# AVAILABILITY OPTIMIZATION OF A PAINT MANUFACTURING PLANT USING GREY WOLF OPTIMIZATION: A METAHEURISTIC APPROACH

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**Abstract**

*The primary objective of present research work is to evaluate and improve the performance and availability of the paint manufacturing plant. Paint manufacturing plant consists of five subsystem naming mixer, grinder, thinner, labelling, and filling unit. Among them labelling and filling unit have two machines in parallel configuration and both are working simultaneously. All failure and repair rates are distributed exponentially. Markov birth-death process is utilized to model the dynamic behavior of the system and its sub-components, enabling a quantitative analysis of system availability. Grey wolf optimization (GWO), a swarm-based optimization technique is used to optimize the availability of the system. Moreover, the research conducts a thorough comparison between the outcomes derived from the Markov birth-death process and the GWO technique. By harnessing the power of GWO, the study aims to further enhance the plant's overall performance.*

**Keywords:** Paint Manufacturing Plant, Markov Birth-death Process, Availability, Grey Wolf Optimization

## I. Introduction

In the contemporary industrial landscape, the pursuit of enhanced operational efficiency and availability remains a paramount concern for manufacturing facilities across various sectors. The paint manufacturing industry plays a pivotal role in sectors such as automotive, construction, and consumer goods. However, the intricacies of operating a paint manufacturing plant entail multifaceted challenges that impact both production efficiency and overall plant availability. The convergence of factors including equipment breakdowns, maintenance scheduling, and process bottlenecks can lead to undesirable downtime and reduced performance. Thus, a systematic investigation into optimizing plant performance is not only a scientific pursuit but a practical necessity.

Historically, the paint manufacturing industry has undergone significant transformations, mirroring advancements in technology, materials, and process optimization. As a result, the industry's journey has been marked by shifts in production methodologies, ingredient formulations, and quality assurance practices. Over the years, the industry's evolution has been propelled by the growing demand for superior quality coatings, environmental sustainability, and cost-effective production. The past era of paint manufacturing was characterized by conventional batch processes and manual labor-intensive operations. These approaches often introduced variability in product quality and production efficiency. However, with the advent of automation, computer-aided design, and advanced process control systems, the industry witnessed substantial improvements in reliability and productivity. Automation minimized human errors, enhanced process repeatability, and facilitated real-time monitoring and control of critical process parameters.

The increasing complexity of paint manufacturing processes, coupled with the demand for higher product quality, has driven the need for sophisticated analytical and optimization tools. In response to this demand, researchers and practitioners have explored various methodologies to enhance the operational reliability and productivity of manufacturing plants. One prominent avenue of exploration has been the integration of metaheuristic techniques, which offer innovative approaches to tackle complex optimization problems. Soltanali et al. [12] aimed to enhance automotive manufacturing productivity and reliability using RAM methodologies. It identified bottlenecks in the vehicle body conveying process and optimized maintenance intervals to improve operational performance. Dahiya and Kumar [4] introduced a novel method for assessing a paint manufacturing plant's performance and availability analysis by employing fuzzy reliability and coverage factors. Ostadi [6] employed a general preventive maintenance model to optimize maintenance costs while ensuring reliability and availability in a flexible manufacturing system (FMS). An optimal preventive maintenance framework was applied to a robot paint sprayer, providing maintenance plans and reliability parameters. Omoregbe and Eniola [7] investigated maintenance practices' impact on competitive advantage in the paint manufacturing industry, revealing a positive relationship between preventive maintenance and competitive advantage. Chanda and Naskar [8] focused on assessing reliability of paint manufacturing plant by collecting breakdown and maintenance data, identifying worker inefficiency and component degradation as primary failure factors. Schultmann et al. [11] addressed challenges faced by small and medium sized companies in supply chains, focusing on reliable throughput times amid uncertainties. It proposed a fuzzy scheduling approach for hybrid flow shops and validated it through a case study in paint manufacturing.

Metaheuristic approaches are widely used in availability optimization problems to find near-optimal solutions for complex problems. Saini et al. [10] assessed cloud infrastructure's availability, crucial for its operation in healthcare and business. Utilizing both, dragonfly algorithm (DA) and grey wolf algorithms (GWO), a stochastic model was optimized, emphasizing the superior performance of the GWO. Saini et al. [9] aimed to create an innovative, efficient irrigation system (EIIS) using a series-configured setup with internal cold standby redundancy for sensor units and optimization was performed with GWO and DA to enhance system efficiency and performance. Kumar et al. [2] employed metaheuristic algorithms genetic algorithm (GA) and particle swarm optimization (PSO), to optimize performance of cooling tower. A novel stochastic model for a six-subsystem cooling tower was developed using Markovian processes, considering factors like random variables, repair, and failure rates. Saini et al. [8] aimed to develop a novel stochastic model for optimizing the availability of embedded life-critical systems by using DA and GWO algorithms. Yadav et al. [13] analyzed the reliability and availability of a repairable system using the Markov approach. The impact of failure rate, repair rate, and operating time on reliability, MTSF, and availability was also discussed. Saini et al. [7] aimed to assess the availability and performance of a sewage treatment plant's primary unit using redundancy. Mirjalili et al. [3] introduced the Grey Wolf Optimizer (GWO), a metaheuristic inspired by grey wolves' social structure and hunting behavior. It outperformed other metaheuristics on various test functions and successfully tackled engineering design problems.

The whole manuscript is divided into five sections. Section 1 includes the introduction of proposed system and previous work done in related area. section 2 provides the insights into used materials and methods for investigation. In section 3, mathematical modelling, steady state diagram and availability analysis of the system is mentioned. Numerical and graphical representation of results is appended in section 4. Section 5 cover the conclusion part of the research.

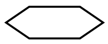
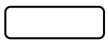
## II. Material and Methods

This section contains the notations and methodology used for the availability investigation of paint manufacturing plant.

### I. Notations

The following nomenclature is used to develop the state transition diagram and mathematical modelling of system.

**Table 1:** *Notations for paint manufacturing plant's sub-system*

| Sr. no. | Sub-systems and notations | Notations for different states function | | | Failure rates ($\alpha_i$) | Repair rates ($\beta_j$) |
|---|---|---|---|---|---|---|
| | | Operative state | Degraded states | Complete failed state | | |
| 1 | Mixer (U) | U | - | u | $\alpha_1$ | $\beta_1$ |
| 2 | Grinder (V) | V | - | v | $\alpha_2$ | $\beta_2$ |
| 3 | Dilution/Thinner (W) | W | - | w | $\alpha_3$ | $\beta_3$ |
| 4 | Labelling unit ($X^2$) (Two parallel machine) | $X^2$ | $X^1$ | x | $\alpha_4$, $\alpha_6$ | $\beta_4$, $\beta_6$ |
| 5 | Filling unit ($Y^2$) (Two parallel machine) | $Y^2$ | $Y^1$ | y | $\alpha_5$, $\alpha_7$ | $\beta_5$, $\beta_7$ |
| 6 | $P_i(t)$ | Probability that the system is in $i^{th}$ state at time t | | | | |
| 7 |  | Operative states | | | | |
| 8 |  | Degraded states | | | | |
| 9 |  | Completely failed states | | | | |

### II. System Description

The proposed paint manufacturing system comprises five sub-systems like mixer, grinder, thinner, labelling unit, and filling unit. The failure and repair rates of all the subsystems follow exponential distribution. All the subsystem arranged in a series configuration and work-flow diagram of system is append in figure 1.

i) Subsystem U (Mixer)
In paint manufacturing, a mixer unit plays a crucial role in blending and homogenizing various raw materials to create consistent and high-quality paint products. The unit's primary purpose is to create a homogeneous mixture by effectively dispersing and combining the ingredients. The failure of this unit can result in the entire system's breakdown.

ii) Subsystem V (Grinder)
A grinder unit serves the essential purpose of reducing solid particles, such as pigments and

fillers, into finer particles to achieve the desired texture and consistency in the final paint product. The grinder unit plays a crucial role in breaking down aggregates and achieving uniform particle size distribution, which directly influences the paint's color, opacity, gloss, and overall quality. The failure of this subsystem can impact the overall functionality of the system.

### iii) Subsystem W (Thinner/Diluter)

Thinner or diluter plays a pivotal role in paint manufacturing as a vital solvent used to modify the viscosity and consistency of paint formulations. Thinner is employed to reduce the thickness of paint, making it easier to apply and ensuring a smooth, even coat. Failure of subsystem can disrupt and compromise the entire operation of the system. Subsystem failures have the potential to disrupt and compromise the entire system's operation.

### iv) Subsystem X (Labelling unit)

A labelling unit plays a pivotal role in ensuring that each container bears essential information, including product details, batch numbers, safety warnings, and regulatory compliance. This system comprises two labelling machines working together in parallel configuration with different failure and repair rates.

### v) Subsystem Y (Filling unit)

A filling unit in a paint manufacturing plant is responsible for accurately filling paint into containers, such as cans or buckets. Its importance lies in ensuring precise and consistent product quantities, which are essential for quality control and cost efficiency. The system consists of two filling machines operating in parallel, each with its own distinct rates of failure and repair.

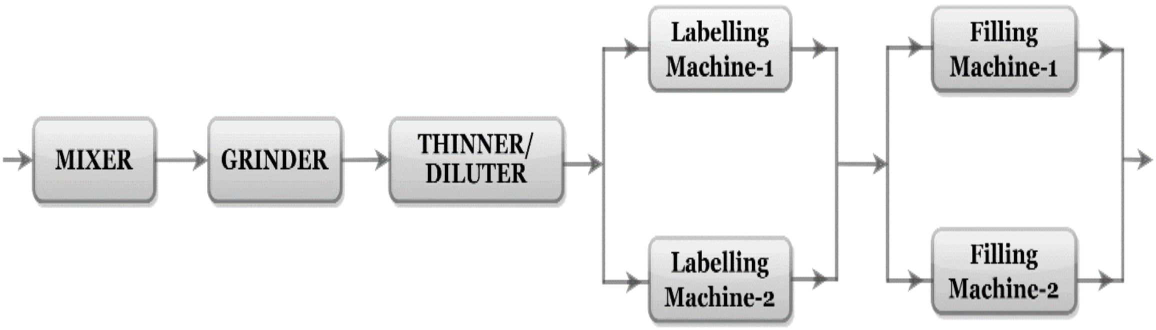



**Figure 1:** *Work-flow diagram of system*

## III. Assumptions

- At time t=0, all subsystems are in good working condition without any failure.
- The rates of failure and repair are exponentially distributed and are equally and independently distributed.
- All subsystems of the paint manufacturing plant are configured in a series format while labelling unit and filling unit have two unit working together in parallel configuration.
- Subsystems works as flawlessly as new after repair.
- An adequate repair facility is always available at operational time.

## III. Mathematical Modelling and Analysis

In this section, a mathematical model for paint manufacturing plant is developed using Markov birth-death process. The Chapman-Kolmogorov differential difference equations derived based on figure 2.

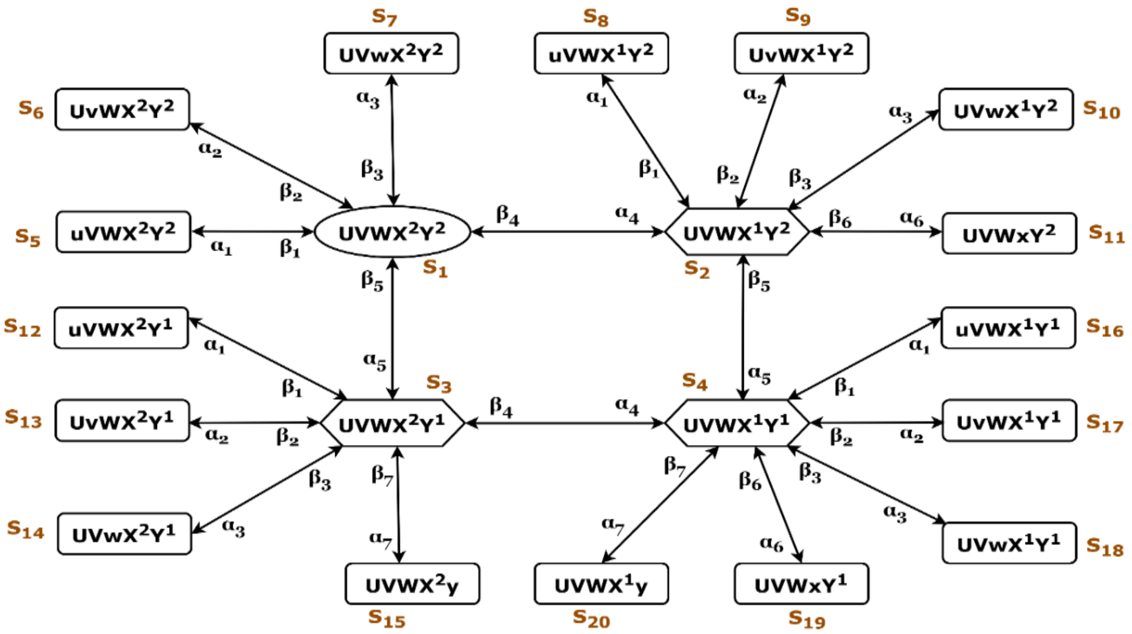



**Figure 2.** *State transition diagram of paint manufacture plants*

## I. Transition Probabilities

$$P_1(t+\Delta t) = (1-\alpha_1\Delta t-\alpha_2\Delta t-\alpha_3\Delta t-\alpha_4\Delta t-\alpha_5\Delta t)P_1(t)+\beta_1P_5(t)\Delta t+\beta_2P_6(t)\Delta t+\beta_3P_7(t)\Delta t + \beta_4P_2(t)\Delta t+\beta_5P_3(t)\Delta t$$

$$P_1(t+\Delta t) = P_1(t)-(\alpha_1\Delta t+\alpha_2\Delta t+\alpha_3\Delta t+\alpha_4\Delta t+\alpha_5\Delta t)P_1(t)+\beta_1P_5(t)\Delta t+\beta_2P_6(t)\Delta t+\beta_3P_7(t)\Delta t + \beta_4P_2(t)\Delta t+\beta_5P_3(t)\Delta t$$

$$\lim_{\Delta t\to 0}\frac{P_1(t+\Delta t)-P_1(t)}{\Delta t} = -(\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5)P_1(t)+\beta_1P_5(t)+\beta_2P_6(t)+\beta_3P_7(t)+\beta_4P_2(t)+\beta_5P_3(t)$$

$$P_1'(t) = -(\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5)P_1(t)+\beta_1P_5(t)+\beta_2P_6(t)+\beta_3P_7(t)+\beta_4P_2(t)+\beta_5P_3(t)$$

Taking limit $\lim_{t\to\infty}$, we get

$$\lim_{t\to\infty} P_1'(t) = -(\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5)P_1(t)+\beta_1P_5(t)+\beta_2P_6(t)+\beta_3P_7(t)+\beta_4P_2(t)+\beta_5P_3(t)$$

$$(\alpha_1+\alpha_2+\alpha_3+\alpha_4+\alpha_5)P_1 = \beta_1P_5+\beta_2P_6+\beta_3P_7+\beta_4P_2+\beta_5P_3 \quad (1)$$

Similarly for others states,

$$(\alpha_1+\alpha_2+\alpha_3+\beta_4+\alpha_5+\alpha_6)P_2 = \beta_1P_8+\beta_2P_9+\beta_3P_{10}+\alpha_4P_1+\beta_5P_4+\beta_6P_{11} \quad (2)$$

$$(\alpha_1+\alpha_2+\alpha_3+\alpha_4+\beta_5+\alpha_7)P_3 = \beta_1P_{12}+\beta_2P_{13}+\beta_3P_{14}+\beta_4P_4+\alpha_5P_1+\beta_7P_{15} \quad (3)$$

$$(\alpha_1+\alpha_2+\alpha_3+\beta_4+\beta_5+\alpha_6+\alpha_7)P_4 = \beta_1P_{16}+\beta_2P_{17}+\beta_3P_{18}+\alpha_4P_3+\alpha_5P_2+\beta_6P_{19}+\beta_7P_{20} \quad (4)$$

$$\textstyle\sum_{i=1}^{3}\alpha_iP_1 = \sum_{j=1}^{3}\beta_jP_{j+4} \quad (5)$$

$$\textstyle\sum_{k=1}^{3}\alpha_kP_2 = \sum_{l=1}^{3}\beta_lP_{l+7} \quad (6)$$

$$\alpha_6P_2 = \beta_6P_{11} \quad (7)$$

$$\textstyle\sum_{m=1}^{3}\alpha_mP_3 = \sum_{n=1}^{3}\beta_nP_{n+11} \quad (8)$$

$$\alpha_7P_3 = \beta_7P_{15} \quad (9)$$

$$\textstyle\sum_{q=1}^{3}\alpha_qP_4 = \sum_{r=1}^{3}\beta_rP_{r+15} \quad (10)$$

$$\textstyle\sum_{s=6}^{7}\alpha_sP_4 = \sum_{t=6}^{7}\beta_tP_{t+13} \quad (11)$$

Initial conditions,

$$P_{\xi}(0) = \begin{cases} 1 & if \quad \xi = 0 \\ 0 & if \quad \xi \neq 0 \end{cases} \tag{12}$$

Solving the linear system of equations (1-11) by using initial conditions mentioned in equation (12), the following probabilities derived at various states and solve them in terms of $P_1$, we get

$$P_2 = GP_1,\ P_3 = HP_1,\ P_4 = IP_1,\ P_5 = \frac{\alpha_1}{\beta_1}P_1,\ P_6 = \frac{\alpha_2}{\beta_2}P_1,\ P_7 = \frac{\alpha_3}{\beta_3}P_1,\ P_8 = \frac{\alpha_1}{\beta_1}P_2,\ P_9 = \frac{\alpha_2}{\beta_2}P_2,$$
$$P_{10} = \frac{\alpha_3}{\beta_3}P_2,\ P_{11} = \frac{\alpha_6}{\beta_6}P_2,\ P_{12} = \frac{\alpha_1}{\beta_1}P_3,\ P_{13} = \frac{\alpha_2}{\beta_2}P_3,\ P_{14} = \frac{\alpha_3}{\beta_3}P_3,\ P_{15} = \frac{\alpha_7}{\beta_7}P_3,\ P_{16} = \frac{\alpha_1}{\beta_1}P_4,$$
$$P_{17} = \frac{\alpha_2}{\beta_2}P_4,\ P_{18} = \frac{\alpha_3}{\beta_3}P_4,\ P_{19} = \frac{\alpha_6}{\beta_6}P_4,\ P_{20} = \frac{\alpha_7}{\beta_7}P_4 \tag{13}$$

Here,

$$G = \left(\frac{\alpha_4}{B} + \frac{I*\beta_5}{B}\right)P_1,\ H = \left(\frac{\alpha_5}{C} + \frac{I*\beta_4}{C}\right)P_1,\ I = \left[\frac{\alpha_4*\alpha_5\left(\frac{1}{C}+\frac{1}{B}\right)}{\left(D-\frac{\alpha_4*\beta_4}{C}+\frac{\alpha_5*\beta_5}{B}\right)}\right],\ A = (\alpha_4+\alpha_5),\ B = (\beta_4+\alpha_5),$$

$C = (\alpha_4 + \beta_5)$, $D = (\beta_4 + \beta_5)$ and '*' represent the multiplication.

By using normalization condition,

$$\sum_{z=1}^{20} P_z = 1 \tag{14}$$

The expression of $P_1$ derived by using equations (13-14) and shown in equation (15) as follows:

$$P_1 + P_2 + P_3 \ldots\ldots\ldots\ldots\ldots + P_{20} = 1$$
$$P_1 = \frac{1}{[1+G+H+I]*\left[1+\left(\frac{\alpha_1}{\beta_1}\right)+\left(\frac{\alpha_2}{\beta_2}\right)+\left(\frac{\alpha_3}{\beta_3}\right)\right]+\left(\frac{\alpha_6}{\beta_6}\right)*I+\left(\frac{\alpha_7}{\beta_7}\right)*(H+I)} \tag{15}$$

The depiction of system availability involves the addition of probabilities in the upstate. Mathematical expression for system availability is formulated as follows:

$$A_\theta = P_1 + P_2 + P_3 + P_4 \tag{16}$$

By putting the values and determine the final availability expression, is as below:

$$A_\theta = \frac{[1+G+H+I]}{[1+G+H+I]*\left[1+\left(\frac{\alpha_1}{\beta_1}\right)+\left(\frac{\alpha_2}{\beta_2}\right)+\left(\frac{\alpha_3}{\beta_3}\right)\right]+\left(\frac{\alpha_6}{\beta_6}\right)*I+\left(\frac{\alpha_7}{\beta_7}\right)*(H+I)} \tag{17}$$

## IV. Numerical Results and Discussion

In this section, the availability of paint manufacturing system is derived by using the expression given in equation (17) and is found 0.950145478. The arbitrary values of failure and repair rates are taken on the behalf of the previous studies and are append in table 2. For enhancement of availability of the system swarm-intelligence based algorithm named GWO is used. For execution of optimization the possible search space for failure and repair rates are append in table 3 and the optimum availability of the system for different iterations and populations are presented in table 4.

**Table 2:** *Failure and repair rates for subsystems of paint manufacturing plant*

| Sr. No. | Name of subsystem | Failure rates ($\alpha_i$) | Repair rates ($\beta_j$) |
|---|---|---|---|
| 1 | Mixer | $\alpha_1$=0.005 | $\beta_1$=0.889 |
| 2 | Grinder | $\alpha_2$=0.051 | $\beta_2$=1.397 |
| 3 | Dilution/ Thinner | $\alpha_3$=0.0052 | $\beta_3$=0.998 |
| 4 | Labelling | $\alpha_4$=0.0727 | $\beta_4$=1.232 |
| 5 | Filling | $\alpha_5$=0.0954 | $\beta_5$=1.244 |
| 6 | Standby labelling machine | $\alpha_6$=0.0778 | $\beta_6$=1.374 |
| 7 | Standby filling machine | $\alpha_7$=0.0955 | $\beta_7$=1.387 |

In figure 3 and 4, the effect of change in failure rate is shown on the other sub-systems availability with increase an 50% in the failure rates and repair rates. It is shown that while varying the failure rate of $\alpha_1$ from 0.001 to 0.007, the availability of subsystems decreases. Subsystem grinder is fluctuated very much by increasing 50% in failure rates and repair rates both. While floating the value of $\beta_1$ from 0.001 to 0.007 and 50% increase in other subsystems repair rates, then the availability is also increase.

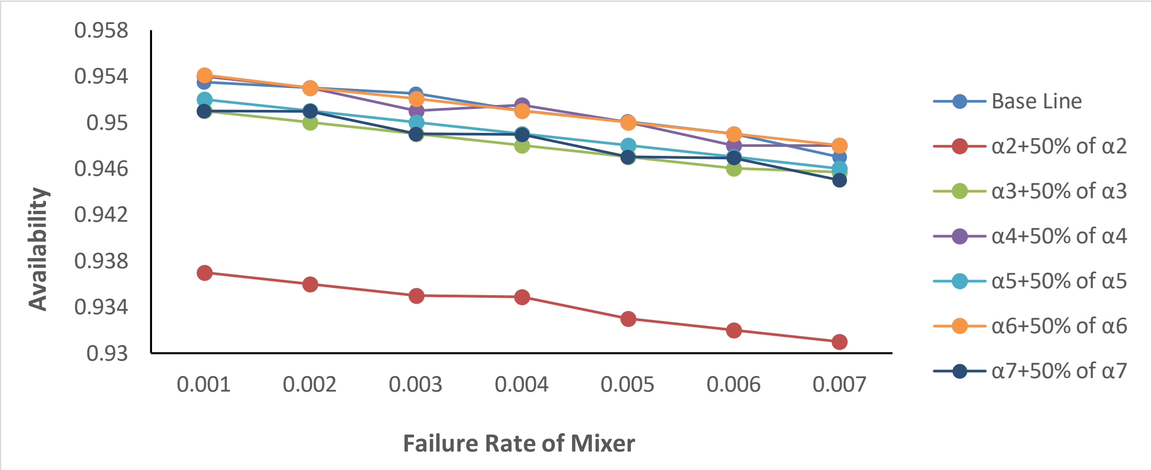



**Figure 3:** *System availability with variation in $\alpha_1$ and subsequent changes in failure rates of subsystems*

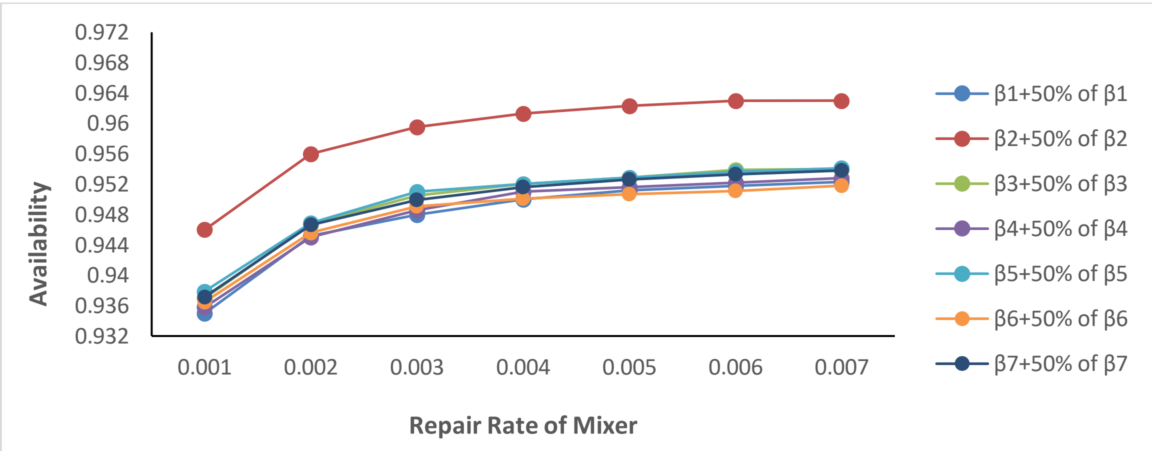



**Figure 4:** *System availability with variation in $\beta_1$ and subsequent changes in repair rates of subsystems*

**Table 3:** *Range of search space for grey wolf optimization*

| Sr. No. | Subsystem | Range of failure rates ($\alpha_i$) | Range of repair rates ($\beta_j$) |
|---|---|---|---|
| 1 | Mixer | [0.0025, 0.0075] | [0.45, 1.34] |
| 2 | Grinder | [0.0260, 0.0770] | [0.70, 2.10] |
| 3 | Dilution/ Thinner | [0.0028, 0.0082] | [0.50, 1.50] |
| 4 | Labelling | [0.0360, 0.1090] | [0.62, 1.85] |
| 5 | Standby labelling machine | [0.0480, 0.1440] | [0.63, 1.87] |
| 6 | Filling | [0.0390, 0.1170] | [0.69, 2.06] |
| 7 | Standby filling machine | [0.0480, 0.1440] | [0.71, 2.09] |

**Table 4:** *Optimum availability of system at different iterations with varying population sizes*

| Iteration \ Population | 100 | 150 | 200 | 250 | 300 |
|---|---|---|---|---|---|
| 10 | 0.983572 | 0.983576 | 0.983575 | 0.983574 | 0.983570 |
| 30 | 0.983573 | 0.983571 | 0.983571 | 0.983575 | 0.983571 |
| 50 | 0.983576 | 0.983575 | 0.983549 | 0.983575 | 0.983572 |
| 70 | 0.983572 | 0.983575 | 0.983569 | 0.983563 | 0.983568 |
| 90 | 0.983577 | 0.983555 | 0.983570 | 0.983570 | 0.983573 |

## V. Conclusion

In this study, a comparative analysis is performed and it provides insights into the strengths and limitations of each methodology. It is shown that the metaheuristic optimization techniques perform better than the traditional techniques. The overall availability of paint manufacturing plant is improved by 0.9501454 to 0.983577 using GWO. Ultimately, the paper offers valuable insights into both the theoretical and practical dimensions of improving paint manufacturing plant performance and availability. The combined usage of Markov analysis and GWO presents a robust approach for achieving the desired goals, contributing to the advancement of industrial reliability and efficiency.

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