

# Optimization of Preventive Maintenance Interval for CMYP Ø50 Guide Bush Based on Wear Progression and Reliability–Maintainability Analysis in Headlining Mold

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**Abstract.** *Guide brushes in the mold headlining system play a crucial role in maintaining the alignment of mold movement and the stability of forming pressure distribution. Dimensional degradation due to wear on these components causes an increase in clearance that can potentially trigger misalignment and product thickness deviation. This study aims to determine the optimal preventive maintenance interval based on the production cycle through the integration of wear progression analysis, reliability maintainability, and total cost function. The method used is a quantitative approach based on mathematical modeling by utilizing actual production data and component dimension measurements. The wear program is modeled linearly against the number of production cycles, then associated with an increase in clearance, product thickness deviation, and a decrease in component reliability function. Optimization of the replacement interval is carried out by minimizing the total cost function that combines preventive costs and the risk of loss due to quality failure. The results show that the guide bush wear rate is 0.99998 mm/cycle which causes an increase in clearance of up to 1 mm in 25 production cycles. This condition results in a product thickness deviation of  $\pm 0.2$  mm, which is still within the design tolerance limit. Reliability analysis shows an  $R$  value of  $\approx 0.3679$  at this interval, with a system availability level of 99.53%. Based on the optimization of the total cost function, the optimal preventive maintenance interval is obtained at 25,000 production cycles, which provides a balance between product quality stability and operational cost efficiency. The contribution of this research lies in the development of an integrative model that links the wear progression of precision components with product quality degradation and risk-based maintenance decisions. This approach provides a more representative analytical framework than conventional operating time-based methods, especially for mold alignment components in the automotive manufacturing industry.*

**Keywords -** Guide brushes; mold headlining; reliability maintainability; measurements; manufacturing industry.

## INTRODUCTION

The automotive manufacturing industry demands consistent product quality with tight dimensional tolerances, particularly for interior components like headlinings [1]. Product thickness is a critical parameter because it affects structural strength, aesthetic quality, as well as installation suitability [2]. Dimensional variations that exceed tolerance limits can increase scrap and rework rates and reduce the stability of the production process [3]. In addition, the reliability of the production system also plays an important role in maintaining quality consistency during repeated operations [4].

The process of forming the headlining using a mold, the precision of alignment between the upper mold and the lower mold is the main factor that determines the uniformity of the distribution of forming pressure [5]. The guide bush functions as a key component in maintaining the stability of the forming pressure alignment [6]. Guide bush serves as a key component in maintaining the stability of the alignment during repeated production cycles [7].

Under operating conditions, guide bushes experience sliding and cyclic contact loads that cause progressive wear [8]. This dimensional degradation due to wear increases radial clearance, potentially reducing the stiffness of the alignment system and leading to mold misalignment [9]. Increased clearance due to wear has a direct impact on the uneven distribution of forming pressure, resulting in non-uniform material deformation and triggering product thickness deviation [10]. This phenomenon shows that quality failure can occur before functional failure of a component, making a degradation condition-based maintenance approach more relevant than a conventional operating time-based approach [11]. Various previous studies have examined preventive maintenance optimization using reliability approaches and total cost functions to minimize production losses [12]. Component degradation-based models have also been developed to improve the accuracy of determining replacement intervals [13].

However, most studies focus on rotating machine components such as bearings and gears or on the general system level. The quantitative relationship between wear progression of precision components, changes in alignment characteristics, and degradation of product dimensional quality has not been systematically discussed [14]. Therefore,

this study proposes an integrative model for optimizing preventive maintenance intervals on CMYP Ø50 guide bushes by combining wear progression analysis, clearance alignment changes and wear progression analysis, product quality deviation, as well as reliability maintainability parameters in a quantitative framework.

This model also integrates the total cost function to determine the technically and economically optimal component replacement interval. This approach is expected to contribute to the development of risk-based maintenance strategies for precision components of mold systems in the automotive manufacturing industry [15].

## METHOD

### Objects and data collection

This research was conducted on the CMYP Ø50 guide bush component which is used as an alignment system in the headlining mold. In one mold there are six guide bushes made of S45C with a hardness of around 55 HRC [16]. The initial component diameter was Ø50 mm. Data was obtained through direct field measurements during the production process. Diameter measurements were performed using a digital caliper with an accuracy of ±0.01 mm [17]. The data collected includes the initial and final diameter of the component, number of cycles, production (shoot), time to replacement (MTTR), as well as data on maintenance costs and production losses [18].

### Wear progression model

Wear is modeled based on the change in diameter against the number of production cycles the wear rate is calculated by

$$\omega = \frac{D_f - D_o}{N} \quad (1)$$

Where:

- $\omega$  = Rate value / rate of change
- $D_f$  = Final data
- $D_o$  = Initial data
- $N$  = Number of intervals

The change in diameter during operation is expressed as.

$$D(N) = D_o + \omega N \quad (2)$$

Where:

- $D(N)$  = Displament diameter value in the N cycle
- $D_o$  = Initial value of diameter
- $\omega$  = Rate of change per cycle
- $N$  = Number of operating cycles

### Clearance and misalignment models

The increase in diameter causes an increase in the clearance between the guide bush and the guide pin which is calculated by [19].

$$C(N) = \frac{D(N) - D_o}{2} \quad (3)$$

Where:

- $C(N)$  = Clearance value of radius change in the N cycle
- $D(N)$  = Displament diameter value in the N cycle
- $D_o$  = Initial value of diameter
- 2 = Conversion factor from diameter change to radial change

Mold misalignment is estimated using a correction factor of 0.4 so that.

$$\delta = 0,4 \times C(N) \quad (4)$$

Where:

- $C(N)$  = Clearance value of radius change in the N cycle
- 0.4 = Correction factor
- $\delta$  = Correction value

### Product thickness deviation model

The thickness deviation due to misalignment is calculated using

$$\Delta t = k \times \delta \quad (5)$$

Where:

- $\Delta t$  = Change of time
- $k$  = Proportionality constant
- $\delta$  = Correction value

With a value of  $k = 0.5$  as the material sensitivity factor, for  $\alpha$  and  $k$  the values are based on an empirical approach to the system under study.

### Reliability and availability analysis

This equation is used to calculate the probability that a component will still function properly after operating for  $N$  years. The larger the value of  $N$ , the smaller the reliability value  $R(N)$ . The larger the MTBF value, the more reliable the component is because the decline in reliability occurs more slowly.

$$R(N) = e^{-N/MTBF} \quad (6)$$

Where:

- $R(N)$  = Component reliability at the  $N$ th cycle
- $e$  = Euler's exponential number ( $e = 2.718$ )
- $N$  = Number of operating cycles
- MTBF = Mean Time Between Failure, which is the average time between component failures

This equation is used to calculate the time the system remains operational. Availability values range from 0 to 1 and can be expressed as a percentage (%)

$$A = \frac{MTBF}{MTBF + MTTR} \quad (7)$$

Where:

- $A$  = Availability
- MTBF = Mean Time Between Failure, which is the average time between component failures.
- MTTR = Mean Time to Repair, which is the average time required to repair a system after a failure occurs.

### Maintenance interval optimization

The optimal replacement interval is determined by minimizing the total cost function

$$C(N) = \frac{C_p}{N} + C_f(1 - R(N)) \quad (8)$$

Where:

- $C(N)$  = Total cost function
- $C_p$  = Preventive replacement cost
- $N$  = Replacement interval
- $C_f$  = Failure cost
- $R(N)$  = Component reliability in the  $N$  cycle

The optimal  $N$  value is found by finding the  $N$  value that results in minimum total costs.

## RESULT AND DISCUSSION

### Wear Progression of Guide Bush

Experimental measurements indicate that the inner diameter of the guide bush increases progressively with the number of production cycles. The estimated wear rate is 0.00008 mm/cycle, obtained from dimensional measurement before and after 25,000 cycles. The relationship between diameter and cycle number follows a linear trend.

$$D(N) = 50 + 0.00008N$$

This linear behavior suggests that the wear mechanism operates under a steady-state regime, where contact load and sliding conditions remain relatively constant. The model shows strong agreement with observed data, indicating that linear approximation is adequate for representing wear progression within the studied operating range. From a

tribological perspective, the observed wear pattern is consistent with mild adhesive and abrasive wear, as confirmed by visual inspection showing uniform surface degradation. The absence of severe wear features (e.g., pitting or scuffing) further supports the assumption of state wear progression.

### Clearance growth and alignment degradation

At 25,000 cycles, the clearance reaches approximately 1 mm, which is significant for a precision alignment-system. This increase reduces the lateral stiffness of the mold guiding system, allowing eccentric displacement during the forming process. Mechanically, increased clearance introduces deviation in the load path, resulting in non uniform pressure distribution across the product surface. This condition is critical because it marks the transition from geometrically stable operation to alignment sensitive behavior.

### An important engineering insight from this study is that

Clearance values approaching 0.8-10 mm represent a critical threshold beyond which alignment degradation begins to significantly affect product quality.

### Impact on product thickness deviation

The effective displacement due to misalignment is estimated using an empirical correction factor.

$$\delta = 0.4 \times C$$

At 25,000 cycles:

$$\delta = 0.4 \times 1 = 0.4 \text{ mm}$$

The resulting thickness deviation is:

$$\Delta t = k \times \delta = 0.5 \times 0.4 = 0.2 \text{ mm}$$

Thus, the product thickness varies between

$$t_{\min} = 2.8 \text{ mm}$$

$$t_{\max} = 3.2 \text{ mm}$$

These values remain within the allowable tolerance of  $3 \pm 0.5$  mm, indicating that the system is still operationally acceptable at 25,000 cycles. However, the margin to the tolerance limit is reduced, implying increased risk of out of specification products beyond this point.

This result confirms that:

Quality degradation occurs progressively before functional failure, highlighting the importance of condition-based maintenance.

### Reliability and availability analysis

The reliability of the guide bush is modeled using an exponential function:

$$R(N) = e^{-N/MTBF}$$

With  $MTBF = 25,000$  cycles

$$R(25,000) = e^{-1} = 0.3679$$

Availability is calculated as:

$$A = \frac{640}{643} = 0.9953 \text{ (99.53\%)}$$

This shows that the system maintains high operational availability despite degradation, reinforcing the need to consider quality-based failure criteria, not only downtime.

### Cost analysis and optimization of maintenance interval

The total cost function is defined as:

$$C(N) = \frac{C_p}{N} + C_f(1 - R(N))$$

Where

$C_p = 62.1$  million IDR (preventive cost)

$C_f = 160$  million IDR (failure cost)

At  $N = 25,000$ :

$$C(N) = 2.484 + 101,136,000 = 101,138,484 \text{ IDR}$$

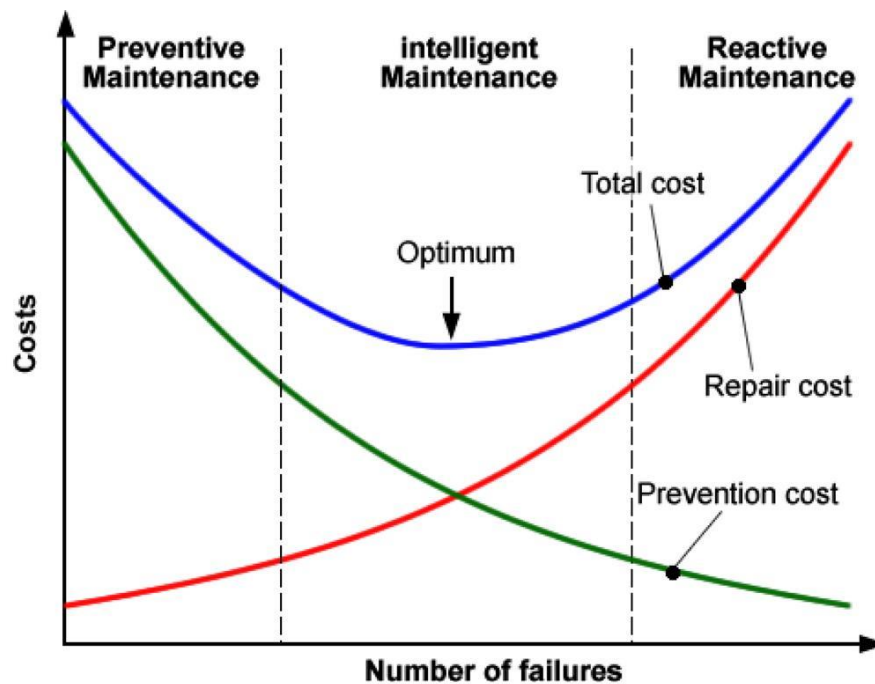


Figure 1. Relationship between maintenance costs and the number of failures.

Figure 1 shows the relationship between maintenance costs and the number of failures in a machinery system. The main cost components analyzed are prevention costs, repair costs, and total costs. Prevention costs, indicated by the green curve, tend to decrease as the number of failures increases. This is due to the reduced frequency of preventive maintenance when the system is maintained less frequently. Conversely, repair costs, indicated by the red curve, increase with the number of failures due to the increasing frequency of breakdowns and the need for repairs. The combination of these two cost components produces a U-shaped total cost curve (blue line). This shape indicates a trade-off between prevention costs and repair costs. Under conditions of a high number of failures, total costs also increase due to the dominance of repair costs.

The minimum point on the total cost curve indicates the optimum maintenance condition, namely the condition where the total system cost is at its lowest. This point represents the balance between preventive and corrective maintenance strategies. Thus, the optimal maintenance strategy is not at the extremes (too frequent or too infrequent maintenance), but rather at a compromise that minimizes total operational costs.

To determine the optimal maintenance interval, the total cost function was evaluated across a range of production cycles. The results exhibit a convex cost curve, indicating a trade-off between preventive maintenance cost and expected failure cost. At shorter intervals the total cost is dominated by frequent preventive interventions, leading to higher maintenance expenses. In contrast, longer intervals increase the probability of failure, resulting in significantly higher failure-related cost. The minimum total cost is observed at approximately 25,000 cycles, indicating the optimal replacement interval. This confirms that the optimal maintenance policy is achieved by balancing preventive intervention frequency and expected failure cost.

## Discussion

Guide bush wear increased linearly with production cycles at a rate of 0.00008 mm/cycle, indicating stable wear behavior under constant operating conditions. At 25,000 cycles, radial clearance reached approximately 1 mm, reducing mold alignment stiffness and causing a thickness deviation of  $\pm 0.2$  mm. Although still within tolerance limits, the reduced safety margin indicates progressive quality degradation prior to functional failure. Reliability analysis showed a decrease to 0.3679 at 25,000 cycles, while system availability remained high at 99.53%, suggesting that quality degradation is more critical than downtime in precision forming systems. Cost optimization identified 25,000 cycles as the optimal preventive replacement interval, where the balance between preventive maintenance cost and failure risk produced the minimum total cost.

This finding is consistent with previous studies on precision mold maintenance, where dimensional wear was reported to gradually reduce alignment accuracy and product consistency. Similar to reliability-based maintenance models proposed in earlier manufacturing studies, the present work confirms that integrating wear progression with cost and reliability analysis provides more effective maintenance scheduling than conventional time-based approaches.

## CONCLUSION

This study developed an integrated method to determine the optimal preventive maintenance interval for the guide bush component in a headlining mold system by considering wear progression, alignment degradation, product quality, reliability, and maintenance cost. The results show that guide bush wear increases linearly with a wear rate of 0.00008 mm/cycle under stable operating conditions. This wear increases radial clearance to approximately 1 mm at 25,000 cycles, reducing mold alignment stiffness and resulting in a thickness deviation of  $\pm 0.2$  mm. Although the deviation is still within tolerance limits, it indicates a decrease in the product quality safety margin. The reliability analysis shows that component reliability decreases exponentially to 0.3679 at 25,000 cycles, indicating a higher risk of quality degradation over time. Even though the system availability remains high at 99.53%, the study confirms that product quality is a more critical indicator than downtime in precision forming systems. Cost optimization results indicate that the optimal preventive replacement interval is approximately 25,000 production cycles, at which the total maintenance cost is minimized while maintaining process stability. This study also highlights important design and practical implications. Guide bush wear significantly affects alignment accuracy and dimensional consistency; therefore, future mold designs should use better wear-resistant materials, improved lubrication systems, tighter clearance control, and easier component replacement methods. Practically, the proposed model can help manufacturers schedule maintenance more effectively, reduce maintenance costs, minimize product defects, and improve production efficiency. However, this study is limited by the assumption of linear wear and constant operating conditions. Future work should include non-linear wear behavior, real-time monitoring, and interactions between multiple components to improve model accuracy and industrial applicability.

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