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An Analytical Study of Powder Plant System

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Abstract

Objective: An investigation was carried out for the seasonal functioning of the powder system in a dairy plant. The paper evaluates the reliability measures of the system in two seasons, which is based on the real-life case study of the system. Solutions are presented numerically as well as graphically. **Methods:** SemiMarkov process and the regenerative point technique have been used for the system analysis wherein the transition and steady-state probabilities are obtained. **Findings:** Numerical results have been found using MATLAB. Code Blocks, excel have been used for the graphical representation. Expressions for a variety of system effectiveness which include MTSF, long-term availability in two seasons, busy period for repair and maintenance in both the seasons, the expected number of repairs and maintenances, and at last the profit generated by the system. A specific case is considered for graphical analysis. **Novelty:** In the previous research paper, reliability modeling of the system was done without describing the seasonal effect; in this paper, reliability analysis is carried out of working of the powder system seasonally. The originality of this research lies in its way of calculating the expressions individually with respect to the seasons, giving a better and more accurate view of the system analysis. **Applications:** The model obtained from this research will benefit the engineers in understanding the systems having similar working conditions; also, the existing model will help in improving system performance in the powder system, attained from the Verka Milk Plant.

Keywords: Powder plant; seasons; semiMarkov process; regenerative point technique; reliability measures

1 Introduction

The impact of machines on our daily lives can be felt in every aspect of our lives. Industries have played a huge role in modern economies. The two determinants of success are quality and availability, which are crucial in an environment of fierce domestic and international competition. Production downtime can have dramatic repercussions. Using actual field data, Vališ et al. (2020)[1] evaluated the reliability of the water distribution network. Gómez-Rocha et al. (2021)[2] pioneered to production planning with random demand of a furniture manufacturing industry. Li et al.

(2021)[3] observed manufacturing industries for reliability modeling. A system of generating electricity has been evaluated by Taneja et al. (2020)[4] for profitability. Bashir and Jan (2021)[5] discussed a non-identical three-unit system stochastically. Single unit modeling with respect to environmental conditions was done by Saini and Kumar (2020)[6]. An analysis of the behavior of a washing unit in a paper mill has been undertaken by Kumar et al. (2019)[7]. In (2021), Sultan et al.[8] conducted stochastically-derived modeling of a standby unit with priority functions. Batra and colleagues (2021)[9] scrutinized a PCB unit's availability and reliability analysis. Model having two types of failure and identical units were inspected by Chaudhary et al. (2019)[10]. The present paper is a sincere effort to contribute to the literature on reliability. Calculation of Interval Reliability Indicators for semiMarkov Systems was done by D' Amico et al. (2021)[11]. Aggarwal, Kumar, and Singh (2016)[12] introduced a study into the design and availability of a skim milk powder system in a dairy plant by using mathematical modeling. A trapezoidal fuzzy number model with different left and right heights is used to analyze the profit of producing skimmed milk powder at a milk plant by Kumari et al. (2021)[13].

The paper discusses a powder encapsulation system. It consists of one drying chamber with three components: The first component is the heating tank, the second component is the condenser, and the third component is the concentrate. They are all in operation when the system begins to process material. During the winter months, a high level of milk production keeps the system operating, but the system goes into cold standby during the summer and is maintained. In the event that one of the three units fails, the entire system fails.

2 Methodology

SemiMarkov process and regenerative point technique are used to obtain the following measures of system effectiveness in steady-state:

- Transition probabilities and mean sojourn times in different states. MTSF of the system.
- Steady-state availability for the system.
- A busy period for the repairman.
- Expected number of repairs.
- Additionally, the system's profit potential is analyzed graphically.

2.1 Model Descriptions and A ssumptions

- The system is initially operative at state 0.
- Time to failure of each unit is assumed to follow an exponential distribution, whereas repair time distribution is taken to be arbitrary.
- There are similarities and statistical independence between the units.
- After each repair, the system works as well as new.

Notations and States of the System Model

- $\lambda \rightarrow$ Failure rate of the drying chamber unit.
- $\lambda_1, \lambda_2, \lambda_3 \rightarrow$ Failure rate of units one, two, and three respectively.
- $\lambda_4 \rightarrow$ Maintenance rate of a powder system.
- $\alpha \rightarrow$ Rate of going to summer.
- $\beta \rightarrow$ Rate of going to winter.
- S $\rightarrow$ Summer.
- W $\rightarrow$ Winter.
- O$\rightarrow$ Operative state.
- cs $\rightarrow$ Cold Standby state.
- um $\rightarrow$ Under maintenance.
- Fr $\rightarrow$ Failure under repair.
- dc $\rightarrow$ Drying chamber of powder plant.
- u1, u2, u3 $\rightarrow$ Units 1,2,3 respectively.
- Odc $\rightarrow$ Drying chamber of the powder system is operating.
- ou1, ou2, ou3 $\rightarrow$ Units 1,2,3 is operating.
- cs dc $\rightarrow$ Drying chamber of the powder system is in the cold standby state.
- cs1, cs2, cs3 $\rightarrow$ Units 1,2,3 is in cold standby state.

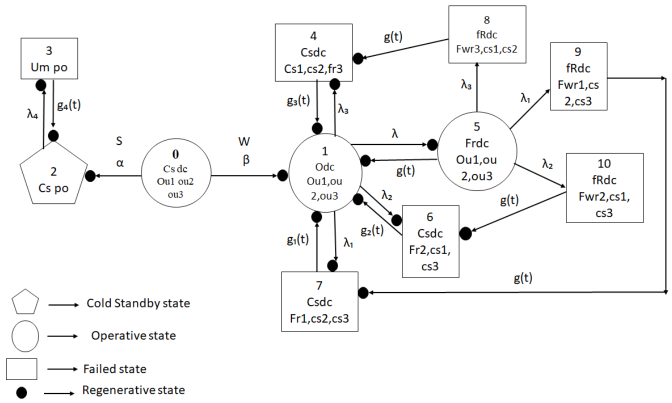

Fig 1. State Transition Diagram

- $G(t)$, $g(t)$ $\rightarrow$ c.d.f. and p.d.f of time to repair the drying chamber unit.
- $G_1(t)$, $g_1(t)$ $\rightarrow$ c.d.f. and p.d.f of time to repair unit one.
- $G_2(t)$, $g_2(t)$ $\rightarrow$ c.d.f. and p.d.f of time to repair of unit two.
- $G_3(t)$, $g_3(t)$ $\rightarrow$ c.d.f. and p.d.f of time to repair of unit three.
- $G_4(t)$, $g_4(t)$ $\rightarrow$ c.d.f. and p.d.f of maintenance of the powder plant.

2.3 Transition Probabilities and Mean Sojourn Time

Figure 1 is the transition diagram showing the various states of the system. The epochs of entry to all states are regenerative states. States 0, 1, 5 are operative states, 2 is a cold standby state, other states 3, 4, 6, 7, 8, 9, 10 are failed states.

The non-zero elements p_{ij} can be represented as below:

$p_{ij} = Q_j(\infty) = \int_0^{\infty} q_j dt$

- $p_{01} = \beta / \beta + \alpha$
- $p_{02} = \alpha / \beta + \alpha$
- $p_{14} = \lambda_3 / \lambda + \lambda_1 + \lambda_2 + \lambda_3$
- $p_{15} = \lambda / \lambda + \lambda_1 + \lambda_2 + \lambda_3$
- $p_{16} = \lambda_2 / \lambda + \lambda_1 + \lambda_2 + \lambda_3$
- $p_{17} = \lambda_1 / \lambda + \lambda_1 + \lambda_2 + \lambda_3$
- $p_{32} = g_4{}^*(0)$
- $p_{41} = g_3{}^*(0)$
- $p_{51} = g^*(\lambda_1 + \lambda_2 + \lambda_3)$
- $p_{58} = p_{54}{}^{(8)} = (\lambda_3 / \lambda_1 + \lambda_2 + \lambda_3)\ (1 - g^*(\lambda_1 + \lambda_2 + \lambda_3))$
- $p_{59} = p_{57}{}^{(9)} = (\lambda_1 / \lambda_1 + \lambda_2 + \lambda_3)\ (1 - g^*(\lambda_1 + \lambda_2 + \lambda_3))$
- $p_{5,10} = p_{56}{}^{(10)} = (\lambda_2 / \lambda_1 + \lambda_2 + \lambda_3)\ (1 - g^*(\lambda_1 + \lambda_2 + \lambda_3))$
- $p_{61} = g_2{}^*(0)$
- $p_{71} = g_1{}^*(0)$
- $p_{84} = p_{97} = p_{10,6} = g^*(0)$

By these transition probabilities it is also verified that

- $p_{01} + p_{02} = 1$
- $p_{14} + p_{15} + p_{16} + p_{17} = 1$
- $p_{51} + p_{58} + p_{59} + p_{5,10} = 1$
- $p_{51} + p_{54}{}^{(8)} + p_{57}{}^{(9)} + p_{56}{}^{(10)} = 1$
- $p_{23} = p_{32} = p_{41} = p_{61} = p_{71} = p_{84} = p_{97} = p_{10,6} = 1$

The unconditional meantime is taken by the system to transit for any regenerative state ‘j’ when t (time) is counted from the epoch of entrance into state ‘i’ is mathematically stated as:

$$m_{ij} = \int_0^{\infty} t dQ_{ij}(t) = -q_{ij}^{*'}(0)$$

- $m_{01} + m_{02} = \mu_0$
  - $m_{14} + m_{15} + m_{16} + m_{17} = \mu_1$
  - $m_{51} + m_{58} + m_{59} + m_{5,10} = \mu_5$
  - $m_{51} + m_{54}^{(8)} + m_{57}^{(9)} + m_{56}^{(10)} = K$

where, $\int_0^\infty \bar{G}(t)dt = K\,(say)$

The mean sojourn time (μ_i) in the regenerative state 'i 'is defined as time of stay in that state before transition to any other state:

- $\mu_0 = 1/\ \alpha + \beta$
- $\mu_1 = 1/\ \lambda + \lambda_1 + \lambda_2 + \lambda_3$
- $\mu_2 = 1\ /\lambda_4$
- $\mu_3 = \int_0^\infty g_4(t)dt$
- $\mu_5 = (1\ /\lambda_1 + \lambda_2 + \lambda_3)\ [1 - g^*(\lambda_1 + \lambda_2 + \lambda_3)]$
- $\mu_4 = \int_0^\infty g_3(t)dt$
- $\mu_6 = \int_0^\infty g_2(t)dt$
- $\mu_7 = \int_0^\infty g_1(t)dt$
- $\mu_8 = \mu_9 = \mu_{10} = \int_0^\infty g\,(t)\,dt$

2.4 Mean Time to System Failure

Mean time to system failure (MTSF) of the system is determined by considering the failed state as an absorbing state. By probabilistic arguments, we obtain the following recursive relations for $\varnothing i(t)$ where i = 0, 1, 2, 4, 5, 6, 16, 18,19 are given by:

$\phi_0(t)= Q_{01}(t) \star \phi_1(t) + Q_{02}(t) \star \phi_2(t)$

$\phi_1(t)= Q_{14}(t) +Q_{15}(t) \star \phi_5(t)+Q_{16}(t)+Q_{17}(t)$

$\phi_2(t)=Q_{23}(t)$

$\phi_5(t)= Q_{51}(t) \star \phi_1(t) + Q_{58}(t) +Q_{59}(t) +Q_{5,10}(t)$

Taking Laplace-Stieltjes Transform (L.S.T.) of the relations given by above equation and solving them for $\varnothing_0{}^{**}(t)$, we obtain $\varnothing_0{}^{**}(t) = \frac{N(s)}{D(s)}$

The reliability R(t) of the system at time t is given as

R(t) = Inverse Laplace transform of $\frac{(1\ \ \phi_0{**}(s))}{s}$

The mean time to system failure (MTSF), when the system started at the beginning of state 0 is:

MTSF $=\int_0^\infty R\,(t)\,dt = \lim_{s\to 0} R*(s)$

Using L' Hospital rule and putting the value of $\varphi_0{}^{**}(s)$ we getMTSF $= T_0 = \lim_{s\to 0}\frac{1-\phi_0^{**}(s)}{s} = \frac{(\mu_0+\mu_2 p_{02})(1-p_{15}p_{51})+\mu_1 p_{01}+\mu_5 p_{01}p_{15}}{(1-p_{15}p_{51})}$

Let $A_0(t)$ be the probability that the system is available in winters at a given time instant t, given that it already entered state "i" at time t. $BR_0(t)$ be the probability that the repairman is busy for repair in winters at a time instant t, given that it already entered state "i" at time t. $BM_0(t)$ be the probability that the repairman is busy for maintenance in summers at a time instant t, given that it already entered state "i" at time t. $VR_0(t)$ be the expected number of repairs in winters at (0, t). $VM_0(t)$ be the expected number of maintenances in summers at (0, t).

As in the case of MTSF, we have derived these measures of system effectiveness (A_0, BR_0, BM_0, VR_0, VM_0) using the same probabilistic arguments as with MTSF, except that here the failed state is not considered the absorbing state.

From the calculated measures profit incurred to the system model in steady state is given by,

$P = C_0A_1 + C_1BR_0 - C_2BM_0 - C_3VR_0 - C_4VM_0$

The costs defined are as follows:

C_0=Revenue per unit up time.

C_1=Cost per unit up time for which the repairman is busy for repair.

C_2=Cost per unit up time for which the repairman is busy for maintenance in winters.

C_3=Cost per repair.

C_4=Cost per maintenance.

$$A_0 = \lim_{s\to 0}(sA_0^*(s)) = \frac{N_1}{D_1}$$

$N_1 = p_{01}(\mu_1 + \mu_5 p_{15})$
$D_1 = \mu_1 + \mu_4(p_{14} + p_{15}p_{54}^{(8)}) + Kp_{15} + \mu_6(p_{16} + p_{15}p_{56}^{(10)}) + \mu_7(p_{17} + p_{15}p_{57}^{(9)})$ ... (1)

$$BR_0 = \lim_{s\to 0}(sBR_0^*(s)) = \frac{N_2}{D_1}$$

$N_2 = W_4p_{01}(p_{14} + p_{15}p_{54}^{(8)}) + W_5p_{01}p_{15} + W_6p_{01}(p_{16} + p_{15}p_{56}^{(10)}) + W_7p_{01}(p_{17} + p_{15}p_{57}^{(9)})$
D_1 is defined in equation 1.

$$VR_0 = \lim_{s\to 0}(sVR_0^*(s)) = \frac{N_3}{D_1}$$

$N_4 = p_{01}(1 + p_{15}p_{54}^{(8)} + p_{15}p_{57}^{(9)} + p_{15}p_{56}^{(10)})$
D_1 is already defined in equation 1.

$$BM_0 = \lim_{s\to 0}(sBM_0^*(s)) = \frac{N_3}{D_2}$$

$N_3 = W_2p_{01}p_{12}$
D_2 is defined in equation 2.

$$VM_0 = \lim_{s\to 0}(sVM_0^*(s)) = \frac{N_5}{D_2}$$

$N_5 = p_{01}p_{12}$
D_2 is defined in equation 2.
Here W_i is the probability that the system is under repair at time "t" before transiting any other state.

3 Results and Discussion

For graphical representation we assume the particular case of exponential distribution, likewise:
$g(t) = \theta e^{-\theta(t)}$, $g_1(t) = \theta_1 e^{-\theta_1(t)}$, $g_2(t) = \theta_2 e^{-\theta_2(t)}$, $g_3(t) = \theta_3 e^{-\theta_3(t)}$, $g_4(t) = \theta_4 e^{-\theta_4(t)}$
for numerical analysis various cut-off points are evaluated from the information gathered at the Verka milk plant
λ_2=.00002898, λ_3=.0000246, λ_4=.000292675, θ=.00392166, θ⊠=.0003165, θ_2=.000298, θ_3=.000896, θ_4=.00125363, α=.00023148, β=.00023148, C_0= 105000, C_1=6700, C_2=2550, C_3=1500, C_4=1000

- Mean time to system failure = 7046.117188 hrs
- Availability in winters = 0.471440
- Busy period for repair =0.498495
- Busy period for maintenance =0.007057
- Expected number of repairs =0.000152
- Expected number of maintenances =0.000007
- Profit = Rs. 46143.08

The numerical values are obtained from the original data collected from the Verka Milk Plant, Bathinda, Punjab. From the data collected various parameters were calculated which include failure and repair rates of the chamber, unit 1, 2, and 3. From these failure rates values were evaluated of the system effectiveness measures using MATLAB and Code Blocks.

Table 1. Numerical data of MTSF λ_1 with failure rate λ_3 obtained using Code Blocks

λ_1=0.00024589	λ_1=0.0005	λ_1=0.0024589	λ_3
801.214172	730.630981	670.514893	0.002
641.27887	570.695557	510.57959	0.003
561.311157	490.727783	430.611786	0.004
513.330505	442.747223	382.631195	0.005
481.343414	410.760132	350.644135	0.006
458.495483	387.912201	327.796204	0.007
441.359558	370.776245	310.660248	0.008
428.031616	357.448303	297.332306	0.009
417.369263	346.78595	286.669952	0.01
408.645508	338.062195	277.946198	0.011

Table 1 is graphically analysed as shown in Figure 2. Here the values obtained are from the original data collected.

Figure 2 shows the trend between failure rateλ_3 and MTSF as failure rate increases mean time to system failure decreases and it also decreases as λ_1 increases.

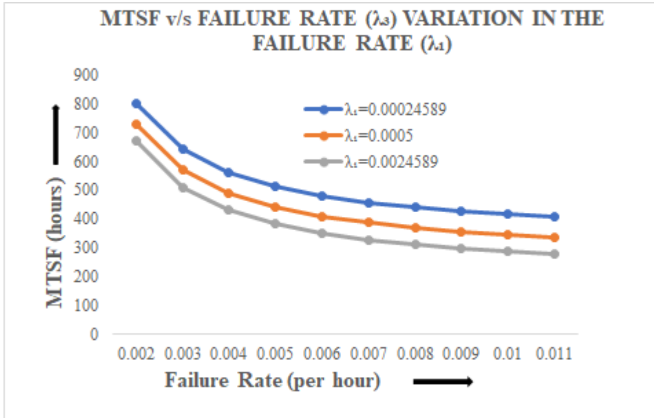

Fig 2. MTSF v/s Failure rate

Table 2. Data of profit and failure rate λ_3

λ_1=0.00024589	λ_1=0.0005	λ_1=0.0024589	λ_3
2055.256592	1865.224609	829.78479	0.002
1833.494507	1643.462524	608.022583	0.003
1696.155029	1506.123047	470.683136	0.004
1602.739014	1412.707031	377.26712	0.005
1535.079956	1345.047974	309.608154	0.006
1483.81616	1293.78418	258.344299	0.007
1443.63208	1253.600098	218.16024	0.008
1411.285889	1221.253906	185.814041	0.009
1384.68859	1194.656616	159.216736	0.01
1362.432251	1172.400269	136.960449	0.011

Data of profit and failure rate λ_3 can graphically be analyzed as given in Figure 3, where the failure rates have been calculated using the original data from the industry and the trend shows that with increasing failure rate λ_3 profit decreases.

Figure 3 shows the similar trend as increasing failure rate decreases profit.

Table 3. Numerical data of profit with cost c_0 varying cost of busy period for repair c_1 obtained using Code Blocks

C_1=6700	C_1=27000	C_1=47000	C_0
-405.397888	-750.289734	-1129.555786	10000
-203.339981	-525.161255	-904.427429	20000
-1.28206	-300.032715	-679.29895	30000
200.775894	-74.904243	-454.17041	40000
402.833771	150.224167	-229.042007	50000
604.891724	375.352722	-3.913464	60000
806.949585	600.481079	221.214951	70000
1009.007568	825.609619	446.343506	80000
1211.06543	1050.738159	671.471924	90000
1413.123413	1275.866577	896.600342	100000
1615.181274	1500.995239	1121.729126	110000

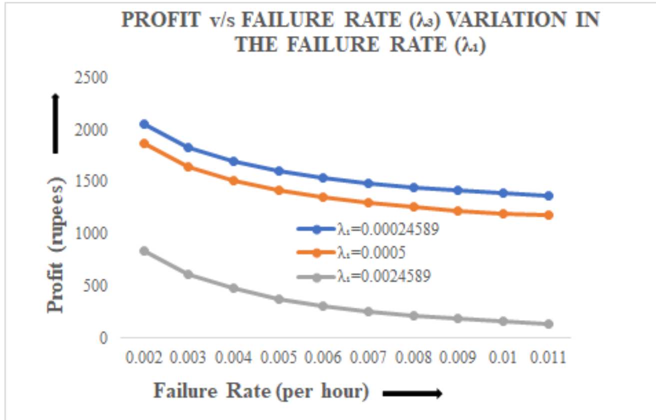

Fig 3. Profit v/s Failure rate

Table 3 depicts the following result (Figure 4)

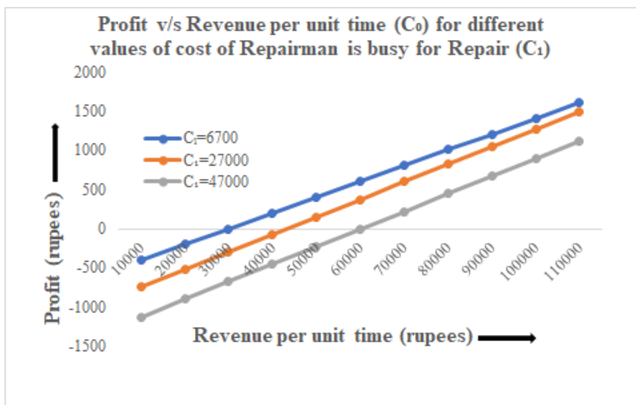

Fig 4. Profit v/s Revenue per unit time

Upward trend in Figure 4 is shown, wherein the profit increases with the increasing revenue per unit time. Thus, increase in revenue per unit time increases the profit.

Using line of regression y = a x + b where a is the slope and b is the intercept more values can be evaluated for the various measures i.e., mean time to system failure, profit, availability etc. some of them have been stated below to save space.

For λ_1=0.0024589 in Profit and revenue the y intercept will b= -2404.74635 and the slope a= 0.29463713 from this line of regression we can find more values with different failure rates.

For λ_1=0.0024589 in MTSF the b = 5003.582 and a = -2251640 we can find more values with different failure rates.

The parameters shown in the Table 4 are calculated using the data collected from the milk industry. Using these values various cut-off points have been obtained which will help the industry improve its performance hence making higher profit.

Cut-off points in the graphical analysis shows at what point the values will start decreasing/increasing. Cut-off points vary widely and by knowing the cut-off points the engineers can know the level of gains or losses, which can be seen in Table 4.

In case of mean time to system failure (MTSF) as the λ increases the MTSF decreases

We can see the cut-off values at λ=.0011 and λ<.0011 in Figure 2 graphically and also in Table 1.

Similar is the case with profit v/s the failure rate where the cut-off values is graphically presented in Figure 3 and numerically in Table 2.

Profit v/s revenue depicts the cut off points as when

i. C_1=6700 the profit depends on C_0=35000,

ii. C_1=27000 the profit depends on C_0=45000,

iii. C_1=47000 the profit depends on C_0=650000.

Table 4. Cut-off points for profit v/s revenue per up time with varying C_0 with different values of C_1

Known Parameter	Varying Parameter	MTSF		
		Decreasing $\lambda \geq .0011$	Increasing $\lambda < .0011$	
λ_2=.00002898, λ_3=.0000246, λ_4=.000292675, θ=.00392166, θ=.0003165, θ_2=.000298, θ_3=.000896, θ_4=.00125363, α=.00023148, β=.00023148, C_0= 105000, C_1=6700, C_2=2550, C_3=1500, C_4=1000	λ=.0002458	408.645508	801.214172	
	λ=.0005	338.062195	730.6300981	
	λ=.002458	277.941698	670.514893	
Known Parameter	Varying Parameter	Profit		
		Decreasing	Increasing	
λ_2=.00002898, λ_3=.0000246, λ_4=.000292675, θ=.00392166, θ=.0003165, θ_2=.000298, θ_3=.000896, θ_4=.00125363, α=.00023148, β=.00023148, C_0= 105000, C_1=6700, C_2=2550, C_3=1500, C_4=1000	λ=.0002458	$\lambda < .0011$	$\lambda \geq .0011$	
	λ=.0005	1362.432251	2055.2565	
	λ=.002458	1172.40026	1865.2246	
		136.96044	829.78479	
Known Parameter	Varying Parameter	Cost		
		Positive	Negative	Zero
λ_2=.00002898, λ_3=.0000246, λ_4=.000292675, θ=.00392166, θ=.0003165, θ_2=.000298, θ_3=.000896, θ_4=.00125363, α=.00023148, β=.00023148, C_0= 105000, C_1=6700, C_2=2550, C_3=1500, C_4=1000	C_1=6700	C0>35000	C0<35000	C0=35000
	C_1=27000	C0>45000		C0=45000
	C_1=47000	C0>6500	C0<45000	C0=65000
			C0<650000	

4 Conclusion

This paper analyses the reliability of a powder system taking into account its seasonal effect. Previously, the reliability analysis of a powder system was carried out without addressing the seasonal effect; The present research will help improve system performance at the Verka Milk Plant, thereby reducing production losses and increasing profit. It will also be helpful in all the other systems with similar working conditions and help understand the seasonal variation in the working of the system. The originality of this study lies in the method of analyzing the system in terms of season-dependent expressions. This gives a better, more accurate view of the whole picture in terms of the system analysis.

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