

Research Article

On the Prediction of Spur Gear Maintainability in Bottling Machines based on Failure Data

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Abstract

In bottling companies, spur gears play a vital role in ensuring efficient mechanical power transmission in bottling machines. Therefore, the maintainability of spur gears in these machines is important because it directly affects the overall efficiency, productivity, and cost-effectiveness of bottling operations. The study focused on data collection for different tasks performed on a failed gear from January to December of a particular year based on task time and frequency of occurrence, which are important factors for maintainability predictions. The monthly failure frequency was used to calculate the monthly failure rate, and the mean time to maintenance action (MTTR) and Maintenance action rate (μ) were used to generate the maintainability model. The results showed that the TPMA peaks at approximately 26 hours in December, likely due to end-of-year maintenance activities. The spike in May, which lasted



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approximately 24 hours, suggests an increased operational load leading to greater wear and tear. The TPMA was at its lowest in October, dropping to around 12 hours. These decreases indicated effective maintenance strategies implemented earlier in the year, reducing the need for extensive repairs during this period. The frequency of tasks performed on a spur gear over 12 months showed that the highest number (16 occurrences) occurred in May, indicating intensive maintenance or corrective actions. February and October also exhibit elevated relative frequencies, reaching 940% and 380%, respectively. This suggests that maintenance activities during these months were essential, possibly related to pre-emptive efforts to ensure reliability.

Keywords

Mean Time to Maintenance Action (MTTR); maintenance action rate; reliability; spur gear failures; Time to Perform Maintenance Action (TPMA)

1. Introduction

Maintainability is exceptionally crucial in design and engineering. It refers to how easily, accurately, safely, and cost-effectively maintenance operations can be performed on equipment or systems. It is the ability of a system to be kept in proper working condition or to be quickly restored to a state where it can perform its required functions with minimum downtime, effort, cost, and risk [1]. The concept of maintainability begins during the design phase of a system, where engineers aim to ensure it can be easily repaired or maintained over its operational life. Metrics such as Mean Time to Repair (MTTR), which measure the average time required to perform corrective maintenance, are often used to measure maintainability [2]. In bottling machines, spur gears play a crucial role in the smooth, efficient transmission of mechanical power, enabling precise movement and control of various components [3]. The maintainability of these spur gears is a critical factor in determining the bottling machine's overall efficiency, reliability, and longevity. Spur gears in bottling machines are subject to constant mechanical stresses, including wear and tear due to friction, necessitating regular maintenance to prevent failures that could disrupt the bottling process. Maintainability for spur gears in bottling machines is extremely important. Bottling machines operate in high-speed environments, and any disruption in the mechanical components, such as spur gears, can lead to significant production downtime and financial losses. Ensuring the maintainability of these gears is essential to minimize downtime and maintain high productivity [4]. High maintainability leads to shorter repair times, reducing the impact of mechanical failures on the entire bottling process and ensuring that production targets are met consistently. From an economic perspective, the maintainability of spur gears plays a considerable role in significantly reducing the total operating expenses of bottling machines. Gears are easier to maintain than the entire machine, as neglecting regular maintenance of the spur gear is less costly. They require fewer resources, both in terms of time and cost, for repairs and upkeep. This, in turn, extends the operational life of the machine and reduces the need for costly replacements [5, 6]. The maintainability of spur gears also directly impacts both the safety of operations/maintenance workers and the overall safety of bottling operations, as it reduces the risk of human error and

accidents during operations and repair activities [7, 8]. Improving the maintainability of these gears ensures maintenance is performed quickly and safely, reducing the likelihood of injuries and improving overall safety in the bottling process [9]. Maintainability prediction for spur gears involves anticipating the ease with which these components can be inspected, serviced, and replaced throughout their operational life. Accurate maintainability prediction is key to minimizing unexpected downtimes, optimizing maintenance schedules, and extending the service life of the gears [10]. Some common causes of spur gear failures in bottling machines include wear and tear, misalignment, lubrication issues, overloading, material defects, fatigue failure, corrosion, vibration and noise. Maintainability prediction based on failure history allows companies to plan maintenance activities more effectively, reducing unexpected downtimes and ensuring that bottling operations run smoothly [11]. Despite the advancements in predictive maintenance technologies, several challenges remain in the practical application of maintainability prediction for spur gears. These challenges include modelling gear interactions within the machine accurately, ensuring the availability of high-quality data for analysis, and integrating predictive maintenance strategies with existing operational workflows [12]. The process used in this research involves analyzing failure patterns monthly from January to December. The monthly frequency of failure was used to calculate the monthly failure rate, and the mean time to maintenance action (MTTR) and Maintenance action rate (μ) were used to generate the maintainability model.

This research aims to predict spur gear maintainability in bottling machines based on failure data.

2. Methodology

2.1 Data Collation

The study focused on data collation for different tasks performed on a failed gear from January to December for a particular year based on task time and frequency of occurrence, which are important factors for maintainability predictions. Table 1 shows the variation in task time and the frequency of failures for each month, with a total of 106 failures.

Table 1 MTTR data and frequency of occurrence.

Month	TPMA (hours)	Frequency of occurrence
January	14.8	7
February	17.1	10
March	14.6	8
April	18	5
May	24	16
June	18.6	6
July	15.3	5
August	17.8	12
September	16.7	11
October	11.2	4
November	21.1	13
December	26.4	9
Total		106

2.2 Determination of Aggregate Task Time, Relative Frequency, and the Overall Percentile

The aggregate task time in hours, the relative frequency of occurrence, and the overall percentile were calculated using the following methods to determine the parameters that could be used in the maintainability model. Table 2 shows the results obtained after the aggregate task time, relative frequency, and percentile computations using equation (1) as described by [13].

$$\text{Relative frequency} = \frac{\text{Frequency of observation}}{\text{total frequency}} \times 100 = \frac{f}{n} \times 100 \quad (1)$$

Table 2 Results of Aggregate task time, Relative frequency, and Percentile.

Month	TPMA (hours)	Frequency of occurrence	Aggregate task time in hours	Relative frequency of occurrence (×100) in %	percentile
January	14.8	7	103.6	660	6.6
February	17.1	10	171	940	16
March	14.6	8	116.8	750	23.5
April	18	5	90	470	28.2
May	24	16	384	1510	43.3
June	18.6	6	111.6	570	49
July	15.3	5	76.5	470	53.7
August	17.8	12	213.6	1130	65
September	16.7	11	183.7	1040	75.4
October	11.2	4	44.8	380	79.2
November	21.1	13	274.3	1230	91.5
December	26.4	9	237.6	850	100
Total		106	2007.5	10000	

2.3 Maintainability Model

Given that the mean time to repair is described by [14] as defined in equation (2);

$$\text{MTTR} = \frac{\eta_{SG} \lambda_{SG} \text{tm}_{SG}}{\eta_{SG} \lambda_{SG}} \quad (2)$$

Where;

η_{SG} - number of components in the system.

λ_{SG} - failure rate of components.

tm_{SG} - predicted/tested maintenance action time.

The failure rate is the frequency with which the component (spur gear) fails, as introduced by [15] in equation (3), expressed in failures per unit of time.

$$\lambda_{SG} = \frac{\text{Total no of monthly failure}}{\text{Total monthly operating time}} \quad (3)$$

The spur gear operates for 24 hours/day for five (5) days a week

Thus, standard operation hours per week = $24 \times 5 = 120$ hours

This implies that in a month, we have $120 \times 4 = 480$ hours

As described by [14], the maintenance action rate (μ) was determined using equation (4)

$$\mu = \frac{1}{\text{MTTR}} = \frac{1}{\phi} \quad (4)$$

Maintainability $[M(t)]$: It is the probability that the spur gear will be restored to operational (specified conditions) effectiveness within a given period, provided the maintenance actions are performed according to prescribed procedures [14].

Given that;

$$M(t) = 1 - \exp(-\mu \cdot t) \quad (5)$$

The time-to-restore probability density function $g(t)$ for the exponential times-to-restore distribution is given by equations (6) and (7) as introduced by [14];

$$g(t) = \mu e^{-\mu t} \quad (6)$$

$$\text{MTTR} = \frac{1}{\mu} \quad (7)$$

2.4 Measure of Maintainability

Using equation (2), the maintainability calculations for the first month (January) were obtained as follows;

$$\text{MTTR} = \frac{\eta_{\text{SG}} \lambda_{\text{SG}} t_{\text{mSG}}}{\eta_{\text{SG}} \lambda_{\text{SG}}}$$

$$t_{\text{mSG}} = 103.6 \text{ (for January)}$$

$$\eta_{\text{SG}} = 1 \text{ (spur gear)}$$

$$\lambda_{\text{SG}} = \text{Failure rate}$$

$$\lambda_{\text{SG}} = \frac{\text{no of failure}}{\text{operating time}}$$

$$\text{operating time of the spur gear} = 480 \text{ hours in the month}$$

$$\text{no of failure} = 7$$

$$\lambda_{\text{SG}} = \frac{7}{480} = 0.0146$$

$$\text{MTTR} = \frac{1 \times 0.0146 \times 103.6}{1 \times 0.0146} = 103.6$$

$$\text{MTTR} = 103.6$$

$$\text{Maintenance action rate, } \mu$$

$$\mu = \frac{1}{\text{MTTR}} = \frac{1}{103.6} = 0.00965$$

$$t = \text{time of check} = 480 \text{ hours (end of the first month)}$$

$$\therefore \text{Maintainability,}$$

$$M(t) = 1 - \exp(-\mu \cdot t) = 1 - \exp(-0.00965 \times 480) = e^{-4.63}$$

$$M(t) = 1 - e^{-4.63}$$

$$M(t) = 1 - 0.00975$$

$$M(t) = 0.9902$$

Table 3 depicts the summary of the analyses based on the model.

Table 3 Maintainability.

Month	Failure rate λ_{SG}	MTTR	Time of check	Maintenance Action Rate (μ)	Maintainability	Maintainability Percentage	Time to restore density function
JAN	0.0146	103.6	480	0.0095	0.9902	99.02	0.000100
FEB	0.0208	171	960	0.0058	0.9962	99.62	0.000022
MAR	0.01667	116.8	1440	0.0086	0.99996	99.996	0.00000034
APR	0.0104	90	1920	0.0111	0.99999972	99.999972	0.0000000031
MAY	0.0333	384	2400	0.0026	0.9981	99.81	0.0000049
JUN	0.0125	111.6	2880	0.0090	0.9999999	99.99999	0.0000000009
JULY	0.0104	76.5	3360	0.0131	0.99999999	99.999999	0.00000000013
AUG	0.0250	213.6	3840	0.0047	0.999985	99.9985	0.00000007
SEPT	0.0229	183.7	4320	0.0054	0.9999999	99.99999	0.00000000054
OCT	0.0083	44.8	4800	0.0223	1	100	0.0000000000
NOV	0.0271	274.3	5280	0.0036	0.999982	99.9982	0.000000065
DEC	0.0188	237.6	5760	0.0042	0.99999992	99.999992	0.00000000034

3. Results and Discussion

Figure 1 presents the plot of TPMA over time. The analysis of the Time to Perform Maintenance Action (TPMA) for a spur gear over twelve months reveals significant insights into the maintenance demands and operational challenges associated with these critical components. The TPMA result shows notable fluctuations, indicating varying maintenance needs throughout the year. For instance, in December, the TPMA peaks at approximately 26 hours, which can be attributed to end-of-year maintenance activities. These are typically more thorough in preparing machinery for the upcoming year, ensuring optimal performance and preventing potential failures. Similarly, the spike in May, which lasted approximately 24 hours, suggests an increased operational load, leading to greater wear and tear. This was due to peak production periods, during which machinery is pushed to its limits, necessitating intensive maintenance.

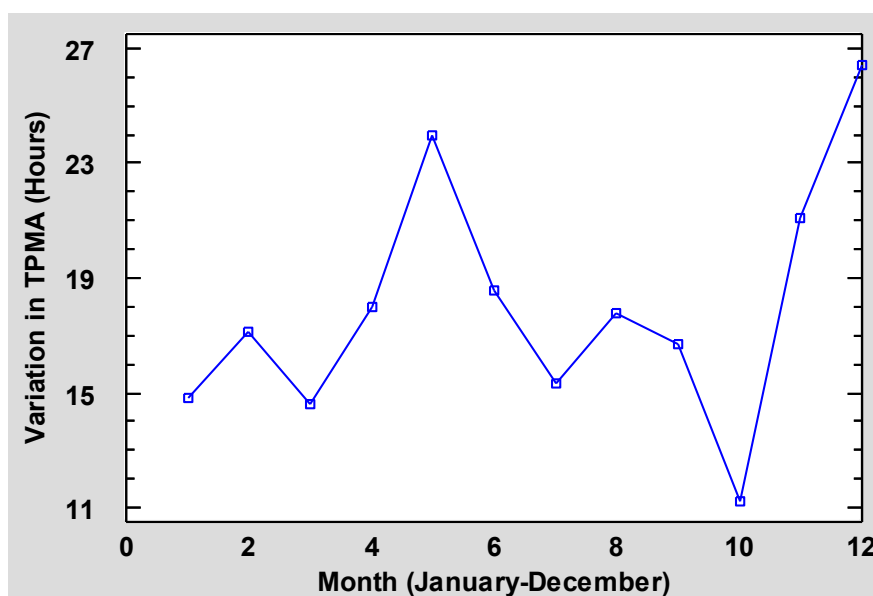


Figure 1 Variation of TPMA with Months for the Spur gear.

Furthermore, the TPMA was at its lowest in October, dropping to around 12 hours. These decreases indicated effective maintenance strategies implemented earlier in the year, reducing the need for extensive repairs during this period. January also showed a relatively low TPMA of about 14 hours, which reflects successful maintenance practices carried out in December of the previous year. Thus, it's noteworthy to establish that the variation in TPMA from January to December could be attributed to many reasons revolving around Moderate maintenance time, possibly due to initial operational adjustments post-holiday season, heightened operational activities leading to increased TPMA, reduction in TPMA occasioned by stable operation, and preparation for higher summer workload resulting in maintenance time increase.

These analyses are crucial for several reasons; first, they aid predictive maintenance planning by identifying peak maintenance periods, enabling better resource allocation and scheduling, as reported in the study [16]. For instance, knowing that May and December are high-maintenance months, companies can allocate more resources and plan for potential downtime. Also, analysing TPMA helps in cost management by providing a basis for budgeting maintenance expenses and

avoiding unexpected costs, as reported by [17]. By anticipating higher maintenance times, organizations can plan their finances more effectively, ensuring that necessary funds are available when needed. Lastly, optimizing maintenance schedules based on TPMA data can enhance operational efficiency and productivity [18]. Companies can minimise downtime and maintain continuous operations by focusing maintenance efforts more intensively during high TPMA months and minor maintenance during low TPMA periods.

Figure 2 shows the variation in TPMA over time. The plot represents the frequency of tasks performed on a spur gear over 12 months, providing insights into the gear's reliability, maintenance, and maintainability. There is significant variation in the number of tasks across months, indicating patterns related to operational load, wear, and preventive maintenance schedules as established in a study by [19]. The plot shows that the highest number of tasks (16 occurrences) was observed in May. This suggests a period of intensive maintenance or corrective actions in the first half of the year, driven by heightened operational demand or accumulated wear. There was a notable reduction in the frequency of tasks in June and July, indicating a period of relative reliability following the maintenance peak in May. This was linked to a preventive maintenance strategy that mitigates failures in these months. August, September, and November showed higher maintenance task frequencies, suggesting a need for reliability enhancements before key operational periods. The resurgence of tasks during these months indicated that preventive maintenance was conducted to prepare the gear for year-end operational demand.

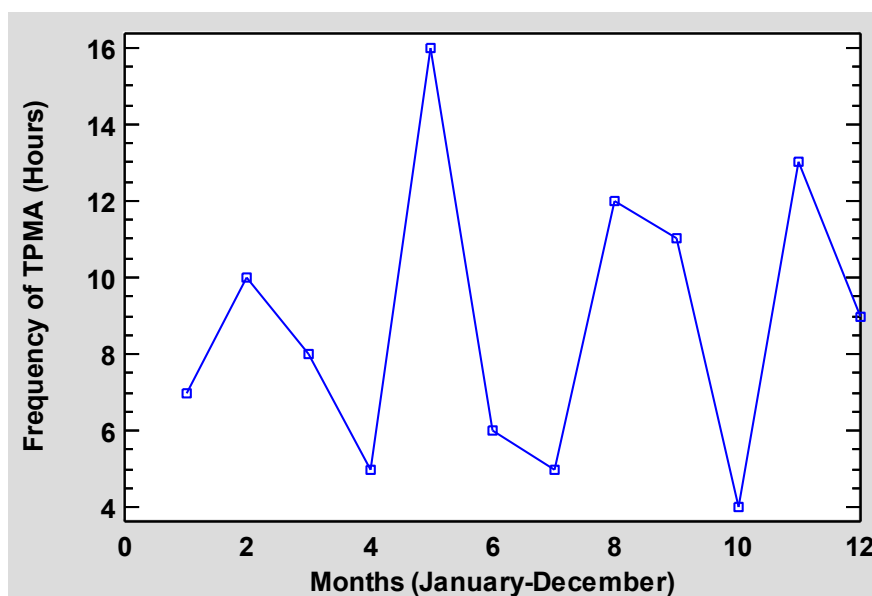


Figure 2 Variation in frequency of TPMA with Months.

The mid-year period (April to July) shows variability in task frequency, and it was due to a combination of planned maintenance and operational stress. This suggests that the reliability of the spur gear is not constant and requires regular intervention. The plot reflects aspects of Preventive Maintenance (PM), particularly in months like May, when task frequency surges. PM aims to address potential issues before they lead to failures, ensuring that the gear remains reliable during periods of heavy usage. However, the subsequent decrease in task frequency in June and July suggests that the earlier PM measures were effective in sustaining performance over a longer duration [20]. This highlights the need for a well-balanced maintenance strategy to optimize the reliability and

maintainability of the spur gear. High-frequency months are critical maintenance periods that ensure the gear's continuous operation during peak demand. Meanwhile, months with lower frequency reflect periods of stability due to effective prior interventions.

Figure 3 illustrates the relationship between the aggregate task time (in hours) required to repair a spur gear across various months. In May, the aggregate task time peaks at approximately 384 hours. This significant increase indicates a major maintenance activity and a higher repair frequency this month. The high frequency of occurrences (16 times) indicates operational stresses or scheduled significant overhauls. Conversely, October records the lowest maintenance time at around 45 hours, with only four occurrences. This reduction was attributed to effective preventive maintenance practices in prior months, leading to fewer breakdowns and repairs. Several factors could result in fluctuations in the aggregate task time. Higher usage during certain months can increase wear and tear, necessitating more repairs. Months with higher repair times could coincide with planned preventive maintenance activities to address potential issues before they lead to significant breakdowns. Changes in environmental (weather) conditions, such as temperature and humidity, can impact the performance and durability of spur gears, influencing the frequency and extent of required maintenance. Variations in the quality and durability of the spur gears used may also contribute to the frequency and duration of repairs [21].

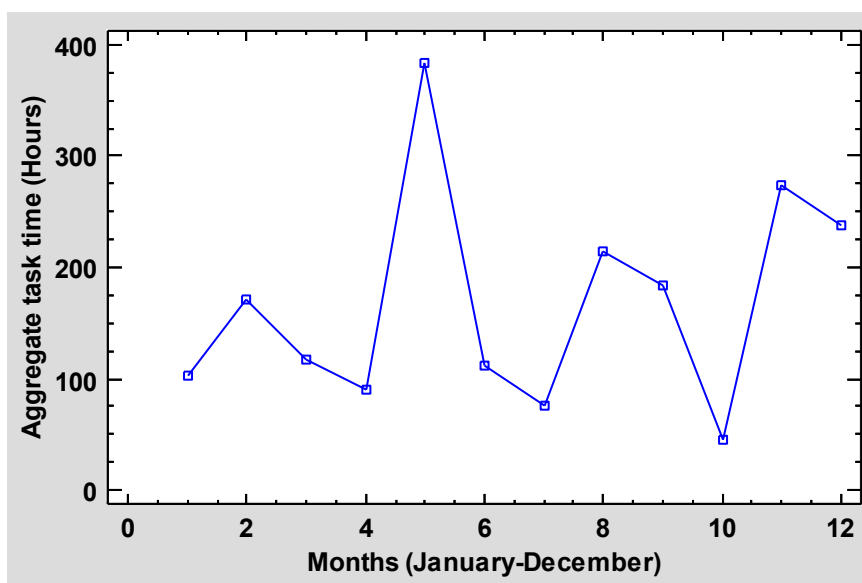


Figure 3 Variation in Aggregate task time with Months.

Understanding and analysing maintenance data is crucial for operational efficiency, cost management, and reliability. Identifying periods with high maintenance demands allows for better planning and resource allocation, minimizing operational disruptions. Efficiently scheduling maintenance activities can help reduce unnecessary repairs and associated costs. Ensuring timely and effective maintenance enhances machinery reliability, reducing the risk of unexpected failures and downtime [22]. The relationship between aggregate task time and the months reveals significant insights into the maintenance patterns of spur gears. By analysing these trends and understanding the underlying factors, organizations can enhance their maintenance strategies, leading to improved operational efficiency, reduced costs, and increased machinery reliability. This

analysis underscores the importance of detailed maintenance data in informing strategic decision-making and optimizing maintenance operations.

The insights gained from analysing aggregate task time can inform strategic maintenance decisions. Adjusting preventive maintenance schedules based on historical data can mitigate high periods of maintenance. Allocating maintenance resources more effectively during peak periods ensures quick and efficient repairs. Implementing predictive maintenance strategies can anticipate and address potential issues before they escalate, thereby reducing overall maintenance time and costs.

Figure 4 displays the relative frequency of maintenance tasks performed on a spur gear over a year, with each month's relative frequency percentage highlighted. This helps to illustrate the variability in task occurrence, providing a comprehensive view of the gear's maintenance history. The data offers insights into the reliability and maintainability of the spur gear system. The most striking feature of the plot is the considerable peak in May, where the relative frequency of tasks reaches 1510%. This substantial spike indicates a period of intensive maintenance activities, possibly scheduled preventive maintenance. This could indicate that the spur gear experienced a critical overhaul or significant wear and tear. Such a peak is often associated with periodic preventive measures to reduce the risk of failure during high-stress operational periods [23].

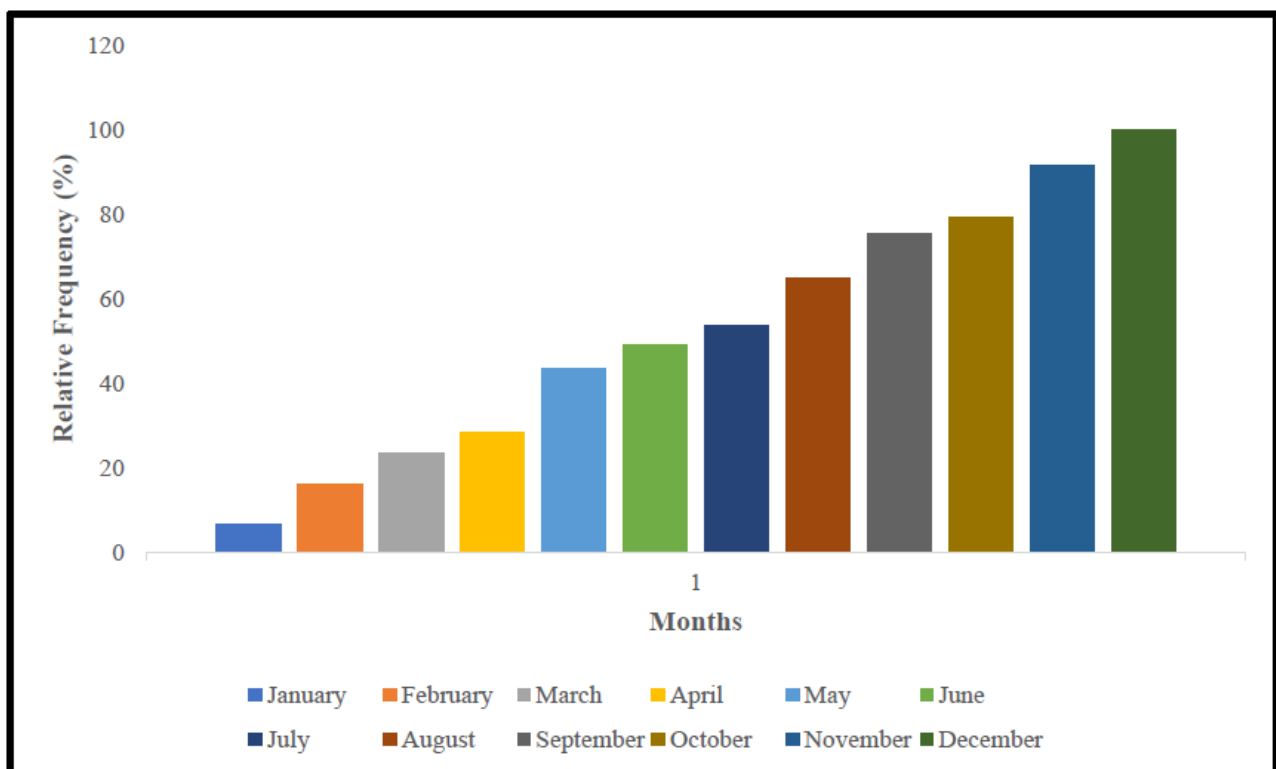


Figure 4 Variation of Relative frequency with months.

February and October also exhibit elevated cumulative frequencies, reaching 9400% and 380% respectively. This suggests that maintenance activities during these months were essential, possibly related to pre-emptive efforts to ensure reliability. These could correspond to secondary preventive or corrective maintenance activities aimed at extending the component's lifespan before critical operational periods [24]. April, June, and July have lower task frequencies, falling below 600%.

These lower frequencies could signify that the gear remained stable following significant maintenance interventions earlier in the year. The reduced need for maintenance indicates that the previous months' activities improved gear performance, reflecting effective maintainability [25]. The remaining months (January, March, August, September, November, and December) exhibit moderately distributed frequencies, indicating a baseline level of maintenance necessary to sustain the gear's operational reliability throughout the year.

Figure 5 illustrates the percentile distribution of the time required to perform maintenance actions on a spur gear across different months. Analysing this data helps understand the maintenance workload over a year and can aid in optimizing maintenance schedules. The plot shows that January has the lowest percentile at 6.6%, indicating minimal maintenance activities. This could be because, at the beginning of the year, equipment is generally in good condition, having undergone maintenance at the end of the previous year. February and March show slight increases, with percentiles of 16% and 23.5%, respectively. This gradual increase can be attributed to the gear starting to experience minor wear and tear from continuous use. In April, the percentile increased to 28.2%, indicating a decrease in maintenance activities. This could be due to effective maintenance performed in the previous months, resulting in fewer breakdowns. However, May shows a significant spike to 43.3%, reflecting the highest aggregate task time for the year. This sharp increase suggests that major maintenance or overhauls were carried out this month to address accumulated issues and prepare for upcoming peak operational periods.

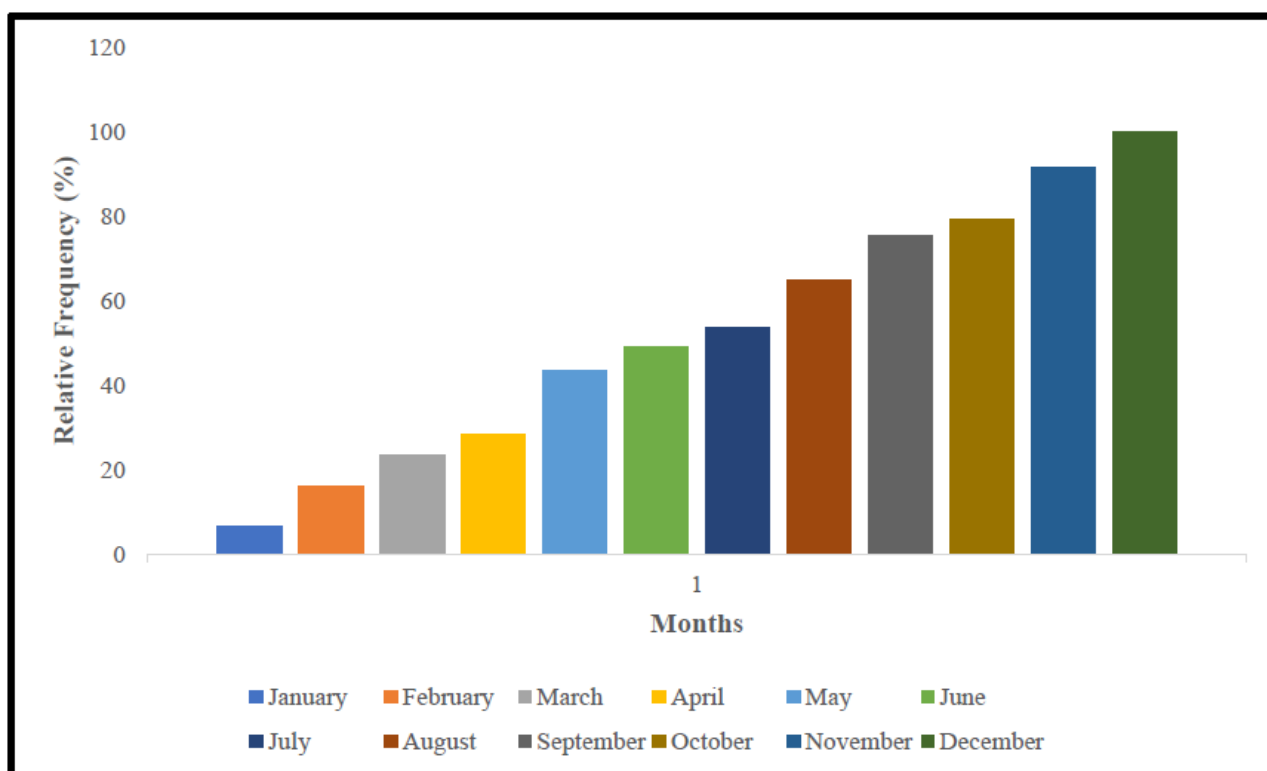


Figure 5 Variation in Percentile with months.

June and July see a reduction in maintenance activity, with percentiles of 49% and 53.7%, respectively. This reduction indicates that the extensive maintenance in May had a positive impact, reducing the need for frequent repairs. However, August shows a notable increase to 65%,

suggesting that the gear again required significant maintenance, possibly due to high operational demands during summer. The trend continued in September and October, with lower percentiles of 75.4% and 79.2%, respectively. This period likely benefited from the extensive maintenance done in August. However, November shows a sharp increase to 91.5%, indicating another peak in maintenance activities, possibly to prepare the gear for intensive use in the year's final months.

December shows the highest percentile at 100%, reflecting the cumulative effect of maintenance activities throughout the year. This peak is attributed to final-year-end maintenance to ensure the gear is in optimal condition for the new year. This data is crucial for planning and resource allocation for maintenance activities. Understanding the trends and patterns can optimise maintenance schedules to prevent unexpected breakdowns and ensure continuous operation. Regular analysis and monitoring of such data support predictive maintenance, extend the lifespan of the spur gear, and improve overall efficiency.

Figure 6 depicts the relationship between the failure rate λ_{SG} of spur gears and the Mean Time to Repair (MTTR) across different months. This comparison highlights the performance and maintenance efficiency of the spur gears over time. The failure rate remains relatively low and stable throughout the months, showing minimal fluctuation. This suggests that while failures occur, they are not excessively frequent or severe. The stability of the failure rate indicates that preventive maintenance may have been effective in keeping failure occurrences at a minimum [26]. In contrast, the MTTR exhibits significant fluctuations, peaking notably in the 5th month. The high MTTR indicates that the time required to repair the spur gear during certain months was considerably extended, possibly due to the complexity of the failure or delays in resource availability. The trend also suggests varying repair efficiency and responsiveness across the months [27]. While the failure rate remains stable, the spikes in MTTR suggest that when failures do occur, they require substantial time to address. The most significant spike in MTTR during the 5th month correlates with a relatively low failure rate, suggesting that, while failures were infrequent, their severity or complexity required extensive repair time [28]. The sharp fluctuations in MTTR highlight the need for more consistent maintenance strategies to reduce repair times and improve maintainability. The relatively low and stable failure rate suggests that maintenance efforts prevent frequent failures, but the variability in MTTR suggests room for improvement in repair processes [29]. The stable failure rate observed in the plot reflects positively on the reliability of the spur gear system, indicating that failures are being kept in check through effective preventive maintenance strategies [30]. The significant fluctuations in MTTR suggest inefficiencies in maintenance practices. High MTTR values indicate potential challenges in repair processes, such as resource availability, technical expertise, or the complexity of failures [31]. The varying MTTR values indicate the maintainability of the spur gear system. Although the failure rate remains stable, MTTR spikes indicate that repair failures can be lengthy, potentially impacting overall system uptime and availability [32].

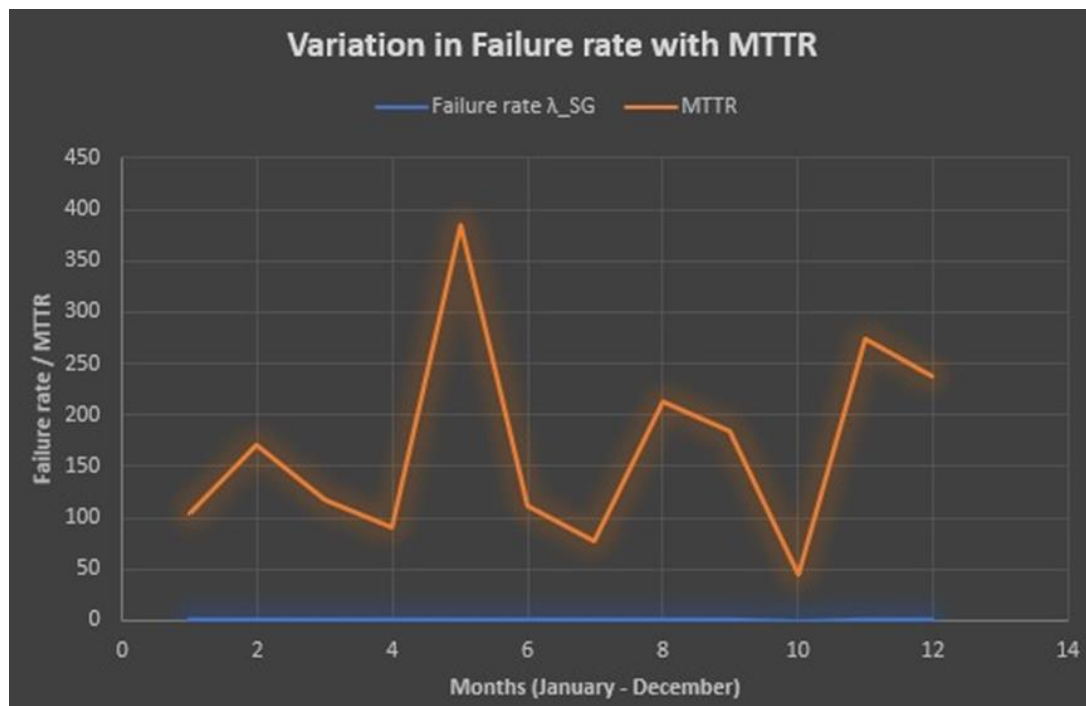


Figure 6 Variation in Failure Rate with MTTR.

According to a study by [33], it is important to maintain low failure rates while focusing on reducing MTTR to improve system uptime and availability. The stable failure rate in the graph aligns with their findings, but the fluctuating MTTR suggests the need for more streamlined repair processes [34]. A study by [31] emphasized the importance of balancing preventive and corrective maintenance strategies to achieve low failure rates and MTTR. Thus, the low failure rate suggests effective preventive maintenance, but the variable MTTR indicates that corrective maintenance practices may need to be optimized, which aligns with the study [35]. According to a study by [36], reducing MTTR is critical for improving the maintainability of industrial systems. The spikes in MTTR observed in the plot suggest that more focus should be placed on reducing repair times to enhance the maintainability of the spur gear system. This failure rate analysis vs. MTTR plot shows how reliability and maintainability interact within the spur gear system. The findings suggest practical preventive maintenance efforts but also highlight the need to improve the speed and efficiency of corrective maintenance to ensure optimal system performance.

Figure 7 illustrates the maintainability of a spur gear across different months. Maintainability is the probability that a failed system will be restored to operational condition within a specified period, given as a percentage. This metric is crucial in assessing the reliability and effectiveness of maintenance strategies over time. The maintainability percentages across all months are high, close to 100%, indicating a highly reliable maintenance system. Variations in maintenance time can be attributed to specific operational and environmental factors that affect the spur gear's performance [37]. Such detailed analysis helps refine maintenance schedules and improve overall system efficiency. Understanding the maintainability of spur gears is essential for several reasons: it helps plan and allocate resources efficiently to ensure maintenance activities are performed optimally. By analysing trends, maintenance actions can be predicted and scheduled proactively, reducing downtime and improving overall system reliability. Improved maintainability can lead to significant cost savings by minimizing the time and labour required for repairs.

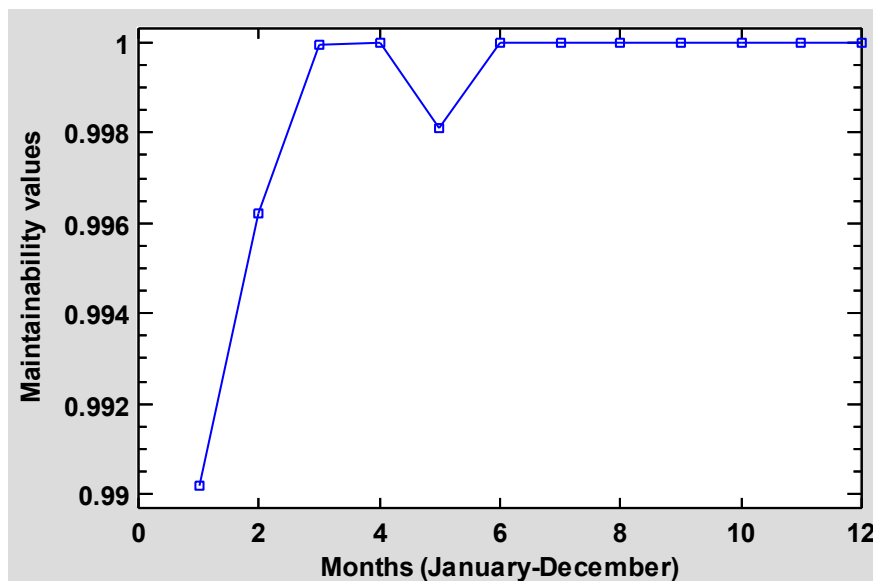


Figure 7 Variation in the measured maintainability with Months.

Figure 8 depicts the calculated failure rate of spur gears over time, showing a dynamic trend that reflects periods of varying reliability. The failure rate in this context is the frequency with which the spur gear system experiences failures per operational cycle or hour. The failure rate starts at around 0.015 in January, increases slightly in February, and then declines steadily to its lowest point in April (~ 0.01). This decline suggests that maintenance activities in the first quarter of the year effectively stabilized the gear's performance [38]. The failure rate surges dramatically in May, reaching a peak of approximately 0.033. This spike could indicate a period of heavy operational stress or reflect the after-effects of suboptimal maintenance in previous months. Such peaks are often associated with unforeseen failures or gear system degradation [39].

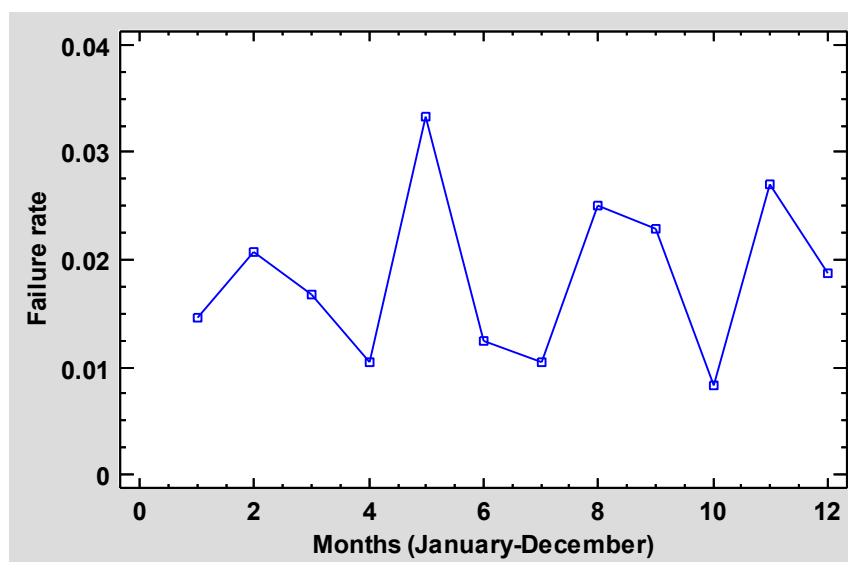


Figure 8 Variation in the failure rate with Months.

After May, there was a sharp recovery, with the failure rate dropping to its lowest point in June (~ 0.013). The significant reduction in the failure rate indicates successful maintenance activities implemented after the peak in May. This period could be attributed to corrective measures aimed

at restoring gear reliability [40]. The failure rate exhibits moderate fluctuations between September and December, peaking again in October before dropping in November and slightly increasing in December. These fluctuations are characteristic of an aging spur gear system where wear and tear begin to impact reliability despite ongoing maintenance efforts. Periodic peaks in the failure rate during this phase suggest that, while maintenance activities are underway, they may not be sufficient to prevent failures entirely, possibly indicating the need for more comprehensive or intensive interventions [41].

The result illustrates the importance of consistent, effective maintenance activities in ensuring the reliability of the spur gear system. Peaks in failure rates, particularly in May and October, reflect vulnerabilities in the gear's operational cycle that could have been mitigated by more frequent or better-timed maintenance activities [42]. The drop-in failure rates following spikes suggest the need to implement both corrective and preventive maintenance strategies. For instance, after the significant peak in May, the sharp decline in June suggests successful corrective maintenance. However, subsequent fluctuations suggest that preventive measures may need to be strengthened to maintain long-term reliability [43]. The recovery periods seen after the spikes demonstrate the maintainability of the spur gear system. The ability to return the failure rate to lower levels following maintenance activities speaks to the effectiveness of the interventions. However, the persistent fluctuations toward the end of the year suggest that the system's maintainability may be challenged by increasing wear and tear [44]. This analysis of the failure rate plot connects the observed trends to broader reliability, maintenance, and maintainability theories, providing a grounded explanation for the spur gear system's performance across the year.

Figure 9 shows the relationship between the time required to restore the density function of a spur gear and the months of the year. This offers significant insights into maintenance scheduling and operational efficiency. The time-to-restore-density function measures the rate at which maintenance actions are completed to restore the gear to operational status, with higher values indicating a higher density of maintenance actions within a given timeframe. The data shows that January has the highest maintenance activity, likely due to accumulated wear and tear from the previous year. This necessitates frequent maintenance actions at the beginning of the year, as evidenced by the 103.6 hours of aggregate task time. As the year progresses, maintenance activity declines from February to April. February's higher failure rate ($\lambda_{SG} = 0.0208$), resulting in 171 hours of maintenance, indicates a period of intensive repair, but subsequent months see reduced activity as initial repairs stabilise the gear's performance. From May to October, the graph shows minimal maintenance activity, suggesting a stable operational phase in which the gear is performing optimally due to prior maintenance efforts. October, in particular, has the lowest time to restore the density function, correlating with only 44.8 hours of aggregate task time. This period of reduced maintenance aligns with the expected performance of well-maintained equipment operating efficiently.

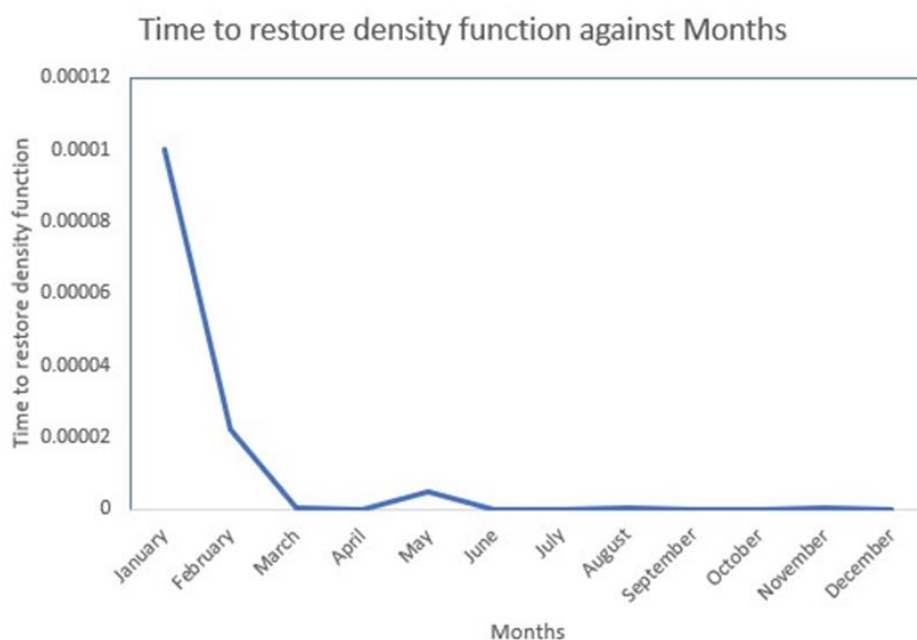


Figure 9 Variation in time to restore the density function with Months.

Towards the end of the year, November and December exhibit a slight increase in maintenance activity. This increase likely reflects preventive maintenance measures taken to prepare the gear for the upcoming year, as indicated by the significant 274.3 hours of maintenance in November. Such proactive measures ensure the gear remains in optimal condition, minimizing the risk of unexpected failures and ensuring smooth operation. Analysing the time to restore the density function provides valuable insights for maintenance scheduling. By understanding high- and low-maintenance activity periods, maintenance teams can plan resources more effectively, reducing downtime and improving overall efficiency.

4. Conclusion

The variation in TPMA from January to December is attributed to several factors, including moderate maintenance time, possibly due to initial operational adjustments post-holiday season, heightened operational activities leading to increased TPMA, a reduction in TPMA occasioned by stable operation, and preparation for a higher summer workload, increasing in maintenance time. The reliability of the spur gear is not constant and requires regular intervention. Variations in the quality and durability of the spur gears used contribute to the frequency and duration of repairs. This highlights the need for a well-balanced maintenance strategy to optimize the reliability and maintainability of the spur gear. Analysing the time-to-restore density function provides valuable insights for maintenance scheduling. By understanding the periods of high and low maintenance activity, maintenance teams can plan resources more effectively, reducing downtime and improving overall efficiency.

Author Contributions

Enesi Y. Salawu – Data analysis, result presentation. Opeyemi E. Akerekan – Equation modelling. Femi E. Adegbite – Equation modelling. Olasehinde O. Nifemi – Data collection. Samson O. Ongbali

– General Review. Joseph O. Dirisu – Drafting of the abstract. Ogunkola B. Abiodun – Drafting of the literature review. Emmanuel O. Ajanaku – Results and Discussion.

Competing Interests

The authors have declared that no competing interests exist.

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