centrifugal Pump

VII. Optimisation

In this particular case, the availability of the juice preparation unit is enhanced through the use of PSO algorithms. The goal of the optimization is to maximize the system's efficiency by appropriately tuning FR and RR values, which are certain constraints of the system. Performance evaluation of the system's different parts is done (operational assessment) and optimization performed by changing the population size (PS) and generation size (GS). In PSO, inspired by birds' flocking behaviors, individuals of a population update their velocity and position based on personal history as well as the surrounding particles while optimization is taking place. The essence of it is how to frame a problem and simulation set-up for optimization. "Particle" is the term used to describe a potential solution together with its fitness in the PSO model. Particles are the agents that move through the solution space – computational domain representing the problem – whose effectiveness is evaluated by an objective function/value measure constructed for that purpose.

Positions and velocities of the particles are altered relative to the best known solution based on their own feedback and the feedback from their neighbors. Hence they need to come together and synchronize at the same area/region in search of the best Global optimum particle swarm optimization (PSO) particle.

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

FR and RR	GS10	GS20	GS30	GS40	GS50	GS60
f_1	0.0035	0.0025	0.0025	0.0015	0.0015	0.0015
f_2	0.0040	0.0030	0.0020	0.0020	0.0020	0.0020
f_3	0.0045	0.0035	0.0030	0.0025	0.0025	0.0025
f_4	0.0050	0.0045	0.0035	0.0030	0.0030	0.0030
r_1	0.018	0.018	0.028	0.038	0.038	0.038
r_2	0.040	0.050	0.080	0.080	0.080	0.080
r_3	0.011	0.021	0.021	0.031	0.031	0.031
r_4	0.027	0.032	0.042	0.047	0.047	0.047
Availability	82.28	86.02	88.56	88.57	88.57	88.57

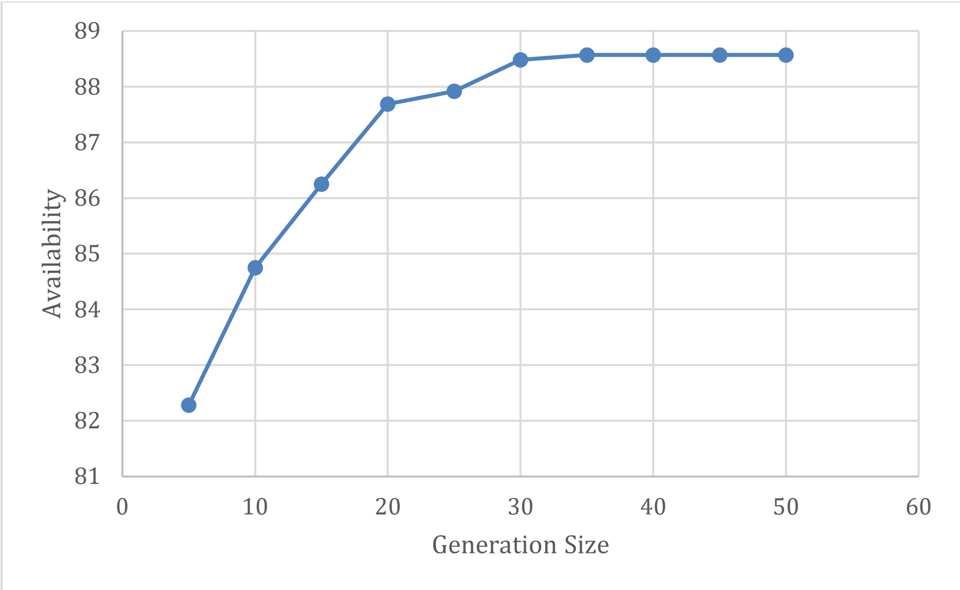


Figure 7: *Impact of GS on System availability*

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

FR and RR	PS5	PS10	PS15	PS20	PS25	PS30	PS35	PS40	PS45	PS50
f_1	0.0035	0.0025	0.0025	0.0025	0.0015	0.0015	0.0015	0.0015	0.0015	0.0015
f_2	0.0040	0.0030	0.0030	0.0030	0.0030	0.0020	0.0020	0.0020	0.0020	0.0020
f_3	0.0045	0.0035	0.0035	0.0035	0.0025	0.0025	0.0025	0.0025	0.0025	0.0025
f_4	0.0050	0.0040	0.0040	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030	0.0030
r_1	0.018	0.028	0.028	0.028	0.028	0.038	0.038	0.038	0.038	0.038
r_2	0.040	0.050	0.060	0.060	0.060	0.080	0.080	0.080	0.080	0.080
r_3	0.011	0.021	0.021	0.021	0.031	0.031	0.031	0.031	0.031	0.031
r_4	0.027	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047	0.047
Availability	82.28	84.75	86.25	87.69	87.92	88.48	88.57	88.57	88.57	88.57

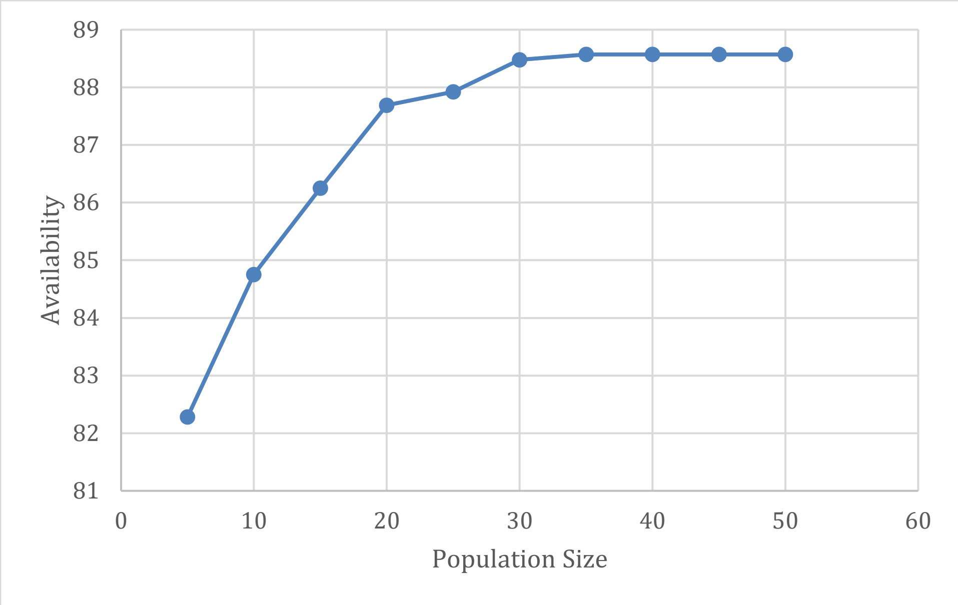


Figure 8: *Effect of PS on System availability*

As stated with PSO, the availability of sugar mills micro components' as PSO with GS = 40, PS = 15, was optimized at 88.57%. The values of the corresponding FR and RR parameters are as follows: f1=0.0015, f2=0.0020, f3=0.0025, f4=0.0030, r1=0.038, r2=0.080, r3=0.031, r4=0.047. Impressive results are shown in Fig 11 where the availability against PS is plotted with variable GS. Concurrently, the summarized available data appears in Table 5 where the corresponding values of GS are displayed from 10 to 60 in step 6, with constant PS. Concurrently, the summarized available data appears in Table 6 where the corresponding values of PS are displayed from 5 to 50 in step 10, with constant GS.

VIII. Conclusion

The purpose of this research is to analyze the micro components of a sugar mill within the sugar industry. The most important part is Clarifier, which must receive attention first or else it will lead to failed systems. The Centrifugal Pump is the least important, and maintenance is performed less often and at lesser costs. A Decision Support System (DSS) model is proposed which should enhance operational efficiency by considerable margins. This research assists maintenance engineers in determining order of importance for repair to physical resources by evaluating subsystem failure criticality. Analysis of failure and repair rates along with optimal performability level determines maintenance planning policy for plant management. The best solution is determined as the configuration with the highest availability determined using the PSO algorithm.

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