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# MATHEMATICAL MODELING AND AVAILABILITY ANALYSIS OF STEEL INDUSTRIAL SYSTEM IN HISAR DISTRICT

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**Abstract:**

This paper presents a mathematical modeling and availability analysis of a steel industrial system located in Hisar District, Haryana, employing the Regenerative Point Graphical Technique (RPGT). The case study focuses on a stainless steel manufacturing plant comprising four essential subsystems Grinding, Descaling, Hot Steckel Mill, and Cutter Machine configured in series. Each subsystem's failure and repair rates are assumed to be constant, and a comprehensive state transition diagram is constructed to depict all possible operational and failed states of the system. Using RPGT, the study derives analytical expressions for critical reliability metrics, including mean time to system failure (MTSF), system availability, mean sojourn times, server busy period, and expected number of server visits. Numerical examples are provided to demonstrate the effect of varying failure and repair rates on system availability and profitability, with results presented through tables and graphical illustrations. The findings offer valuable insights for plant management, supporting improved decision-making for reliability, maintainability, and profit optimization in the context of the steel industry in Haryana.

**Keywords:-** Regenerative Point Graphical Technique (RPGT), Availability, MTSF, Steel Manufacturing, Reliability Analysis, Steady State, Profit Optimization

## 1. Introduction:

The evolution of modern manufacturing has led to highly sophisticated, technologically advanced industries where operational efficiency, reliability, and cost-effectiveness are essential for global competitiveness. Among these, the steel industry stands as a cornerstone of industrial development, forming the backbone of infrastructure, construction, and manufacturing sectors. In India, and particularly in Haryana's Hisar district, the steel industry is emblematic of contemporary process industries that must continuously balance high production standards, system availability, and profitability.

The steel manufacturing process is inherently complex, involving a series of interdependent subsystems such as grinding, descaling, hot Steckel mill, and cutting machines each vital for the seamless transformation of raw materials into finished products. The uninterrupted operation of these subsystems determines the plant's ability to meet production schedules and maintain product quality. However, unplanned failures, maintenance delays, and resource constraints pose ongoing challenges that can severely impact output, operational costs, and customer satisfaction.

Effective management of these challenges requires a rigorous analytical approach, where mathematical modeling plays a pivotal role. Availability analysis, in particular, is central to performance evaluation in complex engineering systems. It quantifies the likelihood that the steel industrial system or its subsystems will function as required at any given time, directly influencing maintenance planning, resource allocation, and long-term investment strategies. High system availability minimizes downtime, maximizes throughput, and enhances overall profitability objectives that are critical for a region like Hisar, known for its vibrant industrial base.

This study focuses on the mathematical modeling and availability analysis of a steel industrial system operating in Hisar District, Haryana. The research employs the Regenerative Point Graphical Technique (RPGT), a robust analytical framework rooted in Markov process theory. RPGT enables the modeling of systems with multiple operational, failed, and repair states, accommodating both constant and variable failure and repair rates. The technique is particularly well-suited for systems where subsystems may have non-identical configurations, regenerative states, and non-exponential repair time distributions—characteristics common in real-world steel plants. Within this case study, the steel plant under analysis comprises four critical subsystems: Grinding, Descaling, Hot Steckel Mill, and Cutter Machine. Each subsystem is subject to potential failure, and their timely repair or replacement is crucial for overall system performance. The methodology begins with the development of a comprehensive state transition diagram, mapping all possible operational and failure states. Subsequently, RPGT is applied to derive closed-form analytical expressions for key performance metrics, including mean time to system failure (MTSF), system availability, mean sojourn times, the expected number of server (repair crew) visits, and the busy period of maintenance personnel. Sensitivity analyses are conducted to explore how changes in failure and repair rates affect system metrics and profitability, offering actionable guidance on where to invest in reliability improvements or optimize maintenance schedules.

In summary, this paper sets the stage for a comprehensive investigation into the mathematical modeling and availability analysis of a steel industrial system in Hisar District. By combining advanced modeling techniques like RPGT with profit and sensitivity analyses, the study aims to bridge the gap between engineering theory and industrial practice. The findings are intended to empower plant management with the analytical tools necessary for proactive maintenance planning, optimal resource allocation, and sustainable operational excellence in the competitive landscape of the steel industry.

## 2. Review of Literature

The literature on mathematical modeling, reliability, and availability analysis in industrial and process systems demonstrates a progressive integration of advanced techniques and real-world applications, particularly in the steel and process industries. **Agrawal et al. (2021)** conducted detailed performance analyses of a reverse osmosis water treatment plant, emphasizing system reliability and the practical implications of system improvement strategies. **Ahmed, Bhatia, and Kumar (2014)** explored the effects of repair delays on system faults, highlighting the importance of timely maintenance and the impact of delays on overall system effectiveness. **Ahmad and Kumar (2015)** presented two complementary studies: one focused on availability analysis and the other on profit analysis for a two-unit centrifuge system accounting for both minor and major faults, as well as system halt states. **Arya and Verma (2025)** contributed to the prediction of reliability and availability in embedded systems by using environment modeling and simulation, suggesting that environmental factors and modeling accuracy are critical for predictive maintenance. **Bansal and Tyagi (2024)** applied artificial neural networks to optimize availability and profit in the continuous casting systems of steel industries, demonstrating the effectiveness of machine learning approaches in industrial reliability optimization. **Bai et al. (2022)** focused on the upgradation of process plants using Reliability, Availability, and Maintainability (RAM) criteria, providing a structured approach for plant improvement and risk reduction**. Bao and Cui (2010)** analyzed availability for series Markov repairable systems, taking into account neglected or delayed failures, and offered analytical techniques for more realistic system modeling. **Bastos and Fujiyama (2023)** showed the application of reliability-centered maintenance in a steel mill, illustrating how targeted maintenance strategies can improve plant performance and reduce unplanned downtime. **Beji et al. (2010)** introduced a hybrid particle swarm optimization algorithm to address redundancy allocation problems, demonstrating the potential of computational intelligence in optimizing complex industrial systems. The literature underscores the essential role of system modeling, timely maintenance, and the integration of economic considerations (profit, cost, risk) in achieving optimal industrial operations, particularly within the steel industry. These foundational works provide the methodological and conceptual basis for the present study on the mathematical modeling and availability analysis of a steel industrial system in Hisar District, Haryana.

### 3. System Description

The Indian steel industry is a significant part of the global steel market, ranking as the world's second-largest producer of crude steel. It has seen substantial growth in both production and consumption, with a strong focus on expanding capacity to meet both domestic and international demand. The industry consists of mainly four subsystems and these are namely: Grinding, Descaling, hot Steckel and Cutter Machine. These are responsible for affecting the availability of the system. Each unit is described in detail below:

**Grinding Machine (A) :** A grinding machine is often used for grinding. In the steel industry, grinding machines are essential for shaping, smoothing, and finishing steel components. A failure in a grinding machine can indeed lead to significant disruptions in the steel manufacturing process. This is because grinding is often the final stage of machining, and if it's not done correctly, it can affect the quality, dimensions, and surface finish of the steel products, potentially rendering them unusable.

**Descaling Machine (B) :** Descaling machine is specifically designed to treat steel strips (carbon alloy or stainless steel) on a continuous passage under the blast streams at a given speed. The Steel Strip Descales have been developed to treat different strip widths (ranging from 50 to 800 mm for the narrow strips and from 800 to 2100 mm for the large strips), horizontally or vertically positioned.

**Hot Steckel Mill (C) :** The classical steckel mill configuration consists of a rougher with an attached edger that jointly rolls out slabs to transfer bar thickness of 25-45mm. The process involves multiple passes, with the strip coiled and reheated in furnaces after each pass to maintain temperature.

**Cutting Machine (D):** There are mainly two types of cutter machines namely SM-8 and SM-10.The SM-8 cutting machine is designed for in-line cutting of billets, blooms and slabs. This machine is an adaptation of the SM-10 and uses the same tubular and vertical drives.

## 4. Assumptions and Notations

1. The framework comprises of three non-identical sub-units. Firstly, two units are active and another unit is kept in cold standby.
2. Switching over is imperfect.
3. A single repairman is available 24*7.
4. Repaired unit is new.
5. The framework is argued under steady state conditions.

$f_j$: Fuzziness measure of the j-state.

$\beta_1$ : Constant failure rate of the unit 'A' from full capacity to complete failure.

$\beta_2$: Constant failure rate of the standby 'B'.

$\beta_3$: Constant failure rate of the unit 'C'.

p : Probability of the switch working properly.

$\alpha_1$: Constant repair rate of main unit.

$\alpha_2$: Constant repair rate of standby.

$\alpha_3$: Constant repair rate of unit 'C'.

$\alpha_4$: Constant repair rate of the switch.

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A/a: Unit ‘A’ in good / failed state.

B/ (B)//b: Redundant unit in operative/ standby / failed state.

S/s: Switch in operative/ failed state.

**5. Transition Diagram of the System**

Following the above assumptions and notations, the transition diagram of the system is as shown in Figure 1. The system can be in any of the following states with respect to the above symbol.

$S_2$ = A(B)CD; $S_3$= a(B)Cd; $S_4$= a(B)CD; $S_5$ = A(B)cD; $S_6$ =A(B)Cd; $S_7$ = a(B)cD; $S_8$ = AbCd; $S_9$= abCD; $S_{10}$ = AbCD; $S_{11}$ = AbcD

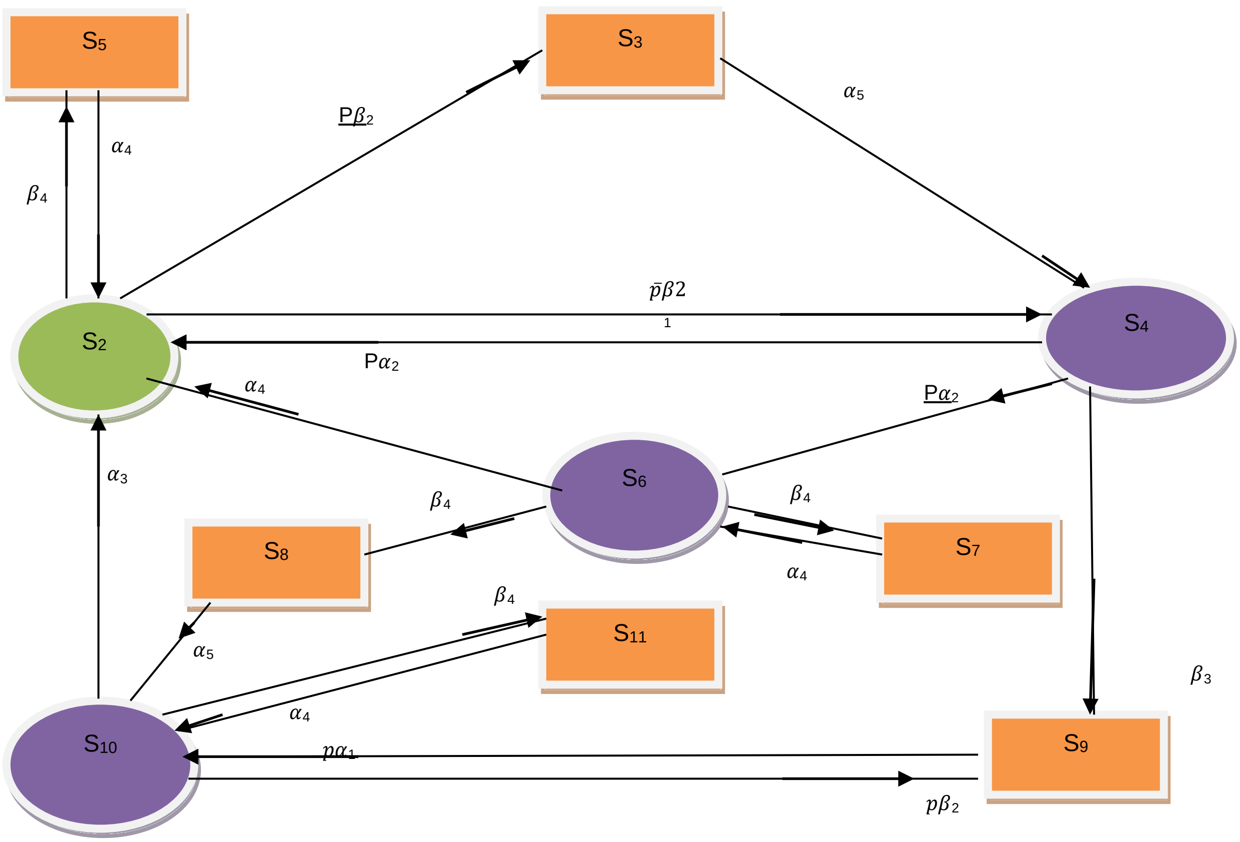


**Figure 1: TRANSITION DIAGRAM OF THE SYSTEM**

**6. Transition Probabilities and Mean Sojourn Times:**

**Table 1: Transition Probabilities**

| $q_{i,j}(t)$ | $p_{i,j}=q_{i,j}^*(0)$ |
|---|---|
| $q_{2,3}=p\beta_2 e^{-(p\beta_2+\bar{p}\beta_2+\beta_4)t}$<br>$q_{2,4}=\bar{p}\beta_2 e^{-(p\beta_2+\bar{p}\beta_2+\beta_4)t}$<br>$q_{2,5}=\beta_4 e^{-(p\beta_2+\bar{p}\beta_2+\beta_4)t}$ | $p_{2,3}=p\beta_2/(p\beta_2+\bar{p}\beta_2+\beta_4)$<br>$p_{2,4}=\bar{p}\beta_2/(p\beta_2+\bar{p}\beta_2+\beta_4)$<br>$p_{2,5}=\beta_4/(p\beta_2+\bar{p}\beta_2+\beta_4)$ |
| $q_{3,2}=\bar{p}\beta_2 e^{-(\bar{p}\beta_2+\alpha_5)t}$<br>$q_{3,4}=\alpha_5 e^{-(\bar{p}\beta_2+\alpha_5)t}$ | $p_{3,2}=\bar{p}\beta_2/(\bar{p}\beta_2+\alpha_5)$<br>$p_{3,4}=\alpha_5/(\bar{p}\beta_2+\alpha_5)$ |
| $q_{4,2}=p\alpha_2 e^{-(p\alpha_2+\bar{p}\alpha_2+\beta_2)t}$<br>$q_{4,6}=\bar{p}\alpha_2 e^{-(p\alpha_2+\bar{p}\alpha_2+\beta_2)t}$<br>$q_{4,9}=\beta_3 e^{-(p\alpha_2+\bar{p}\alpha_2+\beta_3)t}$ | $p_{4,2}=p\alpha_2/(p\alpha_2+\bar{p}\alpha_2+\beta_3)$<br>$p_{4,6}=\bar{p}\alpha_2/(p\alpha_2+\bar{p}\alpha_2+\beta_3)$<br>$p_{4,9}=\beta_3/(p\alpha_2+\bar{p}\alpha_2+\beta_3)$ |
| $q_{5,2}=\alpha_4 e^{-(\alpha_4)t}$ | $p_{5,2}=1$ |
| $q_{6,2}=\alpha_5 e^{-(\alpha_5+\beta_4+\beta_3)t}$<br>$q_{6,7}=\beta_4 e^{-(\alpha_5+\beta_4+\beta_3)t}$<br>$q_{6,8}=\beta_3 e^{-(\alpha_5+\beta_4+\beta_3)t}$ | $p_{6,2}=\alpha_5/(\alpha_5+\beta_4+\beta_3)$<br>$p_{6,7}=\beta_2/(\alpha_5+\beta_4+\beta_3)$<br>$p_{6,8}=\beta_3/(\alpha_5+\beta_4+\beta_3)$ |
| $q_{7,6}=\alpha_4 e^{-(\alpha_4)t}$ | $p_{7,6}=1$ |
| $q_{8,10}=\alpha_5 e^{-(\alpha_5)t}$ | $p_{8,10}=1$ |
| $q_{9,10}=p\beta_4 e^{-(p\beta_4)t}$ | $p_{9,10}=1$ |
| $q_{10,2}=\alpha_3 e^{-(\alpha_3+p\beta_2+\beta_4)t}$<br>$q_{10,9}=p\beta_2 e^{-(\alpha_3+p\beta_2+\beta_4)t}$<br>$q_{10,11}=\beta_4 e^{-(\alpha_3+p\beta_2+\beta_4)t}$ | $p_{10,2}=\alpha_3/(\alpha_3+p\beta_2+\beta_4)$<br>$p_{10,9}=p\beta_2/(\alpha_3+p\beta_2+\beta_4)$<br>$p_{10,11}=\beta_4/(\alpha_3+p\beta_2+\beta_4)$ |
| $q_{11,10}=\alpha_4 e^{-(\alpha_4)t}$ | $p_{11,10}=1$ |

**Table 2: Mean Sojourn Times**

| $R_i(t)$ | $\mu_i=R_i^*(0)$ |
|---|---|
| $R_2(t)=e^{-(p\beta_2+\bar{p}\beta_2+\beta_4)t}$ | $\mu_2=1/(p\beta_2+\bar{p}\beta_2+\beta_4)$ |
| $R_3(t)=e^{-(\bar{p}\beta_2+\alpha_5)t}$ | $\mu_3=1/(\bar{p}\beta_2+\alpha_5)$ |
| $R_4(t)=e^{-(p\alpha_2+\bar{p}\alpha_2+\beta_2)t}$ | $\mu_4=1/(p\alpha_2+\bar{p}\alpha_2+\beta_2)$ |
| $R_5(t)=e^{-(\alpha_4)t}$ | $\mu_5=1/(\alpha_4)$ |

| | |
|---|---|
| $R_6(t) = e^{-(\alpha_5+\beta_4+\beta_3)t}$ | $\mu_6=1/(\alpha_5+\beta_4+\beta_3)$ |
| $R_7(t) = e^{-(\alpha_4)t}$ | $\mu_7=1/(\alpha_4)$ |
| $R_8(t) = e^{-(\alpha_5)t}$ | $\mu_8=1/(\alpha_5)$ |
| $R_9(t) = e^{-(p\beta_4)t}$ | $\mu_9=1/(p\beta_4)$ |
| $R_{10}(t) = e^{-(\alpha_3+p\beta_2+\beta_4)t}$ | $\mu_{10}=1/(\alpha_3+p\beta_2+\beta_4)$ |
| $R_{11}(t) = e^{-(\alpha_4)t}$ | $\mu_{11}=1/(\alpha_4)$ |

**7. Transition Probability Factors:**

The mean time to system failure and all the key parameters of the system (under steady state conditions) are evaluated by using Regenerative Point Graphical Technique (RPGT) and using '2' as the base state of the system as under: -

$V_{2,2}$= 1 (Verified)

$V_{2,3}$= (2, 3) = $p_{2,3}$

$V_{2,4}$= (2, 4) = $p_{2,4}$

$V_{2,5}$= ……continue

**8. Evaluation of Parameters:**

The mean time to system failure and all the key parameters of the system (under steady state conditions) are evaluated by applying Regenerative Point Graphical Technique (RPGT) taking '2' as the base state.

**(a) MTSF ($T_0$):** The regenerative un-failed states to which the system can transit (Initial state '2') before entering any failed state are: for 'ξ' = '2', MTSF is given by

$$\text{MTSF}(T_0) = \left[\sum_{i,s_r}\left\{\frac{\left\{pr\left(\xi\xrightarrow{s_r(s_{ff})}i\right)\right\}\mu_i}{\prod_{m_1\neq\xi}\{1-V_{\overline{m_1,m_1}}\}}\right\}\right] \div \left[1-\sum_{s_r}\left\{\frac{\left\{pr\left(\xi\xrightarrow{s_r(s_{ff})}\xi\right)\right\}\mu_i^1}{\prod_{m_2\neq\xi}(1-V_{\overline{m_2,m_2}})}\right\}\right]$$

= [(2, 2)$\mu_2$ + (2, 3)$\mu_3$ + (2, 3, 4)$\mu_4$ + (2, 4)$\mu_5$ + (2, 4,6)$\mu_6$ + (2, 3, 4,6)$\mu_7$]/

[1 - (2, 4, 2) + (2, 3, 4, 2) + (2, 4, 6, 2) + (2, 3, 4, 6, 2)

**(b) Availability of the System ($A_0$):** The regenerative states at which the system is available are j = 2, 4,6,10 and the regenerative states are i= 2 to 11 for 'ξ'='2', the total fraction of time system is available is given by

$$A_0=\left[\sum_{j,s_r}\left\{\frac{\left\{pr\left(\xi\xrightarrow{s_r}j\right)\right\}f_j\mu_j}{\prod_{m_1\neq\xi}\left\{1-V_{m_1,m_1}\right\}}\right\}\right]\div\left[\sum_{i,s_r}\left\{\frac{\left\{pr\left(\xi\xrightarrow{s_r}i\right)\right\}}{\prod_{m_2\neq\xi}\left(1-V_{m_2,m_2}\right)}\right\}\right]$$

$$A_0=\left[\sum_j V_{\xi,j}.f_j.\mu_j\right]\div\left[\sum_i V_{\xi,i}.\mu_i^1\right]$$

$= [V_{2,2}f_2\mu_2 + V_{2,4}f_4\mu_4 + V_{2,6}f_6\mu_6 + V_{2,10}f_{10}\mu_{10}] \div [V_{2,4}\mu_4^1 + V_{2,2}\mu_2^1 + V_{2,3}\mu_3^1 + V_{2,5}\mu_5^1$
$+ V_{2,6}\mu_6^1 + V_{2,7}\mu_7^1 + V_{2,8}\mu_8^1 + V_{2,9}\mu_9^1 + V_{2,10}\mu_{10}^1 + V_{2,11}\mu_{11}^1]$

**(c) Busy Period of the Server ($B_0$):** The regenerative states where the server is busy while doing repairs are j = 3 to 11

$$B_0=\left[\sum_{j,s_r}\left\{\frac{\left\{pr\left(\xi\xrightarrow{s_r}j\right)\right\}n_j}{\prod_{m_1\neq\xi}\left\{1-V_{m_1,m_1}\right\}}\right\}\right]\div\left[\sum_{i,s_r}\left\{\frac{\left\{pr\left(\xi\xrightarrow{s_r}i\right)\right\}\mu_i^1}{\prod_{m_2\neq\xi}\left(1-V_{m_2,m_2}\right)}\right\}\right]$$

$B_0 = (V_{1,2}n_2+V_{1,3}n_3+V_{1,4}n_4+V_{1,5}n_5+V_{1,6}n_6+V_{1,7}n_7+V_{1,8}n_8+V_{1,9}n_9+ V_{1,10}n_{10})/D$

$D= [V_{2,2}\mu_2+V_{2,3}\mu_3+V_{2,4}\mu_4+V_{2,5}\mu_5 +V_{2,6}\mu_6+V_{2,7}\mu_7 +V_{2,8}\mu_8+V_{2,9}\mu_9+V_{2,10}\mu_{10}+V_{2,11}\mu_{11}]$

**(d) Expected number of server's visits ($V_0$):** The regenerative state to which server visits a fresh are j = 3, 4, 5 and the regenerative states are j = 2 to 11. Therefore no expected no. of server's visit for 'ξ' = '2' is given by

$$V_0=\left[\sum_{j,s_r}\left\{\frac{\left\{pr\left(\xi\xrightarrow{s_r}j\right)\right\}}{\prod_{k_1\neq\xi}\left\{1-V_{k_1,k_1}\right\}}\right\}\right]\div\left[\sum_{i,s_r}\left\{\frac{\left\{pr\left(\xi\xrightarrow{s_r}i\right)\right\}\mu_i^1}{\prod_{k_2\neq\xi}\left(1-V_{k_2,k_2}\right)}\right\}\right]$$

$V_0 = (V_{2,3} +V_{2,4} +V_{2,5})/D$

$D= [V_{2,2}\mu_2+V_{2,3}\mu_3+V_{2,4}\mu_4+V_{2,5}\mu_5 +V_{2,6}\mu_6+V_{2,7}\mu_7 +V_{2,8}\mu_8+V_{2,9}\mu_9+V_{2,10}\mu_{10}+V_{2,11}\mu_{11}]$

**9. Particular Cases**: -

For $\beta_i = \beta$ ; $2 \le i \le 4$; $\alpha_i = \alpha$; $2 \le i \le 5$; p = 1, $\underline{p}$ = 0,

**Analytical Discussion: Behavior Analysis:** Fix; $\alpha = \alpha_i$; $\beta=\beta_i$

**Mean Time to System Failure (MTSF) ($T_0$)**

**Table 3: MTSF**

| $\beta$ \ $\alpha$ | 0.55 | 0.65 | 0.75 |
|---|---|---|---|
| 0.15 | 8.231 | 8.290 | 8.413 |
| 0.25 | 6.835 | 6.915 | 6.988 |
| 0.35 | 4.057 | 4.188 | 4.330 |

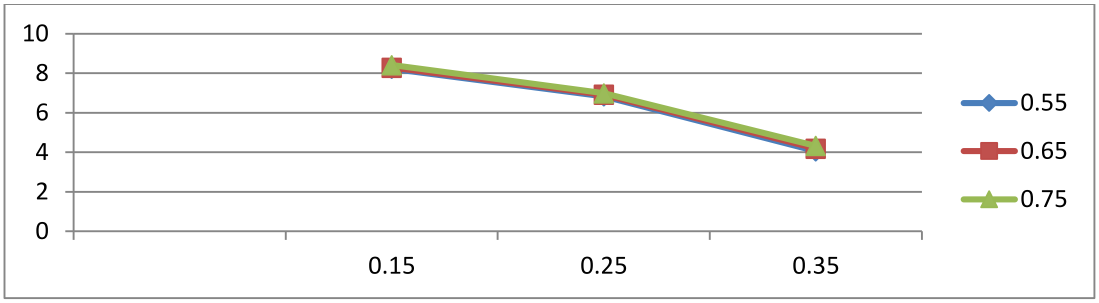


**Figure 2: MTSF**

Table 3 presents the computed values of Mean Time to System Failure (MTSF) for varying combinations of failure rates and repair rates for the steel industrial system. As illustrated in both Table 3 and Figure 2, there is a clear and significant inverse relationship between the system's failure rate and the MTSF. For instance, at a low failure rate of (0.15), the MTSF values are at their highest across the range of repair rates, reaching values such as 8.231, 8.290, and 8.413. However, as the failure rate rises to (0.25), the MTSF drops to 6.835, 6.915, and 6.988 for the same repair rates. This downward trend becomes even more pronounced at a higher failure rate of (0.35), where MTSF values further decline to 4.057, 4.188, and 4.330. These results clearly demonstrate that the reliability and longevity of the steel industrial system are highly sensitive to the failure rates of its critical subsystems. This indicates that, although efficient and rapid repair strategies can somewhat extend the system's operational time, their effect is limited if the underlying failure rate remains high. In summary, the analysis of Table 3 and Figure 2 for the steel industrial system reveals that the Mean Time to System Failure is predominantly dictated by the failure rates of the system's components.

**Availability of the System ($A_0$):**

**Table 4: Availability of System ($A_0$)**

| $\beta$ \ $\alpha$ | 0.55 | 0.65 | 0.75 |
|---|---|---|---|
| 0.15 | 0.759 | 0.865 | 0.903 |
| 0.25 | 0.508 | 0.663 | 0.815 |
| 0.35 | 0.352 | 0.426 | 0.513 |

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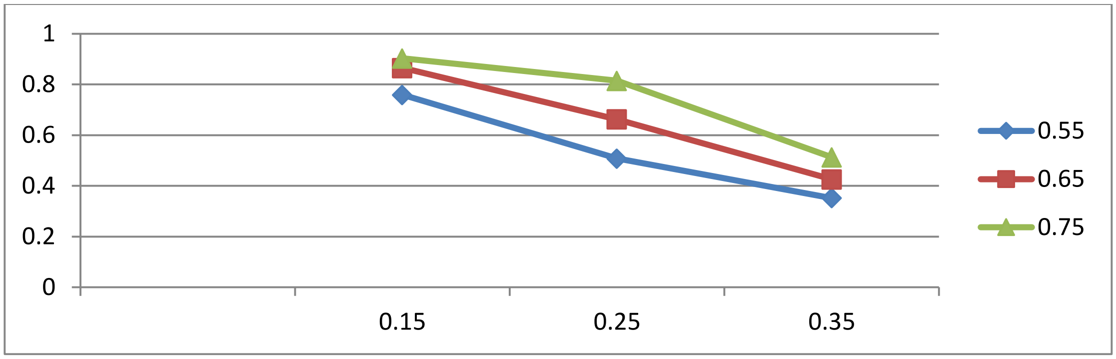


**Fig. 3: Availability of System**

Table 4 presents the steady-state availability ($A_0$) of the steel industrial system for different combinations of failure rates and repair rates. The data, further visualized in Figure 3, reveal important trends regarding the operational performance and reliability of the plant's critical production line. A close examination of the values in Table 4 highlights a distinct and consistent pattern: as the failure rate of the steel plant subsystems increases, the overall system availability decreases sharply, regardless of the level of repair rate. For example, when the failure rate is low (0.15), the availability values are significantly higher across all repair rates, reaching as much as 0.759, 0.865, and 0.903 for repair rates of 0.55, 0.65, and 0.75, respectively. However, as the failure rate is increased to intermediate (0.25) and then to higher levels (0.35), the system's availability drops markedly. At (0.25), availability falls to 0.508, 0.663, and 0.815, and at (0.35), it further declines to 0.352, 0.426, and 0.513, even when the repair rates are high. This can be observed, for instance, at a failure rate of (0.25), where increasing the repair rate from 0.55 to 0.75 lifts the availability from 0.508 to 0.815. Similarly, at (0.35), the availability improves from 0.352 to 0.513. This demonstrates that while an effective and responsive maintenance team is valuable, it cannot fully compensate for frequent breakdowns in the steel plant's core machinery. In summary, Table 4 and Figure 3 collectively emphasize that in the steel industrial system, minimizing failure rates is paramount for optimizing system availability.

**Server of Busy Period ($B_0$):**

**Table 5: Server of Busy Period ($B_0$)**

| β \ α | 0.55 | 0.65 | 0.75 |
|---|---|---|---|
| 0.15 | 0.640 | 0.599 | 0.564 |
| 0.25 | 0.698 | 0.653 | 0.622 |
| 0.35 | 0.798 | 0.687 | 0.659 |

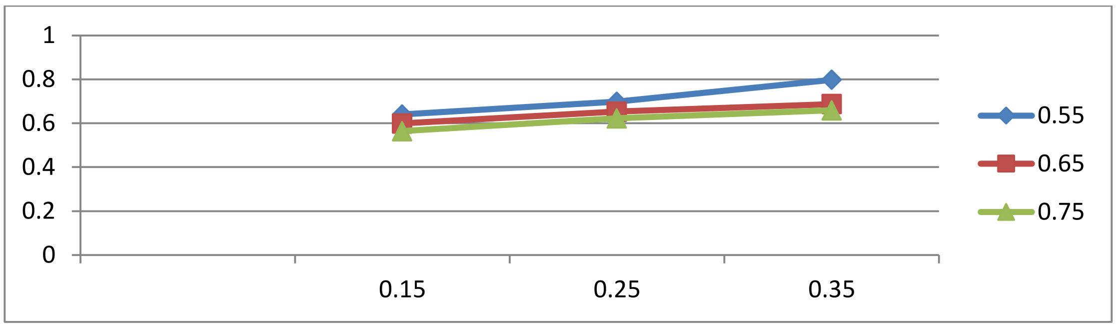


**Fig. 4: Server of Busy Period**

In summary, Table 5 and Figure 4 collectively highlight that the server's busy period in a steel industrial system is predominantly governed by the interplay between equipment failure rates and repair efficiency. Sustained efforts to minimize failure incidents, coupled with investments in advanced repair capabilities, are essential for optimizing maintenance resource utilization and ensuring continuous, reliable production. These findings reinforce the need for a balanced approach that prioritizes both reliability engineering and responsive maintenance planning within the steel industry.

**Expected Number of server's visits ($V_0$)**

**Table 6: Expected Number of server's visits ($V_0$)**

| β \ α | 0.55 | 0.65 | 0.75 |
|---|---|---|---|
| 0.15 | 0.098 | 0.090 | 0.083 |
| 0.25 | 0.114 | 0.100 | 0.089 |
| 0.35 | 0.117 | 0.107 | 0.103 |

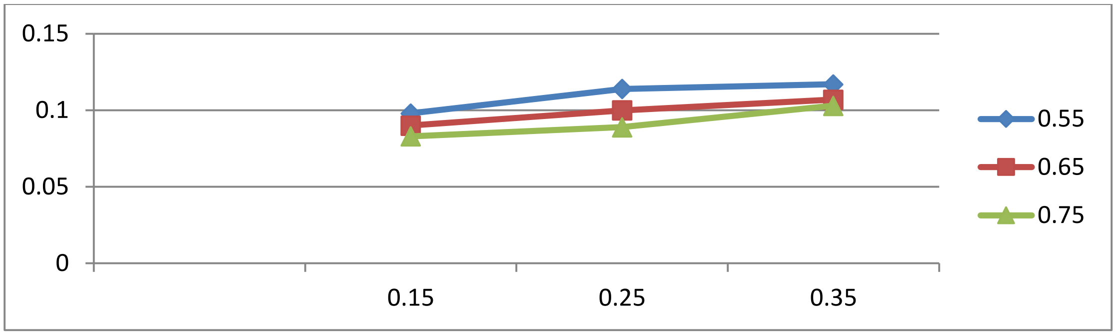


**Fig. 5: Expected Number of Server's Visits**

Table 6 and Figure 5 provide a quantitative view of the expected number of visits made by the maintenance server (repair personnel) to attend to failures within the steel industrial system located in HISAR, Haryana. This metric ($V_0$) is an important indicator of the maintenance workload and the operational reliability of the plant's interconnected subsystems. A closer inspection of the data reveals that as the failure rate of the plant's machinery increases, the expected number of repair visits also rises. For instance, when the failure rate is minimal (0.15), the expected number of visits per unit time remains low, with figures decreasing from 0.098 to 0.083 as the repair rate increases from 0.55 to 0.75. At the highest failure rate examined (0.35), the expected number of server's visits peaks at 0.117 for the lowest repair rate and remains comparatively elevated even as repair efficiency improves. In summary, the analysis of Table 6 and Figure 5 for the Hisar, Haryana steel plant underscores the direct relationship between equipment reliability and maintenance workload. This, in turn, enhances the plant's operational stability, cost-effectiveness, and long-term sustainability in a competitive industrial landscape.

## 10 **Conclusion:**

The comprehensive behavior analysis of the steel industrial system in Hisar, Haryana, highlights the intricate relationship between system reliability parameters specifically failure and repair rates and key performance indicators such as mean time to system failure (MTSF), system availability, server busy period, and the expected number of maintenance interventions. The findings consistently show that minimizing the failure rates of critical subsystems, particularly those in the early and final stages of production, has a substantial positive impact on overall plant performance. Improvements in repair efficiency further enhance system reliability, but their benefits are most evident when coupled with proactive measures to prevent failures from occurring in the first place. Data from the various tables and figures demonstrate that subsystems occupying pivotal positions in the production process especially those prone to frequent breakdowns should be prioritized for targeted maintenance strategies and design improvements. Ensuring high-quality equipment, regular preventive maintenance, and rapid response capabilities in these areas leads to higher availability, reduced downtime, and more efficient use of maintenance resources. Ultimately, for sustained operational excellence in the Hisar facility, plant management should adopt a balanced approach that emphasizes reducing failure incidence, optimizing repair processes, and strategically investing in the most influential units. This integrated strategy will drive productivity, control costs, and support the long-term reliability and competitiveness of the plant.

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