SENSITIVITY AND PROFITABILITY ANALYSIS OF TWO-UNITS AMMONIA/UREA PLANT

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Abstract

This paper presents a reliability modelling of a two-unit ammonia/urea plant. Real maintenance data of the production plant have been used for this purpose. Four types of failure were noted: process, electrical, mechanical and instrumental failures. Both ammonia/urea formation units work in parallel and do not fail simultaneously. Various reliability indices of the plant, such as availability, busy period for repair, and expected number of repairs for each type of failure, have been obtained. Markov processes and regenerative point techniques are used for analysis. Profit analysis for the plant is also done, along with a graphical representation of various parameters. Finally, sensitivity analysis is carried out to see the impact of varied parameters on the profit function of the plant.

Keywords: Ammonia plant; Markov process; regenerative point techniques; repairs; failures

1. Introduction

Many researchers have studied complex industrial systems under various operating conditions and presumptions, contributing to the discipline of reliability modelling and analysis. Rizwan et al. [1, 2] presented a reliability modelling strategy and its application to industries, specificall focusing on a biscuit manufacturing factory controlled by a single-unit and two-unit hot standby PLC system. Mathew et al. [3, 4] discussed the reliability modelling of single-unit and two-unit systems in a continuous casting plant. They utilized real maintenance data from a steel production plant to analyze the system's performance and identify different types of failures. Also, Mathew et al. [5] did a comparative analysis of the two models of the CC plant. Mathew et al. [6, 7] presented reliability modelling in an actual CC plant with different installed and full installed capacities, where two EOT cranes operate in parallel. Padmavati et al. [8–13] evaluated the impact of prioritizing repair over maintenance on the overall reliability and availability of the desalination plant. Also, they discussed the implications of the research for the design and operation of desalination plants in terms of cost-effectiveness and efficienc by taking different assumptions for failures and repairs.Rizwan et al. [14–16] analyzed the reliability of a wastewater treatment plant. They estimated various reliability indices associated with the plant. Also, they highlighted the importance of regular monitoring, repairs, and replacements in maintaining the reliability of systems.

Al Rahbi et al. [17–23] analyzed the reliability of single unit/ multiple units of a rodding anode plant in the aluminium industry with single/numerous repairers and optimized maintenance strategies, improved system reliability, and reduced downtime, leading to increased productivity and cost savings. Taj et al. [24–30, 33] evaluated reliability analysis conducted on the cable plant's single- or three-unit machine subsystem with repair priority over maintenance. Rizwan et al. [31] examined the three pumps' performance in distributing desalinated water. The study included maintenance data collected over five years, encompassing various failure reasons, restoration times, and waiting times. Rizwan et al. [32] explored the reliability and sensitivity analysis of Membrane Biofil Fuel Cells. Thus, the literature has widely discussed the reliability modelling and analysis of complex industrial systems in various failure/maintenance circumstances. But the concept of reliability analysis for ammonia/urea manufacturing plants has yet to be discussed.

The demand for fertilizers is growing day by day around the world to meet agricultural requirements. The most used or consumed fertilizer is UREA, which is manufactured from ammonia, from different industrial chemical reactions. The UREA fertilizer manufacturing facilities consist ammonia manufacturing plant along with a urea plant. To meet the growing demand for urea in the current market, these facilities must keep production continuously with maximum capacity to meet the market's growing demand. For continuous operation, these facilities must function the plant and equipment efficiently throughout the year without significant technical or maintenance issues. Any unexpected operational failure, breakdown, or downtime may cause plant productivity and efficiency. For that, the operation and maintenance strategies are critical as they help maintain the life and smooth operation of the equipment. These strategies also help reduce plant downtime.Also, further analysis and research techniques for plant performance, productivity, reliability, availability, maintainability, sensitivity [34, 35], etc., may be carried out to ensure continuous and smooth plant operations. This paper provides sensitivity and profitability analysis, along with reliability analysis of parallel ammonia and urea plants worldwide that have operated for more than 15 years. The research is based on the actual plant data, with some assumptions, failure rate, or probability.

2. Notations

The following are the notations used in the analysis:
λ_u = failure rate of ammonia plant
$p_1/\ p_2/\ p_3/\ p_4$= probability of process failure/ electrical failure/ mechanical failure/ instrumental failure in unit 1.
$p_5/\ p_6/\ p_7/\ p_8$=probability of process/ electrical/ mechanical/ instrumental failure in unit 2.
$\alpha_1/\ \alpha_2/\ \alpha_3/\ \alpha_4$=repair rate of process/ electrical/ mechanical/ instrumental failure in unit 1.
$\alpha_5/\ \alpha_6/\ \alpha_7/\ \alpha_7$=repair rate of process/ electrical/ mechanical/ instrumental failure in unit 2.
f^u(t) = p.d.f. of failure time.
$g_1(t)/\ g_2(t)/\ g_3(t)/\ g_4(t)$=p.d.f. of repair time due to process/ electrical/ mechanical/ instrumental failure in unit 1.
$g_5(t)/\ g_6(t)/\ g_7(t)/\ g_8(t)$=p.d.f. of repair time due to process/ electrical/ mechanical/ instrumental failure in unit 2.

3. Data Summary

The real data from a urea manufacturing company is summarized as follows:
Probability of process failure in unit 1, $p_1 = 0.2088$
Probability of electrical failure in unit 1, $p_2 = 0.0220$
Probability of mechanical failure in unit 1, $p_3 = 0.1758$
Probability of instrumental failure in unit 1, $p_4 = 0.1978$
Probability of process failure in unit 2, $p_5 = 0.1648$

Probability of electrical failure in unit 2, $p_6 = 0.0220$
Probability of mechanical failure in unit 2, $p_7 = 0.1868$
Probability of instrumental failure in unit 2, $p_8 = 0.0220$
Failure rate of urea plant, $\lambda_u = 0.00031$ per hour
Repair rate of process failure in unit 1, $\alpha_1 = 0.0249$ per hour
Repair rate of electrical failure in unit 1, $\alpha_2 = 0.2$ per hour
Repair rate of mechanical failure in unit 1, $\alpha_3 = 0.0081$ per hour
Repair rate of instrumental failure in unit 1, $\alpha_4 = 0.01833$ per hour
Repair rate of process failure in unit 2, $\alpha_5 = 0.0150$ per hour
Repair rate of electrical failure in unit 2, $\alpha_6 = 0.0175$ per hour
Repair rate of mechanical failure in unit 2, $\alpha_7 = 0.0057$ per hour
Repair rate of instrumental failure in unit 2, $\alpha_8 = 0.0392$ per hour

4. Model Description and Assumptions

- Initially, we have an operative ammonia manufacturing plant composed of two parallel units: Unit 1 and Unit 2.
- The four types of failures are observed in both units, i.e., process, electrical, mechanical, and instrumental.
- Both units cannot fail simultaneously .
- Repair is carried out upon failures.
- Failure rate and repair rates all are taken as general.

5. Stochastic Model

Table 1 shows the rates of transition from state i (S_i) to state j (S_j).The set of states {0,1,2,3...,8} all are operative and regenerative.

Table 1

State Transition Table

S_i/ S_j	S_0	S_1	S_2	S_3	S_4	S_4	S_6	S_7	S_8
S_0	0	$p_1 f^u(t)$	$p_2 f^u(t)$	$p_3 f^u(t)$	$p_4 f^u(t)$	$p_5 f^u(t)$	$p_6 f^u(t)$	$p_7 f^u(t)$	$p_8 f^u(t)$
S_1	$g_1(t)$	0	0	0	0	0	0	0	0
S_2	$g_2(t)$	0	0	0	0	0	0	0	0
S_3	$g_3(t)$	0	0	0	0	0	0	0	0
S_4	$g_4(t)$	0	0	0	0	0	0	0	0
S_5	$g_5(t)$	0	0	0	0	0	0	0	0
S_6	$g_6(t)$	0	0	0	0	0	0	0	0
S_7	$g_7(t)$	0	0	0	0	0	0	0	0
S_8	$g_8(t)$	0	0	0	0	0	0	0	0

where,
State 0 (S_0) - Both urea processing machines unit 1 and 2 operatives.
State 1 (S_1) - Unit 1 failed due to process failure, and Unit 2 is still operative.
State 2 (S_2) - Unit 1 failed due to electrical failure, and Unit 2 is still operative.
State 3 (S_3) - Unit 1 failed due to mechanical failure, and Unit 2 is still operative.
State 4 (S_4) - Unit 1 failed due to instrumental failure, and Unit 2 is still operative.
State 5 (S_5)- Unit 1 is operative, and Unit 2 failed due to process failure.
State 6 (S_6) - Unit 1 is operative, and Unit 2 failed due to electrical failure.
State 7 (S_7) - Unit 1 is operative, and Unit 2 failed due to mechanical failure.
State 8 (S_8) - Unit 1 is operative, and Unit 2 failed due to instrumental failure.

The transition probability from state i (S_i) to state j (S_j), $q_{ij}(t)$ is given by

$q_{01}(t) = p_1 f^u(t)$, $q_{10}(t) = g_1(t)$,
$q_{02}(t) = p_2 f^u(t)$, $q_{20}(t) = g_2(t)$,
$q_{03}(t) = p_3 f^u(t)$, $q_{30}(t) = g_3(t)$,
$q_{04}(t) = p_4 f^u(t)$, $q_{40}(t) = g_4(t)$,
$q_{05}(t) = p_5 f^u(t)$, $q_{50}(t) = g_5(t)$,
$q_{06}(t) = p_6 f^u(t)$, $q_{60}(t) = g_6(t)$,
$q_{07}(t) = p_7 f^u(t)$, $q_{70}(t) = g_7(t)$,
$q_{08}(t) = p_8 f^u(t)$, $q_{80}(t) = g_8(t)$

The steady-state probability, p_{ij} as

$$p_{01} = p_1, \quad p_{02} = p_2, \quad p_{03} = p_3, \quad p_{04} = p_4, \quad p_{05} = p_5, \quad p_{06} = p_6, \quad p_{07} = p_7, \quad p_{08} = p_8$$
$$p_{10} = p_{20} = p_{30} = p_{40} = p_{50} = p_{60} = p_{70} = p_{80} = 1 \tag{1}$$

Sojourn time (μ_i),, i.e., mean stay time in particular state i, is given as

$\mu_0 = \int_0^\infty t.f^u(t)\,dt$, $\mu_5 = \int_0^\infty t.g_5(t)\,dt$,
$\mu_1 = \int_0^\infty t.g_1(t)\,dt$, $\mu_6 = \int_0^\infty t.g_6(t)\,dt$,
$\mu_2 = \int_0^\infty t.g_2(t)\,dt$, $\mu_7 = \int_0^\infty t.g_7(t)\,dt$,
$\mu_3 = \int_0^\infty t.g_3(t)\,dt$, $\mu_8 = \int_0^\infty t.g_8(t)\,dt$,
$\mu_4 = \int_0^\infty t.g_4(t)\,dt$,

The contribution to mean sojourn time, m_{ij},is given by
$m_{ij} = \int_0^\infty t.q_{ij}(t)\,dt$.It can be verifie that
$m_{01} + m_{02} + m_{03} + m_{04} + m_{05} + m_{06} + m_{07} + m_{08} = \mu_0$,

$$m_{10} = \mu_1, \quad m_{20} = \mu_2, \quad m_{30} = mu_3, \quad m_{40} = \mu_4,$$
$$m_{50} = \mu_5, \quad m_{60} = \mu_6, \quad m_{70} = mu_7, \quad m_{80} = \mu_8.$$

6. System Performance Measures

6.1. Availability of the System

Defin
$A_i^u(t)$ = probability that it is operative at time t, given that the system is in state i at time t = 0.

Using the state transitions, we get the following equations:

$$\begin{aligned}
A_0^u(t) &= M_0(t) + q_{01}(t) \copyright A_1^u(t) + q_{02}(t) \copyright A_2^u(t) + q_{03}(t) \copyright A_3^u(t) + q_{04}(t) \copyright A_4^u(t) + q_{05}(t) \copyright A_5^u(t) \\
&\quad + q_{06}(t) \copyright A_6^u(t) + q_{07}(t) \copyright A_7^u(t) + q_{08}(t) \copyright A_8^u(t) \\
A_1^u(t) &= M_1(t) + q_{10}(t) \copyright A_0^u(t) \\
A_2^u(t) &= M_2(t) + q_{20}(t) \copyright A_0^u(t) \\
A_3^u(t) &= M_3(t) + q_{30}(t) \copyright A_0^u(t) \\
A_4^u(t) &= M_4(t) + q_{40}(t) \copyright A_0^u(t) \\
A_5^u(t) &= M_5(t) + q_{50}(t) \copyright A_0^u(t) \\
A_6^u(t) &= M_6(t) + q_{60}(t) \copyright A_0^u(t) \\
A_7^u(t) &= M_7(t) + q_{70}(t) \copyright A_0^u(t) \\
A_8^u(t) &= M_8(t) + q_{80}(t) \copyright A_0^u(t)
\end{aligned} \tag{2}$$

where

$M_i(t)$= probability that the system stays in state i while operating rather than transferring to any other state.

Taking Laplace transform of equations (28)-(36) and solving for $A_0^{u^*}(s)$, we get

$$A_0^{u^*}(s) = \frac{N_1^u(s)}{D_1^u(s)}$$

where

$$N_1^u(s) = M_0^*(s) + q_{01}^*(s)M_1^*(s) + q_{02}^*(s)M_2^*(s) + q_{03}^*(s)M_3^*(s) + q_{04}^*(s)M_4^*(s)$$
$$+q_{05}^*(s)M_5^*(s) + q_{06}^*(s)M_6^*(s) + q_{07}^*(s)M_7^*(s) + q_{08}^*(s)M_8^*(s) \tag{3}$$
$$D_1^u(s) = 1 - q_{01}^*(s)q_{10}^*(s) - q_{02}^*(s)q_{20}^*(s) - q_{03}^*(s)q_{30}^*(s) - q_{04}^*(s)q_{40}^*(s) - q_{05}^*(s)$$
$$q_{50}^*(s) - q_{06}^*(s)q_{60}^*(s) - q_{07}^*(s)q_{70}^*(s) - q_{08}^*(s)q_{80}^*(s) \tag{4}$$

The steady-state availability of the system is given by :

$$A_0^u = \lim_{s \to 0} s.A_0^{u^*}(s) = \lim_{s \to 0} s.\frac{N_1^u(s)}{D_1^u(s)} = \frac{N_1^{u'}(0)}{D_1^u(0)} = \frac{N_1^u}{D_1^u}(\text{say}) \tag{5}$$

where

$$N_1^u = \mu_0 + p_1\mu_1 + p_2\mu_2 + p_3\mu_3 + p_4\mu_4 + p_5\mu_5 + p_6\mu_6 + p_7\mu_7 + p_8\mu_8 \tag{6}$$

$D_1^u = p_1\mu_1 + p_2\mu_2 + p_3\mu_3 + p_4\mu_4 + p_5\mu_5 + p_6\mu_6 + p_7\mu_7 + p_8\mu_8 + \mu_0$

6.2. Busy Period for Repair

The expected time for which the repair man is busy for the repair of unit 1 and unit 2 due to process failure in steady state is given by:

$PB^{u1} = PN_2^{u1}/\ D_1^u$ and $PB^{u2} = PN_2^{u2}/\ D_1^u$

where

$PN_2^{u1} = p_{01}u_1 = p_1u_1$

$PN_2^{u2} = p_{05}u_5 = p_5u_5$

The expected time for which the repair man is busy for the repair of unit 1 and unit 2 due to electrical failure in steady state is given by:

$EB^{u1} = EN_2^{u1} / D_1^u$ and $EB^{u2} = EN_2^{u2} / D_1^u$

where

$EN^{u1} = p_{02} u_2 = p_2 u_2$

$EN^{u2} = p_{06} u_6 = p_6 u_6$

The expected time for which the repair man is busy for the repair of unit 1 and unit 2 due to mechanical failure in steady state is given by:

$MB^{u1} = MN_2^{u1} / D_1^u$ and $MB^{u1} = MN_2^{u1} / D_1^u$

where

$MN_2^{u1} = p_{03} u_3 = p_3 u_3$

$MN_2^{u2} = p_{07} u_7 = p_7 u_7$

The expected time for which the repair man is busy for the repair of unit 1 and unit 2 due to instrumental failure in steady state is given by:

$IB^{u1} = IN_2^{u1} / D_1^u$ and $IB^{u1} = IN_2^{u1} / D_1^u$ where

$IN_2^{u1} = p_{04} u_4 = p_4 u_4$

$IN_2^{u2} = p_{08} u_8 = p_8 u_8$

6.3. Expected Number of Repairs

The expected number of repairs in unit 1 and unit 2 due to process failure in steady state is given by:

$PR^{u1} = PN_3^{u1} / D_1^u$ and $PR^{u2} = PN_3^{u2} / D_1^u$

where

$PN_3^{u1} = p_{01} p_{10} = p_1$

$PN_3^{u2} = p_{05} p_{50} = p_5$

The expected number of repairs in unit 1 and unit 2 due to electrical failure in steady state is given by:

$ER^{u1} = EN_3^{u1} / D_1^u$ and $ER^{u2} = EN_3^{u2} / D_1^u$

where

$EN_3^{u1} = p_{02} p_{20} = p_2$

$EN_3^{u2} = p_{06} p_{60} = p_6$

The expected number of repairs in unit 1 and unit 2 due to mechanical failure in steady state is given by:

$MR^{u1} = MN_3^{u1} / D_1^u$ and $MR^{u2} = MN_3^{u2} / D_1^u$

where

$MN_3^{u1} = p_{03} p_{30} = p_3$

$MN_3^{u2} = p_{07} p_{70} = p_7$

The expected number of repairs in unit 1 and unit 2 due to instrumental failure in steady state is given by:

$IR^{u1} = IN_3^{u1} / D_1^u$ and $IR^{u2} = IN_3^{u2} / D_1^u$

where

$IN_3^{u1} = p_{04}p_{40} = p_4$
$IN_3^{u2} = p_{08}p_{80} = p_8$

7. Profit Analysis of the System

The profi equation of the system is as follows:

$$P^u = C_0A_0^u - C_1(PB^{u1} + PR^{u1}) - C_2(PB^{u2} + PR^{u2}) - C_3(EB^{u1} + ER^{u1}) - C_4(EB^{u2} + ER^{u2})$$

$$-C_5(MB^{u1} + MR^{u1}) - C_6(MB^{u2} + MR^{u2}) - C_7(IB^{u1} + IR^{u1}) - C_8(IB^{u2} + IR^{u2})$$

where
C_0= Revenue generated by the system
$C_1(C_2)/\ C_3(C_4)/\ C_5(C_6)/\ C_7(C_8)$: - Cost per unit time for engaging the repair man and cost for repair due to process/electrical/mechanical/instrumental failure in unit 1 (unit 2).

8. Numerical Analysis

In this section, interpretation from graphs and tables has been made for the above-obtained system measures in Section 4 and Section 5. Let us assume all the failures and repair times follow exponential distribution along with their p.d.f. as:

$$f^u(t) = \lambda_u e^{-\lambda_u t},$$
$$g_i(t) = \alpha_i e^{-\alpha_i t}, i = 1, 2, 3, ..8.$$

Using the values as written in Section 3 that is calculated from real data from a manufacturing company , we get system effectiveness measures as:

- Availability of Ammonia Plant, $A_0^u = 1$
- Busy Period for Repair of Unit 1 due to Process Failure, $PB^{u1} = 0.0025$
- Busy Period for Repair of Unit 2 due to Process Failure, $PB^{u2} = 0.0033$
- Busy Period for Repair of Unit 1 due to Electrical Failure, $EB^{u1} = 3.3209 * 10^{-5}$
- Busy Period for Repair of Unit 2 due to Electrical Failure, $EB^{u2} = 3.7953 * 10^{-4}$
- Busy Period for Repair of Unit 1 due to Mechanical Failure, $\mathrm{MB}^{u1} = 0.0066$
- Busy Period for Repair of Unit 2 due to Mechanical Failure, $\mathrm{MB}^{u2} = 0.0099$
- Busy Period for Repair of Unit 1 due to Instrumental Failure, $\mathrm{IB}^{u1} = 0.0033$
- Busy Period for Repair of Unit 2 due to Instrumental Failure, $\mathrm{IB}^{u2} = 1.6943 * 10{-}4$
- Excepted no. of Repair of Unit 1 due to Process Failure, $\mathrm{PR}^{u1} = 6.3036 * 10^{-5}$
- Excepted no. of Repair of Unit 2 due to Process Failure, $\mathrm{PR}^{u2} = 4.9753 * 10^{-5}$
- Excepted no. of Repair of Unit 1 due to Electrical Failure, $\mathrm{ER}^{u1} = 6.6418 * 10^{-6}$
- Excepted no. of Repair of Unit 2 due to Electrical Failure, $\mathrm{ER}^{u2} = 6.6418 * 10^{-6}$

- Excepted no. of Repair of Unit 1 due to Mechanical Failure, $\mathrm{MR}^{u1} = 5.3074 * 10^{-5}$
- Excepted no. of Repair of Unit 2 due to Mechanical Failure, $\mathrm{MR}^{u2} = 5.6395 * 10^{-5}$
- Excepted no. of Repair of Unit 1 due to Instrumental Failure, $\mathrm{IR}^{u1} = 5.9715 * 10^{-5}$
- Excepted no. of Repair of Unit 2 due to Instrumental Failure, $\mathrm{IR}^{u2} = 5.8712 * 10^{-5}$

The graph of profit Function (Pu) w.r.t. revenue (C0) for different values of repair rate (α_1) has been shown in Figure 1.

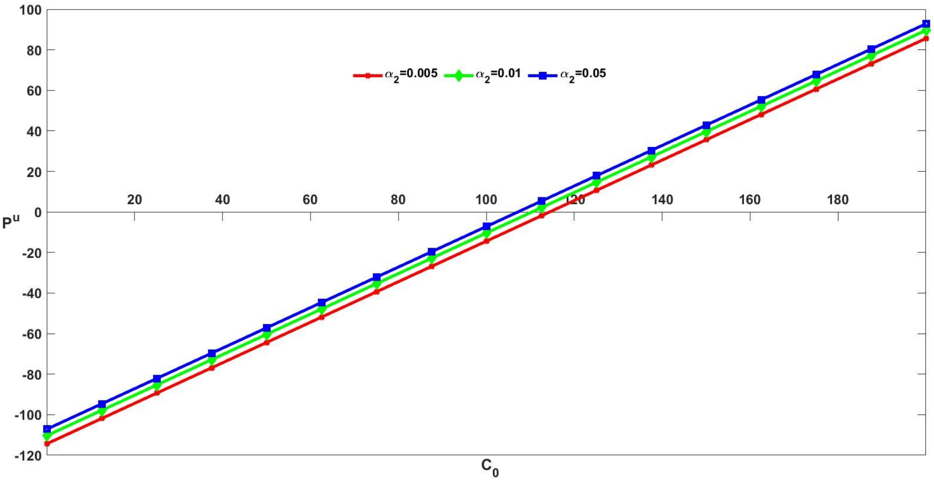

Figure 1: *Change in Profit w.r.t. Revenue and Repair Rate*

It shows that the increase in revenue and repair rate increases profit Also, the cut-off points for the system to be profitable can be observed in Fig. 1.:

- For $C_0 > 108.2567$ and $\alpha_2 = 0.05$, $P^u > 0$.
- For $C_0 > 112.6834$ and $\alpha_2 = 0.01$, $P^u > 0$.
- For $C_0 > 115.8273$ and $\alpha_2 = 0.005$, $P^u > 0$

Similarly, we can draw graphs of the profit function with other parameters to see its effect and cut-off points when the system is profitable

Table 2. Sensitivity and Relative Sensitivity Analysis of Profit Function

Parameter	Sensitivity Analysis	Relative Sensitivity Analysis
λ_u	$-3.3476 * 10^5$	-0.0212
α_1	59.2593	$3.0154 * 10^{-4}$
α_2	1.0047	$4.1063 * 10^{-5}$
α_3	$3.8409 * 103$	0.0064
α_4	$3.5789 * 103$	0.0134
α_5	17.3446	$5.3167 * 10^{-5}$
α_6	5.0857	$1.8188 * 10^{-5}$
α_7	578.7666	$6.7416 * 10^{-4}$
α_8	3.7234	$2.9827 * 10^{-5}$
C_0	1	1.0218
C_1	-0.0026	$-3.6631 * 10^{-4}$
C_2	-0.0034	$] - 1.2854 * 10^{-4}$
C_3	$-3.9851 * 10^{-5}$	$-5.0143 * 10^{-5}$
C_4	$-3.8617 * 10^{-4}$	$-2.6915 * 10^{-5}$
C_5	-0.0066	-0.0065
C_6	-0.01	$-8.9916 * 10^{-4}$
C_7	-0.0033	-0.0137
C_8	$-1.7607 * 10^{-4}$	$-3.4829 * 10^{-5}$

Table 2 shows the sensitivity and relative sensitivity analysis [34] of the profit function concerning different parameters that affect the system's profit It shows that the profit function decreases rapidly with the change in C_3 and increases with the shift in α_3.
Also, the decreasing order in which parameters affect the profit function from Table 2 as:
$C_0 > \lambda_u > C_7 > \alpha_4 > C_5 > \alpha_3 > C_6 > \alpha_7 > C_1 > \alpha_1 > C_2 > \alpha_5 > C_3 > alpha_2 > C_8 > \alpha_8 > C_4 > \alpha_6$.

9. Conclusion

In this paper, the parallel functioning of two units of an ammonia/urea plant reliability modelling has been examined. The availability of the plant, the busy period for repairs, and the anticipated number of repairs for each type of failure have all been obtained as reliability indices. Profit analysis for the plant is also carried out along with the graphical representation with respect to various parameters. Profit increases when revenue and repair rates both increase. The cut-off point is also drawn to determine when a system is profitable Finally, sensitivity analysis is performed to assess the effect of various parameters on the plant's profit function. It demonstrates that, in comparison to other factors, revenue and system failure rate have the most significant impact on the profit function. The model forecasts the failure and repair conditions based on the optimized reliability and profitability results.

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