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Stochastic process assessment for XP600 printhead failures: A Weibull method study

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Abstract
This research presents a thorough reliability assessment of XP600 printheads using the Weibull method, examining the variables "Time to Failure" and "Total Runs" to understand their distributional characteristics and implications for maintenance. Both variables share a shape parameter (β) of 2.06187, indicating a right-skewed distribution. Notably, "Time to Failure" exhibits lower variability with a scale of 29.7615 weeks, while "Total Runs" reveals broader variability with a scale of 5449829 feet. Anderson-Darling goodness-of-fit tests underscore the superior reliability of "Time to Failure" (adjusted value: 0.970). Practical applications advocate for a time-based maintenance strategy, with the categorization of printheads based on both time and total runs for risk-based interventions. The integrated approach proposed extends beyond XP600 printheads, offering a nuanced decision-making framework for industrial printing technologies. Future research should explore intricate relationships between time and total runs, translating findings into actionable strategies for enhanced performance and longevity. This research serves not only as a reliability exploration but also as a catalyst for efficient maintenance practices in industrial printing technologies.
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Keywords: Printhead, Reliability, Weibull, Failure, Maintenance.

1. Introduction

Printheads are essential components that power a wide range of applications, from advanced manufacturing to inkjet printing, ensuring accuracy and high-quality output (Shah et al., 2021). These tiny but essential equipment are in charge of converting digital data into tangible outcomes, such as a sharp picture printed on paper or precisely positioned components in a three-dimensional print. As a result, printhead reliability is crucial since it directly affects the effectiveness and caliber of these operations (Wang et al., 2020).

The XP600 printhead which is built on Piezoelectric technology has become a prominent player in the printhead market distinguished by its precision, and versatility(Bischoff et al., 2022). Used as the major print component of large format inkjet printing machines, Its piezoelectric technology, featuring a high nozzle density, ensures precise droplet placement, resulting in sharp and vibrant prints(Shah et al., 2021). With a resolution of up to 1440 dpi (dots per inch), this printhead offers exceptional image clarity and detail. Its application spans diverse needs, from the production of fine art prints and textile printing to packaging and label production. The XP600 printhead's appeal lies in its ability to deliver high-quality output consistently, making it a popular option for manufacturers and end users alike (Yesuf & Abdul, 2023).

However, XP600 printheads are subject to wear and tear issues just like any other mechanical or electromechanical component. Failures might happen, causing delays in operations and additional maintenance costs. The reliability of nozzles, crucial components in this technology, is subject to various challenges. These challenges stem from several factors, including intermediate drying, air ingestion, vibrations within the printing system, nozzle plate flooding, and clogging caused by airborne and inkborne contaminants.(Reinhold et al., 2016) While some of these issues can be attributed to the design of the printing system, the majority are linked to the inherent operation of the printhead itself. Factors such as crosstalk, temperature variations, and water hammer phenomena may pose risks to the stability of the ink-printhead combination. The problem is further compounded by the scarcity of information regarding the failure pattern of this printhead. Users of large format printers that rely on XP600 printheads always base their maintenance and replacement plans on guesses and assumptions that rarely work. This is because this vital and very expensive machine component is procured with no warranty/guarantee and without any expected failure time. There is no accurate information and consensus concerning, how long it stays before it fails and how much work it does before failing. While some believe that once the printhead is installed on the machine, it must fail after a given time whether it works or not. Some believe that it only fails as a result of work done and not the time it lasts. Still, many believe that the two factors play a role in its failure. As a result, end users of XP600-based large format machines are either faced with the sudden and unplanned breakdown of this component or resort to keeping excess inventory of the printhead to forestall downtimes Ensuring reliability is a prominent and intricate aspect of XP600 technology. It is therefore not only desirable but also necessary to understand the reliability and failure patterns of XP600 printheads to maintain smooth operations while producing high-quality outputs.

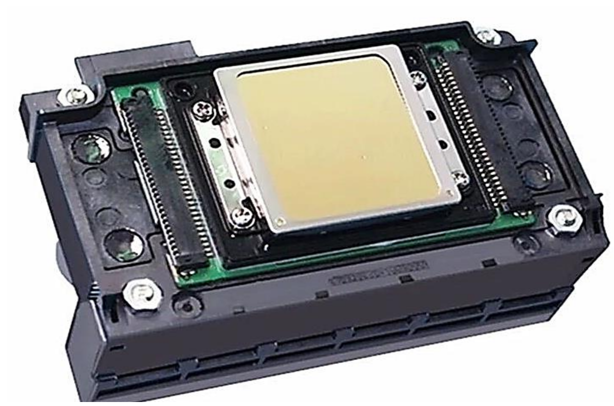

Figure 1: XP600 Printhead

In the face of the challenges confronting XP600 printheads, our study introduces an innovative approach utilizing statistical methodologies, particularly the Weibull method. This approach offers a thorough assessment and prediction of the printhead failures, deviating from conventional maintenance practices based on guesswork. Our method delves into comprehensive data analysis, focusing on the total number of operational runs and weeks of usage. The precision of our methodology lies in unraveling the intricate dynamics of reliability. Statistical methodologies have proven to be invaluable (Lakin, 2019). In this research, we delve into the stochastic assessment of XP600 printhead failures, with a primary focus on applying the Weibull method, a robust statistical tool, for in-depth analysis. The Weibull method provides a methodical way to model and examine the failure behavior of different parts and systems (Barraza-Contreras et al., 2020; Xiong et al., 2019). It is particularly suitable for assessing the distribution of failure times and predicting potential breakdowns.

Our investigation addresses a crucial gap in understanding the reliability and failure patterns of XP600 printheads. The limited information available regarding the failure patterns of this essential machine component poses a significant challenge. Our study makes a valuable contribution by providing a systematic and in-depth analysis, moving away from uncertainties surrounding the maintenance and replacement plans for XP600 printheads. Through the identification of trends, patterns, and potential causes of failures, our research aims to bring clarity and make a substantial contribution to enhancing efficiency in processes that rely on XP600 printheads. This empowers end-users and manufacturers to make well-informed decisions, ultimately enhancing operational efficiency in large format printing. In the following sections, we will delve into the Literature review, methodology, data analysis, and the industrial implications of our research. We'll also address limitations and suggest avenues for further investigation, contributing to the broader understanding of printhead reliability and enhancing the efficiency of processes employing XP600 printheads.

The work of Wang et al. (2020), exemplifies the critical role of printhead reliability across industries. Their comprehensive review underscores the adverse impacts of printhead failures, including production interruptions, increased operational costs, and compromised output quality. But a deeper look at current approaches shows both their strengths and limitations, calling for a more critical evaluation. In industries like textile production and packaging, where continuous, high-quality output is imperative, printhead reliability becomes paramount. A deep understanding of failure modes, root causes, and patterns is indispensable for minimizing disruptions and ensuring optimal productivity.

Printhead failures manifest in various forms, encompassing nozzle clogs, dropouts, misfiring, and electrical malfunctions (Wang et al., 2020). Reinhold et al. (2016) underscore that these failures can be attributed to factors such as wear and tear, environmental conditions, and manufacturing defects. In the case of inkjet printheads, nozzle blockages, and clogs can significantly affect print quality and consistency, leading to wasted materials and operational downtime. Furthermore, Ding et al. (2021) opines that in additive manufacturing, especially in 3D printing, where precision and consistency are paramount, the reliability of printheads is of utmost importance. Even minor malfunctions can lead to defects, layer misalignment, and the rejection of printed objects. Understanding the root causes of printhead failures is pivotal for these applications. While these insights are valuable, it is crucial to recognize that the complexity of printhead failure mechanisms may not be fully captured by these general categories.

In light of these challenges, addressing printhead failures often involves the development of more robust hardware and the implementation of routine maintenance and monitoring protocols. Manufacturers and researchers alike rely on reliability engineering and statistical analysis to assess and predict printhead reliability (Lakin, 2019). To complement the insights of these foundational works, numerous other studies have focused on specific failure modes and mechanisms of printheads in different contexts. Bernasconi et al. (2022) explored the impact of ink viscosity on nozzle clogs, offering insights into the prevention of this common failure. Gao et al. (2022), conducted a study on thermal printhead failures and examined the role of temperature control in enhancing reliability. Additionally, Colton et al. (2021) investigated the effects of varying environmental conditions, such as temperature and humidity, on printhead performance. Their research underlines the importance of environmental control in maintaining reliability. However, a critical examination of these studies reveals a gap in the comprehensive understanding of the interconnections between different failure modes and the collective impact on printhead reliability.

Cameron et al. (2020) examined the role of material properties in printhead failures, providing a deeper understanding of the interplay between material selection and reliability. Their work highlights the significance of material-related failures in applications like 3D printing. While this sheds light on one aspect, the limitations of material-centric approaches, especially in predicting failures related to other factors, should be acknowledged. Furthermore, Ding et al. (2021) offer an analysis of the economic implications of printhead failures and the cost-effectiveness of maintenance strategies, shedding light on the financial incentives of reliability improvements. Focusing on a narrower scope, Kamyshny et al. (2022), explored the effects of ink type on printhead reliability, emphasizing the need for compatibility and maintenance. They address the challenge of choosing the right ink for specific printhead technologies. Liu et al. (2023), studied the effects of process parameters on microdroplet jetting characteristics by piezoelectric printhead. They demonstrated how the radius of the nozzle and the pulse width of the piezoelectric actuation signal have a significant impact on the jetting properties of piezoelectric printheads. Gautero et al. (2019), delve into the impact of printhead maintenance on overall system reliability and productivity, offering insights into the importance of routine servicing. Though these studies offer valuable insights, a more critical analysis within the context XP600 printhead reliability need to be addressed,

The existing literature provides a foundation for understanding the significance of printhead reliability, the various causes of printheads' failure and the role of reliability analysis in this context. However, there remains a gap in the specific analysis of XP600 printheads using the Weibull method, which this research aims to address.

2.0 Material and methods

2.1 Data collection

The research method employed in this study is fundamentally quantitative, focusing on the systematic analysis of failure data from thirty (30) different XP600 printheads collected from various printing firms. The following steps outline the data collection process:

2.1.1 Data source
The failure data was sourced from multiple printing firms, representing diverse operational environments and usage conditions. This diverse dataset enhances the generalizability of the findings.

2.1.2 Data variables
The key variables collected include the time of failure (weeks), the total number of runs before failure (feet (ft), the month of failure, and the probable cause of failure. These variables are integral to conducting a Weibull analysis and understanding the reliability dynamics of XP600 printheads.

2.1.3 Data Collection Process
The failure data was obtained through machine operators, technicians, and print shop owners who have direct observation and monitoring of the XP600 printheads' performance in their respective printing environments. This collection was done over a period of 12 months. Each instance of printhead failure was meticulously documented, capturing the necessary data variables.

2.2 Weibull Analysis
The quantitative analysis in this research primarily revolves around the application of the Weibull method. This method enables the modeling of the distribution of failure times and is well-suited for assessing the reliability and failure behavior of components and systems.

2.2.1 Data preprocessing
Before conducting the Weibull analysis, the failure data underwent rigorous preprocessing. This involved:
- **Data Cleaning:** Removal of any outliers or erroneous data points that could skew the analysis.
- **Data Validation:** Ensuring the accuracy and consistency of the failure time records

2.2.2 Weibull Parameters Estimation:
The Weibull analysis hinges on the estimation of three key parameters: the shape parameter (β), the scale parameter (η), and the Mean Time To Failure (MTTF). These parameters are critical for characterizing the failure distribution and reliability assessment.
- **Shape Parameter (β):** The shape parameter determines the type of failure distribution. When β < 1, it indicates early-life failures, β = 1 suggests a constant failure rate, and β > 1 implies wear-out failures. The shape parameter is estimated using Maximum Likelihood Estimation (MLE):

  $$\beta = \left(\frac{1}{n}\sum_{i=1}^{n} \ln\left(\frac{t_i}{t^0}\right)\right)^{-1} \quad (1)$$

  Where:
  n is the total number of observed failures.
  t_i denotes each observed failure time.
  β is the shape parameter.

- **Scale Parameter (η):** The scale parameter represents the characteristic life of the component. It is estimated as:

  $$\boldsymbol{\eta} = \left(\frac{1}{n}\sum_{i=1}^{n}(t_i)^{\beta}\right)^{\frac{1}{\beta}} \quad (2)$$

  Where:
  η represents the scale parameter.
  n is the total number of observed failures.
  t_i denotes each observed failure time.
  β is the shape parameter.

- **Mean Time To Failure (MTTF):** This is a measure that represents the average time a system or component is expected to operate before experiencing a failure. MTTF is often used to quantify the reliability of a system. It is given as:

  $$MTTF = \eta \,.\, \tau\left(1 + \frac{1}{\beta}\right) \quad (3)$$

  Where:
  MTTF is the Mean Time To Failure.

η is the scale parameter.
Γ is the gamma function.
β is the shape parameter.

2.2.3 Reliability modeling

The Weibull distribution is applied to model the reliability of the XP600 printheads. The reliability function for the Weibull distribution is defined as:

$$R(t) = e^{-\left(\frac{t}{\eta}\right)^{\beta}} \quad (4)$$

Where:
R(t): Represents the reliability at time t.
η: Denotes the scale parameter.
β: Indicates the shape parameter.
e: Represents the base of the natural logarithm.

2.3 Software

Minitab 17, a statistical software is employed in this study to run the analysis

3.0 Results and Discussions

3.1 Correlation analysis

The result returned for the correlation of the two key variables: Time to Failure (Weeks), and Total Runs (ft) is as follows:

Correlation: TIME TO FAILURE (WEEKS), TOTAL RUNS (FT)
Pearson correlation of TIME TO FAILURE (WEEKS) and TOTAL RUNS (FT) = 0.086
P-Value = 0.652

The Pearson OF 0.086 implies that there is a very weak positive correlation between "Time to Failure (Weeks)" and "Total Runs (FT). And the correlation is not statistically significant based on the high p-value of 0.652. Thus, suggesting that the relationship between "Time to Failure (Weeks)" and "Total Runs (FT)" is not strong.

3.2 Goodness of Fit test

The reliability assessment tool has four major methods used for data distribution and analysis. The four methods include the Weibull method, the lognormal method, the exponential method, and the log-logistic method. The printhead data is subjected to the four reliability assessment methods to determine the best method that will achieve improved and reliable solutions for the prediction of the estimated life cycle for the printhead. Three key factors are observed and considered, namely: Anderson-Darling, table of Distribution characteristics, and the probability plot. The best distribution method is chosen.

Table 1: Anderson-Darling test

Distribution	Anderson-Darling (adj)
Weibull	0.789
Lognormal	1.225
Exponential	4.520
Loglogistic	0.895
3-Parameter Weibull	0.813
3-Parameter Lognormal	0.768
2-Parameter Exponential	2.927
3-Parameter Loglogistic	0.719
Smallest Extreme Value	1.512
Normal	0.838
Logistic	0.794

From the results: Table 1, Table 2, and Figure 2a-c, the Weibull reliability consistently demonstrates the best fit for the assessment. It has a lower Anderson-Darling of 0.789. Table 2 shows that the Weibull distribution has a mean of 26.9742 which is close to the observed data and reasonably narrow confidence interval. Figure 2a-c shows clearly that the Weibull distribution maintained a better straight line of its plots. The best distribution method for the xp600 printhead dataset is adjudged to be the Weibull method.

Table 2: Table of Distribution characteristics

Distribution	Mean	Standard Error	95% Normal CI Lower	95% Normal CI Upper
Weibull	26.9742	2.22650	22.9451	31.7109
Lognormal	27.5407	2.91580	22.3798	33.8917
Exponential	26.9667	4.92342	18.8547	38.5687
Loglogistic	29.2439	2.95861	23.9838	35.6575
3-Parameter Weibull	26.9345	2.23772	22.8871	31.6976
3-Parameter Lognormal	26.9688	2.24419	22.5703	31.3673
2-Parameter Exponential	26.9666	3.95996	20.2223	35.9603
3-Parameter Loglogistic	27.1482	2.40655	22.4314	31.8649
Smallest Extreme Value	25.8764	2.97061	20.0541	31.6987
Normal	26.9667	2.23333	22.5894	31.3439
Logistic	26.5306	2.18313	22.2517	30.8094

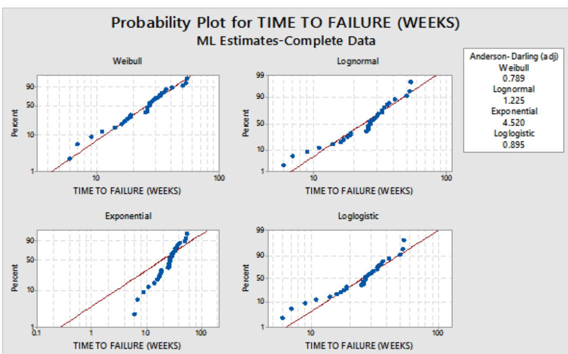

Figure 2a: Distribution ID Plot

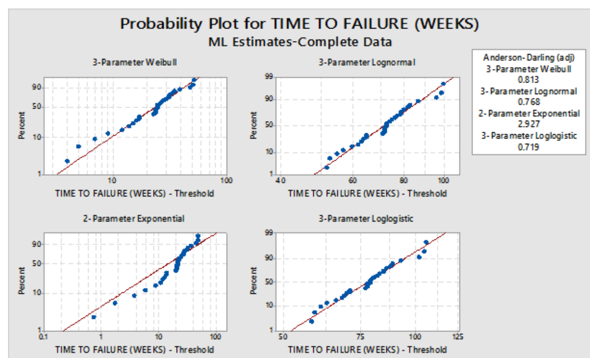

Figure 2b: Distribution ID Plot

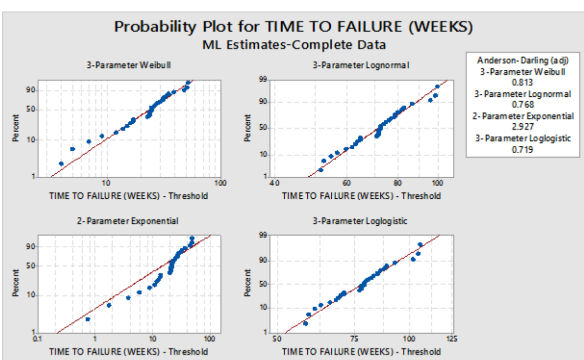

Figure 2c: Distribution ID Plot

3.3 Reliability Analysis

Two (2) major variables were considered in running this reliability assessment viz: the total number of weeks the printhead worked before failing and the total length (in feet) the printhead traveled in performing its work before failing.

For the analysis of the first variable: **TIME TO FAILURE (WEEKS).** Results obtained show a negative log-likelihood of -117.230 and an Anderson-Darling (adjusted) of 0.970. Both values suggest a reasonably good fit of the Weibull distribution to the data.

Table 3 shows that the Shape Parameter (β) = 2.06187, Standard Error=0.224490 at 95% CI: (1.66565, 2.55233) Since the shape parameter is greater than 1, it indicates an increasing failure rate over time, this explains the fact that the XP600 printhead fails as it ages. The table also shows the Scale parameter (η) = 29.7615, Standard Error=2.69052 at 95% CI: (24.9289, 35.5308) This result suggests that the XP600 printhead failure times can be reasonably modeled at an average time to failure around 29.7615 weeks which is approximately 30 weeks. The observed values of the range between the lower and upper bounds of the confidence interval for the shape(β) and scale(η) parameters (1.66565, 2.55233) and (24.9289, 35.5308) respectively indicate more precise estimation and higher confidence in the determined shape and scale parameters.

Table 3: Parameter Estimates for Time To Failure (weeks)

			95.0% Normal CI	
Parameter	**Estimate**	**Standard Error**	**Lower**	**Upper**
Shape (β)	2.06187	0.224490	1.66565	2.55233
Scale (η)	29.7615	2.69052	24.9289	35.5308

Table 4 provides a detailed understanding of the distribution of time to failure for the XP600 printheads, offering a clue into identifying central tendencies and variability in different segments of the dataset. The MTTF value of 26.3638 indicates that on average, it is expected that the XP600 printheads operate for approximately 26.36 weeks before failure. Q1 (First Quartile) value of 16.2641 weeks indicates that approximately 25% of the XP600 printheads have a time to failure of 16.2641 weeks or less. Further, the table shows that Q2 (Second Quartile, Median) is equal to 24.9147 weeks. This implies that the median time to failure for the XP600 printheads is 24.9147 weeks. It is the middle point of the dataset, separating the lower 50% from the upper 50%. Q3 (Third Quartile) = 34.8702, suggests that approximately 75% of the XP600 printheads have a time to failure of 34.8702 weeks or less. This represents the lower boundary of the upper quarter of the data. IQR (Interquartile Range) value of 18.6061 indicates that the middle 50% of the data falls within a range of 18.6061 weeks.

Table 4: Characteristics of Distribution for Time To Failure (weeks)

			95.0% Normal CI	
	Estimate	Standard Error	Lower	Upper
Mean(MTTF)	26.3638	2.37728	22.0929	31.4603
Standard Deviation	13.4085	1.60755	10.6005	16.9602
Median	24.9147	2.39653	20.6338	30.0838
First Quartile(Q1)	16.2641	1.98516	12.8036	20.6598
Third Quartile(Q3)	34.8702	3.08786	29.3141	41.4792
Interquartile Range(IQR)	18.6061	2.11892	14.8839	23.2591

Table 5 presents estimates of the time to failure at various percentiles. These estimates provide an idea of when a certain percentage of the XP600 printheads are expected to fail. For instance 90th Percentile is estimated at 44.5993, thus implying that the estimated time at which 90% of the XP600 printheads will fail is 44.5993 weeks, with a 95% confidence interval of [37.2234, 53.4367] weeks. Further, the 99th Percentile estimate is at 62.4204, which indicates that the estimated time at which 99% of the XP600 printheads will fail is 62.4204 weeks with the associated uncertainties represented by the standard errors and confidence intervals.

Table 5: Table of Percentiles for Time To Failure (weeks)

			95.0% Normal CI	
Percent	Percentile	Standard Error	Lower	Upper
0.00001	0.0119861	0.0104739	0.0021621	0.0664487
0.0001	0.0366163	0.0275711	0.0083704	0.160179
0.001	0.111859	0.0707386	0.0323879	0.386334
0.01	0.341726	0.175059	0.125206	0.932677
0.1	1.04417	0.410421	0.483277	2.25602
1	3.19682	0.881475	1.86214	5.48813
2	4.48522	1.08143	2.79609	7.19476
3	5.47347	1.21012	3.54873	8.44215
4	6.30874	1.30598	4.20469	9.46567
5	7.04755	1.38259	4.79788	10.3521
6	7.71871	1.44645	5.34605	11.1444
7	8.33926	1.50123	5.85996	11.8675
8	8.92025	1.54921	6.34668	12.5374
9	9.46935	1.59190	6.81121	13.1649
10	9.99210	1.63038	7.25720	13.7576
20	14.3787	1.89297	11.1086	18.6115
30	18.0513	2.06763	14.4215	22.5947
40	21.4866	2.22501	17.5397	26.3216
50	24.9147	2.39653	20.6338	30.0838
60	28.5260	2.60856	23.8453	34.1255
70	32.5652	2.89657	27.3553	38.7673
80	37.4879	3.32956	31.4985	44.6161
90	44.5993	4.11367	37.2234	53.4367
91	45.5776	4.23531	37.9886	54.6827
92	46.6456	4.37167	38.8182	56.0513
93	47.8258	4.52657	39.7281	57.5739
94	49.1508	4.70563	40.7416	59.2958
95	50.6707	4.91747	41.8938	61.2864
96	52.4674	5.17649	43.2423	63.6605
97	54.6915	5.50942	44.8924	66.6295
98	57.6723	5.97576	47.0727	70.6586
99	62.4204	6.76259	50.4786	77.1872

For the analysis of the second variable: **TOTAL RUNS (FEET).** Results obtained show a log-likelihood of -487.710 and an Anderson-Darling (adjusted) of 2.089. Both values indicate that the data poorly fits the distribution. Table 6 shows that the Shape Parameter (β) = 2.06187, Standard Error=0.224490 at 95% CI: (1.66565, 2.55233), the same value with time to failure, thus, also implying relatively higher probability of shorter runs spans to failure compared to longer ones. The table also shows the Scale parameter (η) = 5449829, Standard Error=489303 at 95% CI: (4570455, 6498399) This result suggests that the XP600 printhead failure times may be modeled at an average total runs before failure of around 5449829 ft. However, the wide confidence interval (4570455, 6498399) indicates a substantial variability in the total runs. This implies that XP600 printheads might fail after a broad range of job lengths. This implies that it might be more challenging to predict when a printhead needs replacement based solely on the length of job runs.

Table 6: Parameter Estimates for Total Runs (ft)

			95.0% Normal CI	
Parameter	Estimate	Standard Error	Lower	Upper
Shape (β)	2.06187	0.224490	1.66565	2.55233
Scale (η)	5449829	489303	4570455	6498399

Figures 3 to 5 show that both variables exhibit similar survival, hazard, and probability trends.

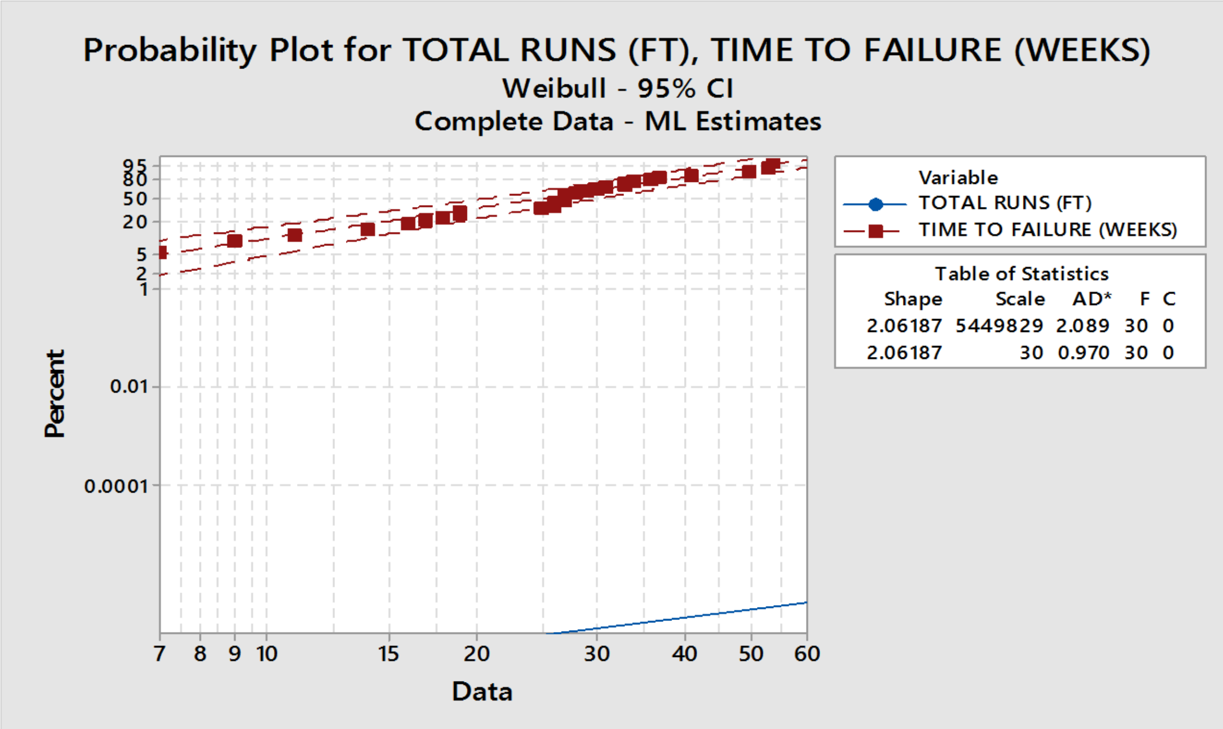

Figure 3: **Probability Plot for Total runs (ft), Time to failure (weeks)**

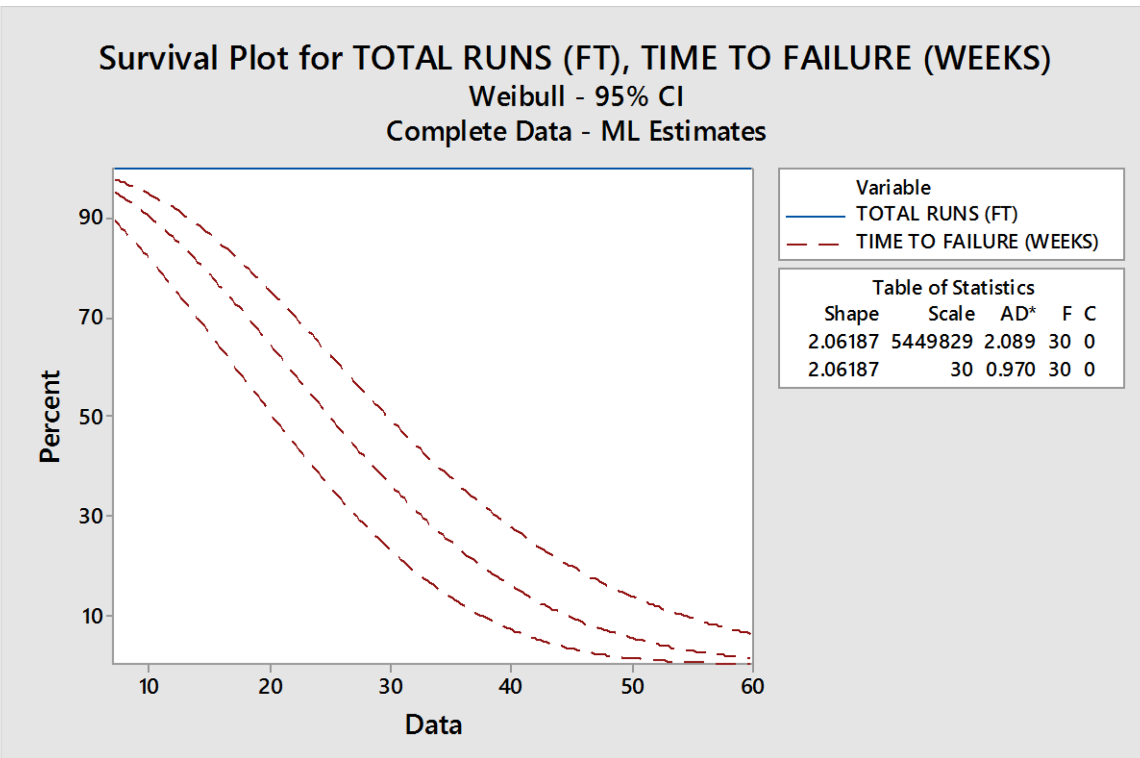

Figure 4: **Survival Plot for Total runs (ft), Time to failure (weeks)**

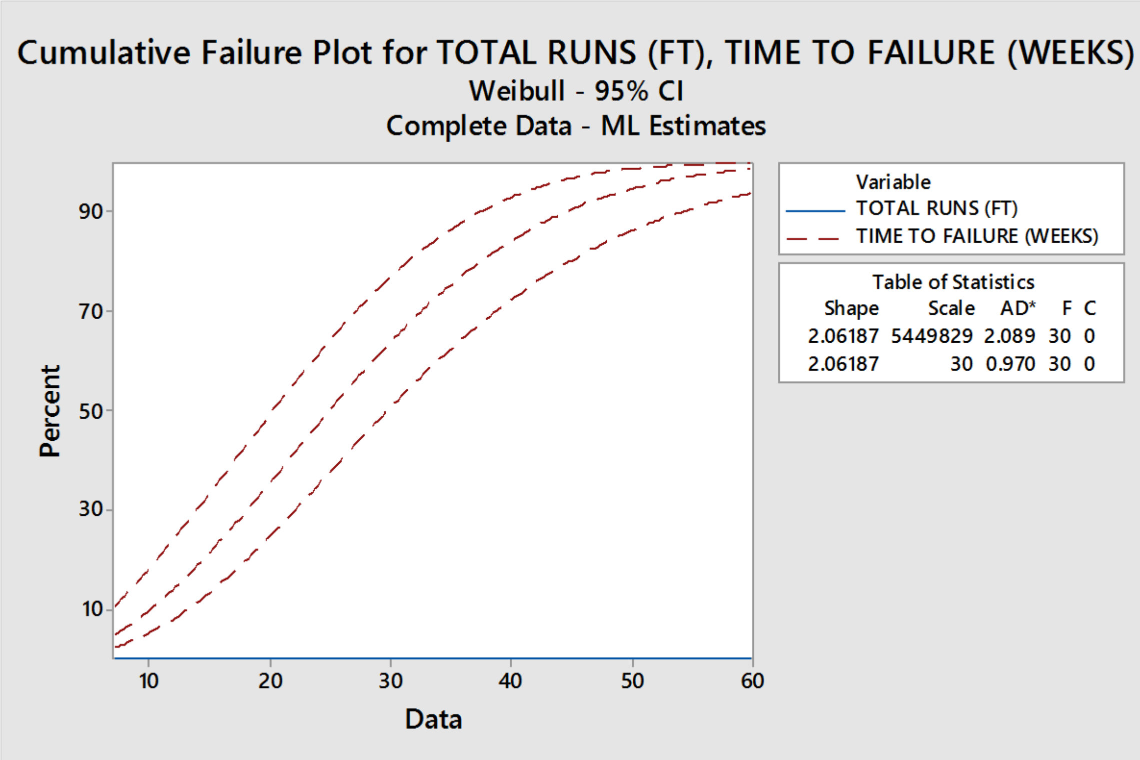

Figure 5: Cumulative Failure Plot for Total runs (ft), Time to failure (weeks)

3.4 Research Findings, Applications, Recommendations, and Contribution to Knowledge

The following Findings, Applications, and Recommendations as well as contributions to knowledge can be proffered based on the research results:

- The values of the shape parameter (β) for both variables indicate that the XP600 printhead fails as it ages and as it runs more work.
- The Anderson-Darling goodness-of-fit test adjusted values suggest the implementation of a time-based maintenance strategy for XP600 printheads, considering the relatively better fit and lower variability in the "Time to Failure" variable.
- This study suggests the Establishment of regular maintenance intervals based on the estimated average time to failure, e.g., every 30 weeks, to address potential issues proactively. (such maintenance plan may also consider intervals based on the total length of runs like every 5,000,000 ft but should not consider it in isolation)
- Understanding of XP600 printhead reliability by providing insights into the distributional characteristics of both time-based and usage-based failure metrics.
- The findings offer practical insights leading to more effective and tailored maintenance strategies for Print shop owners, operators, and technicians involved in managing and maintaining XP600 printheads.

3.5 **Limitations and Bias**

While this study aimed to offer valuable insights into the reliability dynamics of XP600 printheads, it is crucial to acknowledge certain limitations that may impact the interpretation and generalizability of the findings.

Sample Representativeness: The study's reliance on data collected from multiple printing firms introduces variability in operational environments and usage conditions. However, the representativeness of the sample is influenced by the selection criteria and the willingness of printing firms to participate.

Data Collection Challenges: The data collection process heavily relied on machine operators, technicians, and print shop owners for reporting instances of printhead failure. The accuracy of the collected information is dependent on the observers' diligence and precision.

Generalizability to Other Printhead Models: The study's exclusive focus on XP600 printheads constrain the broader applicability of findings to other printhead models.

4.0. Conclusion

In conclusion, this study conducted a comprehensive reliability assessment of XP600 printheads, focusing on the "Time to Failure" and "Total Runs" variables. The research aimed to discern distributional characteristics and implications for maintenance strategies, employing the Weibull distribution as a fitting model.

The findings revealed a shared shape parameter (β) of 2.06187 for both variables, indicating an increasing failure rate as printheads age and engage in more work. Specifically, the "Time to Failure" variable exhibited a scale parameter (η) of 29.7615 weeks, suggesting a more concentrated distribution. In contrast, the "Total Runs" variable displayed a larger scale of 5449829 feet, indicating wider variability in job run lengths.

The Anderson-Darling goodness-of-fit tests underscored the robustness of the Weibull distribution, particularly in the "Time to Failure" variable with an adjusted value of 0.970. This superior fit suggests a reliable modeling of XP600 printhead failures over time.

Connecting these findings to the research objectives, the shared shape parameter (β) aligns with the objective of understanding failure dynamics as printheads age and accumulate more work. The distinct scale parameters (η) for each variable provide insights into the concentration and variability of failure times and job run lengths, linking back to the aim of discerning distributional characteristics.

As a practical recommendation, the study suggests implementing a time-based maintenance strategy for XP600 printheads, leveraging the superior fit and lower variability in "Time to Failure." This translates the research results into actionable insights for more effective maintenance practices.

Looking ahead, future research should delve deeper into the intricate relationships between time to failure and total runs, unraveling additional factors influencing printhead reliability. Collaboration with industry stakeholders and manufacturers is crucial to translating these findings into strategies that enhance the performance and longevity of industrial printheads. In essence, this research serves as a catalyst for informed decision-making, propelling the industry towards more resilient and efficient maintenance practices in the dynamic landscape of industrial printing technologies.

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