Performance Modeling and Availability Analysis of Cane Juice Extraction System of A Sugar Industry

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Abstract-This paper discusses the performance modeling and availability analysis of Cane Juice Extraction System of Sugar Industry. The Sugar Industry is a complex and repairable engineering system. Cane Juice Extraction System of Sugar Industry consist of five subsystems arranged in series configuration. The failure and repair rates of each subsystems are assumed to be constant. For performance modeling and analysis of availability, a performance evaluating model has been developed with the help of mathematical formulation based on Markov Modeling. The differential equations have been developed on the basis of Probabilistic Approach using a Transition diagram. These equations have further been solved using normalizing condition in order to develop the steady state availability, a performance measure of the system concerned. The effect of repair rate on most vulnerable items of the system is examined to realize the highest level of performance. Increase in availability of system confers many benefits such as more profit, improved delivery performance and reduced lead times. The findings of this paper are therefore, considered to be useful for the analysis of availability and determination of the best possible maintenance strategies which can be implemented in future to enhance the system performance.

Keywords-Availability Analysis, Markov Process, Performance Modeling, Steady State Availability.

I. INTRODUCTION

Reliability has always been an important aspect in the assessment of industrial products and/or equipment. With the emerging demand of automation in the various industrial segments, the high capital investment is required for installing the production plants especially process plants like chemical, sugar, beverage, thermal, paper and fertilizers etc. It is essential to have high productivity and maximum profit from process plants for their survival. To achieve this end, availability and reliability of equipment in process must be maintained at the highest order. Further the failure is a random phenomenon, always associated with the operating state of any physical system and its causes are either deterioration in the components of the system and/or man handling errors. Therefore the main concern is to maintain system performance measures such as reliability and availability to achieve high profit goals and productivity in regard to system failures. These measures are considered as most significant factor associated with non - repairable and repairable system, respectively. Now a days industries are becoming quite complex in structure due to the advancement in the technology and therefore it is a difficult job for plant personnel/system analyst to decide proper maintenance policy. By properly designing the system, the factor such as performance, quality, productivity and profit can easily be enhanced up to desired goal of demand. While designing, it is convenient to demonstrate the system behaviour among its units having varying failure and repair policies. Hence the job of plant personnel or system analyst is to examine, specify and determine the system behaviour so that the acceptable choice of components will assist in increasing the efficiency of the system.

II. LITERATURE REVIEW

In the Literature various techniques have been used to analyze the behaviour of systems and find their reliability, availability and maintainability. Ashish and Krishna (2012) discussed the reliability analyses of Programmable Logic Controller (PLC) system based on Markov model. The author conclude through quantitative analysis and case study that the Markov model is good in evaluating the reliability of hot standby repairable system. Carazas et al. (2011) presented a method for reliability and availability evaluation of Heat Recovery Steam Generator (HRSGs) installed in combined cycle gas and steam turbine power plant. The availability and reliability of the HRSGs presented in the study reflect on-site behaviour, including the effect of changes in feed water system maintenance policy. Dekker and Groenendijk (1995) discussed the importance of various analytical and simulation technique for availability modeling and effective assessment of continuous production system with main objective of economic optimization. Gupta (2009) presented a simulated model and performance evaluation of ash handling unit of a steam power plant by making a performance analysis and modeling using probability theory and Markov birth-death process. Kapil and Sanjay (2014) developed the performance analysis of a ball mill system in a process industry. The

Markov birth-death process has been used to generate differential equations which were further solved for steady state availability. Khanduja et al. (2010) described the mathematical modeling and performance optimization for paper making system in a paper plant using genetic algorithm. The mathematical formulation of the problem was done using probabilistic approach and differential equations are developed based on Markov birth-death process. Pervaiz and Uduman (2014) reported mathematical modeling and performance analysis of stock preparation unit in a paper plant. Differential equations had been derived based on Markov birth-death process using probabilistic approach. Sunil Kadiyan et al. (2013) reported the availability analysis of Empty Bottle Inspection system in a process industry. Using Markov birth-death process, the probabilities of the system were determined. The decision matrix were developed using MATLAB programming. Sanjeev et al. (2009) studied the performance evaluation and availability analysis of ammonia synthesis unit of fertilizer plant. A performance evaluating model had been developed with the help of mathematical formulation based on Markov process using probabilistic approach. Tewari et al. (2013) discussed the performance modeling and availability analysis of yarn dyeing system of a textile industry. For the evaluation of performance and analysis of availability, a performance evaluating model had been developed with the help of mathematical formulation based on Markov process using probabilistic approach.

This paper analyzes the Cane Juice Extraction System (part of Sugar Manufacturing Industry, situated in Ajnala, Punjab India) for its steady state behaviour. In this paper a subsystem of the plant, which is a continuous production system, is considered and the availability analysis of the complex mechanical system under preemptive resume priority repair is carried out Laplace Transform is used for solving differential equations to obtain steady state probabilities. Numerical results based upon true data collected from industry are presented to illustrate the steady state behaviour of the system under different plant condition.

III. SYSTEM DESCRIPTION

The process flow diagram of Cane Juice Extraction System of a Sugar Industry is shown in Figure1. It consists of five sub-systems as described below:

A. Cane Milling/Crushing unit (M)

The manufacturing of Sugar begins when harvested cane is received at the mill gate, after which cane is weighed on the platform type weighbridges. Cane is weighed using an electronic weighbridges and unloaded into cane carriers. It is then prepared for milling by knives and shredders. A mill can refer to a factory that processes sugar cane to produce raw or white sugar. It can also mean the piece of equipment that crushes the sticks of sugarcane to extract the juice. The dry pulpy residue left after the extraction of juice from sugarcane is called bagasse. It is used as a biofuel.

B. Juice Heating Unit (H)

The juice extracted by mills is measured by juice flow system. The measured juice is heated in juice heater. The juice is heated by vapours from fourth and third bodies of evaporators in different heaters. This heating is called primary heating.

C. Juice Liming and Sulphitation Unit (S)

The heated juice is treated with milk of lime and sulphur dioxide to coagulate maximum impurities and sent for secondary heating. The secondary heating is done withvapours from the second body of evaporators and vapours from the first body or exhaust steam. The juice are treated simultaneously with milk of lime (Cao) and sulphur dioxide (by air forced through sulphur furnaces) after which the juice is transferred to an open boiling pan and quickly heated to 90°c or above. The lime and heat treatment form a heavy precipitants that flocculates carrying with it most of the suspended impurities in juice.

D. Clarifier Unit (C)

The treated juice is passed to clarifier, where in clear juice is removed from the top and settled mud at the bottom is suspended. To extract sugar from mud, it is taken to vacuum filter in which juice and filter cake are separated. Juice is taken back to process and the mud is disposed as a solid waste.

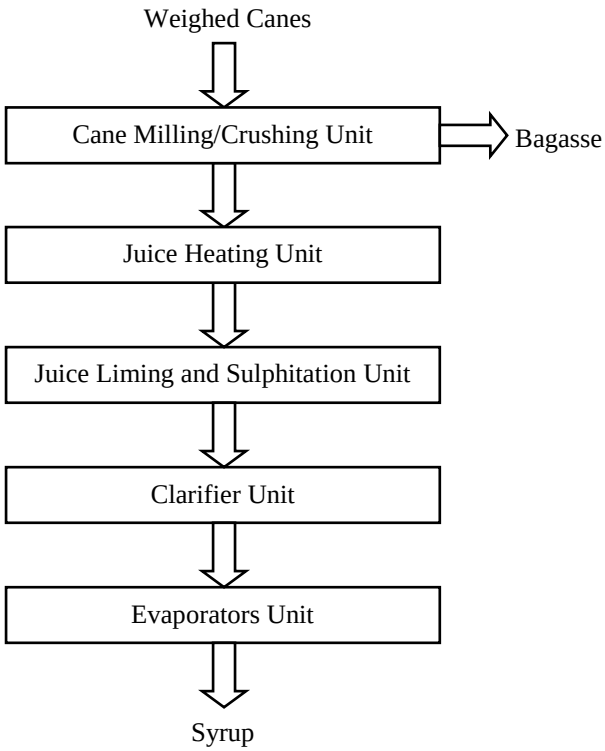

Fig 1: Process flow Diagram

E. Evaporators unit (E)

Clear juice from clarifier is taken to evaporators for evaporating its water content. Evaporator stations consist of a series of evaporators, termed multiple effect evaporators. Steam from large boilers is used to heat the first evaporator and steam from the water evaporated in the first evaporator is used to heat the second evaporator. This heat transfer process continuous through the five evaporator and as the temperature decreases (due to heat loss) from evaporator to evaporator, the pressure inside each evaporator also decrease which allows the juice to boil at lower temperature in the subsequent evaporator. The evaporator station in cane sugar manufacture typically produces a syrup with about 65% solids and 35% water. The juice after evaporation is called syrup.

IV. NOTATIONS

: Indicates the system working at full capacity

:Indicates the system in failed condition.

Subsystem (M): Cane Milling/Crushing unit subjected to major failure only.

Subsystem (H) :Juice Heating Unit subjected to major failure only.

Subsystem (S):Juice Liming and Sulphitation unit subjected to major failure only.

Subsystem (C) : Clarifier Unit subjected to major failure only.

Subsystem(E):Evaporators Units subjected to major failures only

λ_i: Failure rates of M, H, S, C, E Units (i=1,2,3,4,5).

μ_i: Repair rate of M, H, S, C, E Units (i=1,2,3,4,5).

o:Indicates components/sub-system is operative.

r: Indicates components/sub-system is under repair.

g:Indicates components/subsystem is worKing in good condition.

q^r: Indicates components/sub-system is in queue for repair.

$P_i(t)$: State probability that the system is in i^{th} state at time t.

s : Laplace transform variable

Dash(′) : Represent derivatives w,r,t ‘t’

V. ASSUMPTIONS

i. All the sub-systems are initially operating.

ii. All the sub-systems are initially in good condition.

iii. Each unit has two states viz, good and failed.

iv. It is also assumed that there is only one repair facility and priority will be given to the sub-systems M, H, S, C, E for repair activity.

v. Each unit is as good as new after repair.

vi. The failure rates and repair rates of all units are taken constant.

vii. Failure and repair events are statistically independent.

VI. PERFORMANCE ANALYSIS OF THE SYSTEM

Probability consideration gives the following differential equations associated with the state transition diagram as shown in figure 2.

$P_0'(t) + \alpha_1 P_0(t) = \mu_1 P_1(t) + \mu_2 P_2(t) + \mu_3 P_3(t) + \mu_4 P_4(t) + \mu_5 P_5(t)$

Where $\alpha_1 = \lambda_1 + \lambda_2 + \lambda_3 + \lambda_4 + \lambda_5$

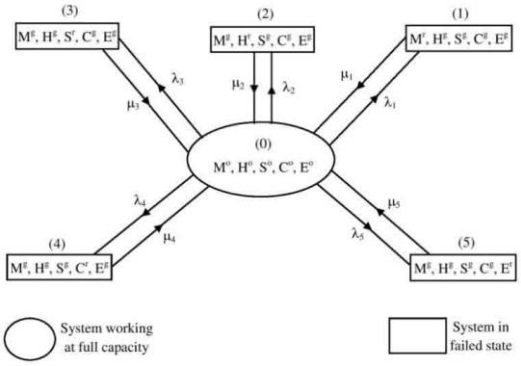

Fig: 2 Transition Diagram of Cane Juice Extraction System

$P_1'(t) + \mu_1 P_1(t) = \lambda_1 P_0(t)$

$P_2'(t) + \mu_2 P_2(t) = \lambda_2 P_0(t)$

$P_3'(t) + \mu_3 P_3(t) = \lambda_3 P_0(t)$

$P_4'(t) + \mu_4 P_4(t) = \lambda_4 P_0(t)$

$P_5'(t) + \mu_5 P_5(t) = \lambda_5 P_0(t)$

With Initial conditions at time t = 0

$P_i(t) = 1$ for $i = 1$

$P_i(t) = 0$ for $i \neq 0$

Solutions of equations

Taking Laplace transform of the above equations

$$sP_0(s) + \alpha_1 P_0(s) = \mu_1 P_1(s) + \mu_2 P_2(s) + \mu_3 P_3(s) + \mu_4 P_4(s) + \mu_5 P_5(s) \quad (1)$$

$$sP_1(s) + \mu_1 P_1(s) = \lambda_1 P_0(s) \quad (2)$$

$$sP_2(s) + \mu_2 P_2(s) = \lambda_2 P_0(s) \quad (3)$$

$$sP_3(s) + \mu_3 P_3(s) = \lambda_3 P_0(s) \quad (4)$$

$$sP_4(s) + \mu_4 P_4(s) = \lambda_4 P_0(s) \quad (5)$$

$sP_5(s) + \mu_5 P_5(s) = \lambda_5 P_0(s)$ (6)

Solving equations (2), (3), (4), (5), (6) we get

$P_1(s) = \frac{\lambda_1}{(s+\mu_1)} P_0(s)$; $P_1(s) = K_1 P_0(s)$

Where $K_1 = \frac{\lambda_1}{(s+\mu_1)}$

$P_2(s) = \frac{\lambda_2}{(s+\mu_2)} P_0(s)$; $P_2(s) = K_2 P_0(s)$

Where $K_2 = \frac{\lambda_2}{(s+\mu_2)}$

$P_3(s) = \frac{\lambda_3}{(s+\mu_3)} P_0(s)$; $P_3(s) = K_3 P_0(s)$

Where $K_3 = \frac{\lambda_3}{(s+\mu_3)}$

$P_4(s) = \frac{\lambda_4}{(s+\mu_4)} P_0(s)$; $P_4(s) = K_4 P_0(s)$

Where $K_4 = \frac{\lambda_4}{(s+\mu_4)}$

$P_5(s) = \frac{\lambda_5}{(s+\mu_5)} P_0(s)$; $P_5(s) = K_5 P_0(s)$

Where $K_5 = \frac{\lambda_5}{(s+\mu_5)}$

Put values of $P_1(s)$, $P_2(s)$, $P_3(s)$, $P_4(s)$, $P_5(s)$ in equation (1) and by using normalizing condition,

$sP_0(s) + \alpha_1 P_0(s) = 1 + \mu_1 K_1 P_0(s) + \mu_2 K_2 P_0(s) + \mu_3 K_3 P_0(s) + \mu_4 K_4 P_0(s) + \mu_5 K_5 P_0(s)$

$(s + \alpha_1) P_0(s) = 1 + (\mu_1 K_1 + \mu_2 K_2 + \mu_3 K_3 + \mu_4 K_4 + \mu_5 K_5) P_0(s)$

$P_0(s) = [(s + \alpha_1) - (\mu_1 K_1 + \mu_2 K_2 + \mu_3 K_3 + \mu_4 K_4 + \mu_5 K_5)]^{-1}$

Availability function for A(s) system is given as

$A(s) = P_0(s)$

Inversion of A(s) gives the availability function A(t)

STEADY STATE BEHAVIOUR OF THE SYSTEM

The Steady State behaviour of the system can be analyzed by setting $t \to \infty$, $\frac{d}{dt} \to 0$, the state probabilities

$\alpha_1 P_0 = \mu_1 P_1 + \mu_2 P_2 + \mu_3 P_3 + \mu_4 P_4 + \mu_5 P_5$

$\mu_1 P_1 = \lambda_1 P_0$

$\mu_2 P_2 = \lambda_2 P_0$

$\mu_3 P_3 = \lambda_3 P_0$

$\mu_4 P_4 = \lambda_4 P_0$

$\mu_5 P_5 = \lambda_5 P_0$

On solving equations recursively, we get

$P_i = L_i P_0$ for i = 1 to 5

Where

$L_1 = \frac{\lambda_1}{\mu_1} P_0$ $L_2 = \frac{\lambda_2}{\mu_2} P_0$

$L_3 = \frac{\lambda_3}{\mu_3} P_0$ $L_4 = \frac{\lambda_4}{\mu_4} P_0$

$L_5 = \frac{\lambda_5}{\mu_5} P_0$

Using normalizing condition,

$\sum_{i=0}^{5} P_i = 1$, we get

$[P_0 + P_1 + P_2 + P_3 + P_4 + P_5] = 1$

$$P_o = \left[1 + \sum_{i=1}^{5} \frac{\lambda_i}{\mu_i}\right]^{-1} \quad (7)$$

The overall steady state availability of the system when running at full capacity is

$A_O = P_0$

Where P_0 is given by equation (7)

$$A_o = \left[1 + \sum_{i=1}^{5} \frac{\lambda_i}{\mu_i}\right]^{-1}$$

NUMERICAL RESULTS

The overall steady state availability of the system by taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_4 = 0.005$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

$$P_o = \left[1 + \sum_{i=1}^{5} \frac{\lambda_i}{\mu_i}\right]^{-1}$$

$A_O = 0.8924$

VII. AVAILABILITY ANALYSIS

The effect of various parameters on availability is studied. If the failure rate and repair rate are altered, the availability is affected. This effect is shown in following tables obtained for the availability of Cane Juice Extraction System.

(a) Effect of Failure rate of Cane Milling/Crushing Unit on availability A_O :Taking $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_4 = 0.005$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

Table 1: Steady State availability versus failure rate of Cane Milling/Crushing Unit

λ_1	0.001	0.002	0.003	0.004
A_O	0.8924	0.8547	0.8196	0.7874

(b) Effect of Failure rate of Juice Heating Unit on availability A_O :Taking $\lambda_1 = 0.001$, $\lambda_3 = 0.003$, $\lambda_4 = 0.005$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

Table 2: Steady State availability Versus failure rate of Juice Heating Unit

λ_2	0.004	0.005	0.006	0.007
A_0	0.8924	0.8904	0.8873	0.8849

(c) Effect of Failure rate of Juice Liming and Sulphitation Unit on availability A_0 :Taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_4 = 0.005$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

Table 3: Steady state Availability versus Failure rate of Juice Liming and sulphitation unit

λ_3	0.003	0.004	0.005	0.006
A_0	0.8924	0.8884	0.8849	0.8810

(d) Effect of Failure rate of Clarifier Unit on availability A_0 :

Taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

Table 4:Steady State availability versus failure rate of Clarifier Unit

λ_4	0.005	0.006	0.007	0.008
A_0	0.8924	0.8907	0.8884	0.8865

(e) Effect of Failure rate of Evaporators Unit on availability A_0 :Taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_4 = 0.005$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

Table 5: Steady State availability versus failure rate of Evaporators Unit

λ_5	0.01	0.02	0.03	0.04
A_0	0.8924	0.8695	0.8474	0.8257

(f) Effect of Repair rate of Cane Milling/Crushing Unit on availability A_0 :Taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_4 = 0.005$, $\lambda_5 = 0.01$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

Table 6: Steady State availability versus repair rate of Cane Milling/Crushing Unit

μ_1	0.020	0.04	0.08	0.16
A_0	0.8924	0.9128	0.9233	0.9287

(g) Effect of Repair rate of Juice Heating Unit on availability A_0 :Taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_4 = 0.005$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_3 = 0.20$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

Table 7: Steady State availability versus repair rate of Juice Heating Unit

μ_2	0.30	0.6	1.2	2.4
A_0	0.8924	0.8975	0.9002	0.9015

(h) Effect of Repair rate of Juice Liming and Sulphitation Unit on availability A_0 ;Taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_4 = 0.0095$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_4 = 0.40$, $\mu_5 = 0.33$

Table 8: Steady state availability versus repair rate of Juice Liming and Sulphitation Unit

μ_3	0.20	0.4	0.8	1.6
A_0	0.8924	0.8984	0.9015	0.9030

(i) Effect of Repair rate of Clarifier Unit on Availability A_0 :Taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_4 = 0.005$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_5 = 0.33$

Table 9: Steady state availability versus repair rate of Clarifier Unit

μ_4	0.40	0.8	1.6	3.2
A_0	0.8924	0.8974	0.8999	0.9012

(j) Effect of Repair rate of Evaporators Unit on availability A_0 :Taking $\lambda_1 = 0.001$, $\lambda_2 = 0.004$, $\lambda_3 = 0.003$, $\lambda_4 = 0.005$, $\lambda_5 = 0.01$, $\mu_1 = 0.020$, $\mu_2 = 0.30$, $\mu_3 = 0.20$, $\mu_4 = 0.40$

Table 10: Steady state availability versus repair rate of Evaporators Unit

μ_5	0.33	0.66	1.32	2.64
A_0	0.8924	0.9044	0.9106	0.9138

VIII. RESULTS AND DISCUSSION

From analysis part it is being found that increase in failure rate of Cane Milling/Crushing Unit, Juice Heating Unit, Juice Liming and Sulphitation Unit, Clarifier Unit and Evaporators unit reduces the availability of the system. Table 1 to 5 highlight the effect of failure rate of Cane Milling/Crushing Unit, Juice Heating Unit, Juice Liming and Sulphitation Unit, Clarifier Unit and Evaporators Unit on the long run availability of the Cane Juice Extraction System. On the other hand, the repair rates of the constituent component increase the availability of the system. This effect is shown in table 5 to 10. The respective improvement in the availability of the system are 3.63%, 0.91%, 1.06%, 0.88% and 2.14% on increasing the repair rate of Cane Milling/Crushing Unit, Juice Heating Unit, Juice Liming and Sulphitation Unit, Clarifier Unit and Evaporator Unit from 0.020 to 0.16, 0.30 to 2.4, 0.20 to 1.6, 0.40 to 3.2 and 0.33 to 2.64 repairs per hour respectively.

IX. CONCLUSION

The performance modeling and availability analysis of Cane Juice Extraction System of Sugar Industry have been carried out using Markov process and Probabilistic approach. Table 11 clearly specifies that the Cane Milling/Crushing unit is the most critical sub-systems as far as maintenance aspect is concerned and given top priority. The Evaporator unit should be given second priority as the effect of its failure and repair rates on the system performance is much higher than that of Juice Heating Unit, Juice Liming and Sulphitation Unit and clarifier units. Therefore on the basis of above performance analysis, the maintenance priorities should be given as per following order :

TABLE 11

Maintenance Priorities for Various Subsystems of Cane juice Extraction System.

S. No.	Subsystem	Maintenance Priorities
1	Cane milling/crushing unit	I
2	Evaporators unit	II
3	Juice Liming and Sulphitation unit	III
4	Juice Heating unit	IV
5	Clarifer unit	V

The findings of this paper are discussed with the concerned Sugar Industry Management. These results are found to be highly beneficial to the Plant Management for the evaluation of performance and analysis of availability of Cane Juice Extraction System and hence to decide about the maintenance repair priorities of various sub-systems of the system concerned in a Sugar Industry.

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