Proceedings of the 35th European Safety and Reliability & the 33rd Society for Risk Analysis Europe Conference
Edited by Eirik Bjorheim Abrahamsen, Terje Aven, Frederic Bouder, Roger Flage, Marja Ylönen

doi: 10.3850/978-981-94-3281-3_ESREL-SRA-E2025-P6502-cd

Reliability assessment of centrifugal pumps using warranty drive data as a field fault

C. V. de J C de A Julio[1], A. S. Nicolau[1]

[1] *Program of Nuclear Engineering, COPPE, Federal University of Rio de Janeiro, Rio de Janeiro, Brazil.*
E-mails: carolina.eng@ufrj.br, andressa@lmp.ufrj.br.

A. F. B. Costa[2], J. H. D. Gaudêncio[2]

[2] *Production Engineering Program, IEPG, Federal University of Itajubá, Brazil.*
E-mails: fbranco@unifei.edu.br, juliana.gaudencio@unifei.edu.br.

This study presents a reliability assessment of centrifugal pumps utilizing warranty data to analyze field failures, emphasizing the importance of reliability in determining product quality and competitiveness. Many manufacturers, often lacking adequate resources, launch products without proper reliability assessments, leading to elevated repair costs associated with warranty returns. This research capitalizes on warranty data as a valuable and cost-effective means to evaluate product reliability and implement continuous improvement. It specifically examines the reliability of hydraulic pumps produced by a leisure equipment company with over 50 years of experience, employing failure data collected by Costumer Service. The Statistical Theory of Reliability was applied through probabilistic modeling up to the first failure, with adjustments made to the Weibull model via Maximum Likelihood estimation and validation through the Anderson-Darling test. The analysis utilized MINITAB® software (closed source) and was replicated in RStudio (open source), providing an accessible alternative for data analysis. Given the uncertainty and censoring inherent in the warranty data, results from the Weibull model were compared to those from the Kaplan-Meier model, underscoring the necessity for refinement in failure data interpretation. Complementary tools such as Failure Modes and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) were employed to identify underlying causes and effects of failures. Findings revealed a reliability rate of approximately 40% halfway through the warranty period; however, this may not accurately reflect true product reliability due to data limitations. The study advocates for future research to enhance the methodology and explore its applicability for small and medium-sized enterprises (SMEs), ultimately promoting a culture of reliability with significant social impact.

Keywords: Reliability, Warranty, Field Failure, Centrifugal Pumps, Pumps, Weibull, Kaplan-Meier, Parametric Modeling, Non-parametric Modeling, FMEA, FTA.

1. Introduction

Quality has a direct impact on customer satisfaction, loyalty, and trust, while reliability, defined as the probability of a product operating without failure for a specified period (ABNT NBR 5264:1994), is essential for competitiveness and cost control (Oliveira and Turrioni, 2016). Reliability and quality are complementary: while quality refers to the performance perceived by the user (Pasetto, 2002), reliability is related to sustained performance over time (Muthy, 2007 apud Oliveira and Turrioni, 2016). Low reliability results in high costs (Souza, 1999) and damages the company's reputation (Schneider, 2001), especially in small and medium-sized enterprises (SMEs), which often do not assess the reliability of their products due to limited resources. Statistical Reliability Theory, which originated in sectors such as the aerospace and nuclear industries, provides essential tools for risk analysis, quality control, and product development (Santos, 2011; Fogliatto and Ribeiro, 2011). However, its application requires the robust collection of failure data and can become more challenging when involving complex statistical calculations, especially for less experienced manufacturers (Dillenburg, 2005; Falcetta, 2000).

This raises an important question: how can these manufacturers begin developing a culture of reliability assessment for their products, even with limited experience, in a way that can subsequently improve the quality perceived by their customers? In this scenario, warranty trigger data, collected by Customer Service, offers an accessible alternative for quantifying failures and estimating reliability. These data, mostly already available in the company's database, can help identify real issues in the field and provide a closer view of the user experience (Dillenburg, 2005).

This study presents the application of Statistical Reliability Theory to hydraulic centrifugal pumps in a medium-sized company that had never assessed the reliability of its products, aiming to demonstrate a method for conducting the evaluation using warranty claim data as field failure data. Methods such as Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) complement the analysis, helping identify factors affecting product reliability and demonstrating a practical and accessible approach for small and medium-sized enterprises (SMEs), as discussed by Julio (2024). The objective is to exemplify the application of Statistical Reliability Theory using warranty data, encouraging the adoption of this practice in companies across different sectors. The low-cost approach facilitates the implementation of management practices that enhance product quality and performance, being easily replicable. The demonstration of the application in both commercial and free software reinforces this positioning.

2. Warranty trigger data as field fault data

Customers relate product reliability to the credibility of the company and the warranty period, which is generally regulated by law (Santos, 2008a; O'Connor, 1991, apud Souza, 1999). Warranty data collected by Customer Service is valuable for estimating reliability, identifying root causes and improving products at reduced costs, as it represents real failures in the field under random variables, unlike controlled laboratory tests (Dillenburg, 2005; Fogliatto and Ribeiro, 2011; Oliveira and Turrioni, 2016).

Researchers have applied this data in modeling: Falcetta (2000) and Guimarães (2002) used parametric and Bayesian methods; Pasetto (2002) analyzed customer perception; Santos (2008a) proposed a model based on warranty data; Bonetti (2009) used Weibull functions; Schneider (2001) estimated Mean Time to Failure (MTTF) with stochastic modeling; and Dillenburg (2005) suggested non-parametric methods, such as Kaplan-Meier and Nelson-Aalen, for censored data. Oliveira and Turrioni (2016) also highlighted non-parametric estimators for multiple failure modes.

The Systematic Literature Review revealed a scarcity of studies on warranty data as a basis for reliability assessment, although its social and scientific benefits are clear (Dillenburg, 2005). Reliability, as a multidisciplinary field, combines qualitative and quantitative methods to address special and common cause failures, reducing uncertainties and improving systems (Santos, 2008b). Methods such as FMEA (Failure Mode and Effect Analysis) and FTA (Fault Tree Analysis) complement the Statistical Theory of Reliability and the use of warranty data. While FMEA qualitatively identifies critical items, FTA quantitatively analyzes failure probabilities, offering a detailed view of systems and failure modes, essential for improving reliability and reducing failures during the warranty period (Souza, 1999; Vesely et al. 2002; Falcetta, 2000).

2.1. *Characterization of censorship in guarantee data as a field failure*

Although it is an accessible and feasible solution for companies, using warranty data in reliability assessments presents challenges. Despite its benefits, such as reduced cost and reflecting the actual product usage, some limitations must be considered: (a) Incomplete reports: Unreported failures result in left-censored data (Oliveira and Turrioni, 2016); (b) Warranty period: Limits analyses to failures within the coverage period, generating right-censored data (Santos, 2008a, b); (c) Imprecise records: Incomplete data compromise the reliability analysis (Dillenburg, 2005); (d) Delayed claims: Delays create uncertainties and partial censoring (Souza, 1999); (e) Shelf time: Makes tracking failures in low-value items difficult (Fogliatto and Falcetta, 2001, apud Guimarães, 2002).

To address censored data, Fogliatto and Ribeiro (2011) suggest three approaches: ignoring censored values, waiting for censored data to fail, or using the Maximum Likelihood Estimation (MLE), the latter being the most accurate (Freitas and Colosimo, 1997, apud Bonetti, 2009). Parametric methods are applicable, but non-parametric techniques such as Kaplan-Meier and Nelson-Aalen are recommended for censored scenarios. The concept of multi-censoring, described by Fogliatto and Ribeiro (2011), addresses the coexistence of different types of censoring, common in warranty data, which may cause biased inferences (Schneider, 2001; Santos, 2008a). Despite challenges such as censoring, reactive claims (Santos, 2008a, b), and difficulties in statistical fitting (Oliveira and Turrioni, 2016; Falcetta, 2000), warranty data provide valuable insights into actual product usage, guiding improvements in reliability, design, and manufacturing processes (Pasetto, 2002; Dillenburg, 2005; Alam and Suzuki, 2009).

3. Computer resources for reliability assessment

Given the complexity of the mathematical models in Reliability Statistical Theory, their application can be challenging, especially for less experienced manufacturers (Dillenburg, 2005; Falcetta, 2000). Computational tools can simplify extensive calculations, making reliability assessments more accessible (Dillenburg, 2005; Falcetta, 2000). In this regard, the commercial software MINITAB® stands out due to its intuitive interface and robust features. As a free alternative, RStudio provides advanced and flexible tools for reliability analysis. In addition to its widespread use in statistics, R offers specialized packages and benefits from an active user community (Kronthaler and Zöllner, 2021).

4. Methodology

The research was conducted at a water leisure equipment manufacturer in Rio de Janeiro, with over 50 years in the market and no history of reliability assessments. The company operates in both Business-to-Business (B2B) and Business-to-Consumer (B2C) models. The study, using an applied and exploratory approach with quantitative and qualitative methods, employed Modeling and Simulation (Turrioni and Mello, 2012). Real failure data were analyzed with statistical models, and computer simulations optimized complex calculations. Further details of this work can be found in Julio (2024).

The first step was to identify the product under study. Failure data from the manufacturer's Enterprise Resource Planning (ERP) system pointed to the "Pumps with prefilter" as the primary focus due to the high number of failures reported during the warranty period. The creation of a Pareto Diagram confirmed that these pumps were responsible for the majority of the failures when compared to other products manufactured by the same company. Figure 1 is an exploded view of the pump, the subject of the study, with its components numbered.

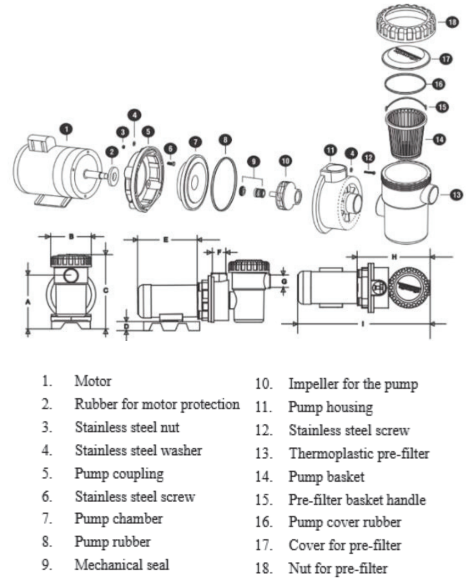

Figure 1 - Illustrative image with exploded view of the Pump with Prefilter and legend with numbering of pump components.

The "*Pumps with prefilter*", classified as hydraulic centrifugal turbomachines, depend on the continuous operation of their components due to their serial operation (Fogliatto and Ribeiro, 2011). The failure is characterized by the loss of the main function of transferring or lifting a fluid, converting mechanical energy into kinetic energy through the rotor (Santos et al. 2023). The warranty provided by the manufacturer, according to the Consumer Protection Code (Brazilian Law N°. 8,078/1990), is one year, starting from the date of the invoice issuance.

The second step involved collecting failure data from warranty claims for these pumps from the Customer Service Department, with assistance from the Quality Department. Due to disorganization, three attempts were necessary, with only the third being successful. The data consisted of Service Order (SO) records for warranty claims, focusing solely on "Pumps with prefilter," regardless of the model. These failure data (warranty claims records) were stored in the

ERP system of the studied company. A total of 538 failure records for centrifugal pumps under warranty (from January 2022 to February 2024) were gathered, excluding outliers such as returns and courtesy replacements. Given the low traceability, the MTTF index was chosen as the most appropriate metric for the manufacturer's warranty data, as MTBF was not feasible. Time to Failure (TTF) was calculated based on the operation start date, marked by the invoice issuance and the customer's warranty claim, excluding shelf time. B2B period calculations were not possible. This made right-censoring more prominent, while left-censoring was less significant. To assess these uncertainties, a comparison between parametric and non-parametric analyses was performed. Due to insufficient details in the warranty claim SOs, failure mode analysis was not possible. Thus, a single failure mode, loss of the main function, was adopted (Hoyland and Rausand, 1994, apud Falcetta, 2000)

4.1. *Parametric Probabilistic Modeling*

In the third step, the 538 failure records (records of the start-of-operation date and warranty activation) were entered into the commercial software MINITAB® for analysis. The TTF was calculated in "*Calc > Calculator*" as the difference, in days, between the invoice date (start of operation) and the warranty activation date (failure). Descriptive analyses were performed in "*Stat > Basic Statistics > Graphical Summary",* selecting the TTF (in days) with a 95% confidence level. Data with TTF above 365 days (warranty limit) were treated as outliers, resulting in the exclusion of 31 out of the 538 records, leaving 507 for analysis.

It was identified that the data did not follow a normal distribution, so estimation began using other parametric distributions with MLE, a common method in reliability analysis (Fogliatto and Ribeiro, 2011). This method maximizes the Likelihood Function to estimate parameters based on known distribution parameters (Fogliatto and Ribeiro, 2011; Dillenburg, 2005). The Weibull, Exponential, and Lognormal distributions were evaluated. The analysis was conducted in "*Stat > Quality Tools > Individual Distribution Identification*", evaluating the Weibull, Exponential, and Lognormal distributions. This analysis in the software worked as follows: after the data were estimated by MLE (the chosen estimation method), the fit to the data for these distributions is automatically tested and provided by the software through Probability Paper Charts and the Anderson-Darling (AD) goodness-of-fit test (Fogliatto and Ribeiro, 2011; Santos, 2008a). For the AD test in this study, the null hypothesis (H_0) was considered as the statement that "the data follows the analyzed distribution," while the alternative hypothesis (H_1) states that it does not. H_0 is accepted if the p-value exceeds 0.05 (95% confidence level); otherwise, the distribution is adjusted.

The data analysis yielded a mean of 124.937, a standard deviation of 108.063, and a median of 97. Maximum likelihood estimates for the Weibull distribution showed a shape parameter (γ) of 0.93793 and a scale (η) of 121.75094, while the exponential distribution had a scale of 124.93688. For the lognormal distribution, the location parameter was 4.13721, with an adjusted scale of 1.48584. Goodness-of-fit tests indicated AD values of 8.737 (P-value < 0.010) for Weibull, 10.866 (P-value < 0.003) for exponential, and 15.340 (P-value < 0.005) for lognormal, suggesting varying degrees of fit for each distribution.

The P-value results (< 0.05) reject the null hypothesis (H_0) that the data follow the analyzed distributions. However, as noted by Falcetta (2000), the best model should be chosen when the data don't fit well. The AD values showed that the Weibull distribution best represents the failure data, with the lowest AD value. Thus, Weibull, with a P-value closest to 0.05, was considered the best option. An alternative evaluation path, considering censoring in the MLE calculations, was tested. MLE equations vary by distribution and censoring, requiring adjustments and iterative methods (Dillenburg, 2005; Fogliatto and Ribeiro, 2011).

The procedure adopted in MINITAB, considering censoring in the MLE calculations, was as follows: "*Stat > Reliability/Survival > Distribution Analysis (Right Censoring) > Distribution Identification Chart*". In the "Options" button, the estimation method selected for this research was MLE. Unlike the previous path, this procedure does not present P-value values in the output. Analysis of the Probability Paper Charts generated as results confirmed that the failure data fit the Weibull distribution better, with an AD value of 8.710, slightly lower than the previous value (8.737, Table 2), due to the inclusion of censoring which alters the MLE. This variation reflects the sensitivity of the Weibull in adjusting the parameters, while the Exponential and Lognormal distributions are less sensitive. The AD and P-value values reinforce the choice of the Weibull to model the data and estimate the reliability indices.

The graph showed challenges in fitting field failure data to parametric models, emphasizing the value of non-parametric modeling as a complement. After identifying Weibull as the best fit, reliability indices (Probability Density Function (PDF), Cumulative distribution function (CDF), Reliability function (R(t)) and Failure rate (h(t)) were calculated via MLE using the path: “Stat > Reliability/Survival > Parametric Distribution Analysis (Right Censored) > Parametric Distribution Analysis.” The Weibull distribution parameters were estimated for complete or censored data (Fogliatto and Ribeiro, 2011), using a two-parameter model. Figures 2, 3, and 4 display the indices, calculated with the Weibull parameters and generated in MINITAB®.

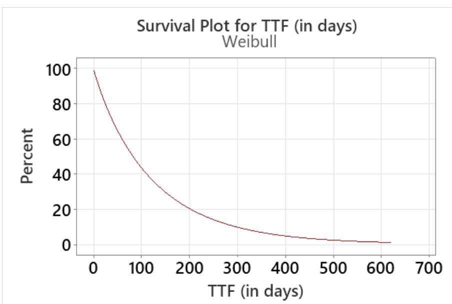

Figure 2. Weibull Reliability Function Graph

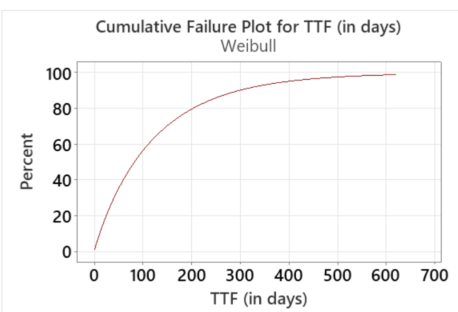

Figure 3. Cumulative Failure Function graph using the Weibull distribution

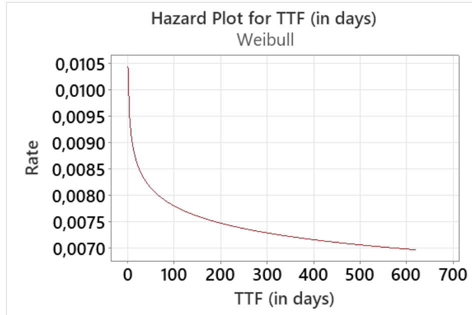

Figure. 4. Weibull Failure Rate Function graph

For the analysis, approximate results (based on software output) were highlighted for intervals of 90, 180, and 365 days, aligning with the product's warranty period. The MTTF was estimated at 125 days, as detailed in Table 1.

Table 1 - Summary of reliability index estimation results using the Weibull distribution

Days	(R(t))	(f(t))	(h(t))	MTTF
90	43,98~34,18%	0,34%	0,78%	
180	20,9% ~ 16,4%	0,20%	0,76%	~125 days
365	5%	0,05%	0,76%	

4.2. Non-parametric probabilistic modeling

Non-parametric modeling was performed in MINITAB® using the Kaplan-Meier method via “*Stat > Reliability/Survival > Distribution Analysis (Right Censored) > Non-Parametric Distribution Analysis*.” Figures 5, 6, and 7 display the indices graphs, calculated and generated by MINITAB®.

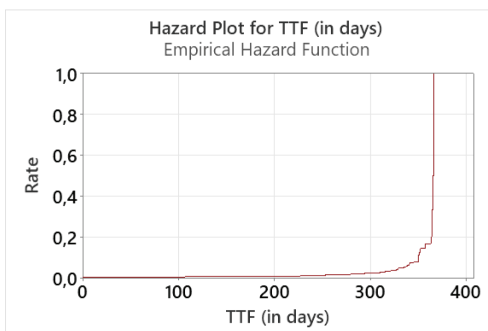

Figure 5. Kaplan-Meier Failure Rate Function Graph

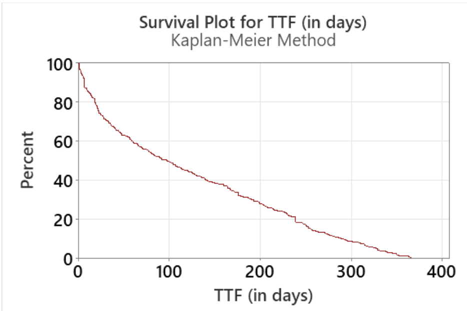

Figure 6. Kaplan-Meier Reliability Function Graph

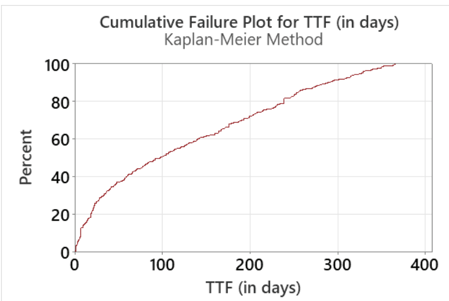

Figure 7. Kaplan-Meier Cumulative Failure Function graph

The results for the survival probability of the "*Pump with Prefilter*" using the Kaplan-Meier method are shown in Table 2.

Table 2 - Summary of reliability index estimation results using the Kaplan-Meier model

Days	(R(t))	MTTF
90	51,28%	~124 days
180	31,36%	
365	0,20%	

4.3. Reproducing the model in RStudio

Since MINITAB® is not free and the research uses low-cost warranty activation data, an alternative approach using RStudio was proposed. The analysis followed the same procedures as MINITAB®, including descriptive statistics, fitting of parametric distributions, and calculation of parametric and non-parametric reliability indices (Kaplan-Meier). The step-by-step process with scripts and packages used is outlined in Julio (2024) study, and the results were identical to those obtained using MINITAB®.

4.4. Conducting the FTA and FMEA

Reliability, as a multidisciplinary field, integrates both qualitative and quantitative methods, enhancing traditional statistical modeling. This approach allows for a more comprehensive analysis, addressing failures of special, common causes, or both, which is essential for accurate reliability estimates (Santos, 2008b; Falcetta, 2000). After statistical modeling, an FTA was applied to identify failure modes and causes based on warranty issues reported by the customer. For this step, a multidisciplinary team was formed, including manufacturer experts.

The failure data from the warranty activation records identified the following failure symptoms reported by the customer: (a) "*Leakage*"; (b) "*Vibration*," "*Noise*," "*Excessive noise*"; (c) "*Pump not working*", "*Pump not turning on", "Motor not turning on*".

Based on the work of Vesely et al. (2002), an FTA was developed using a basic and generalized approach, employing the logical operator "OR." Figure 11 illustrates one of the results generated by the FTA.

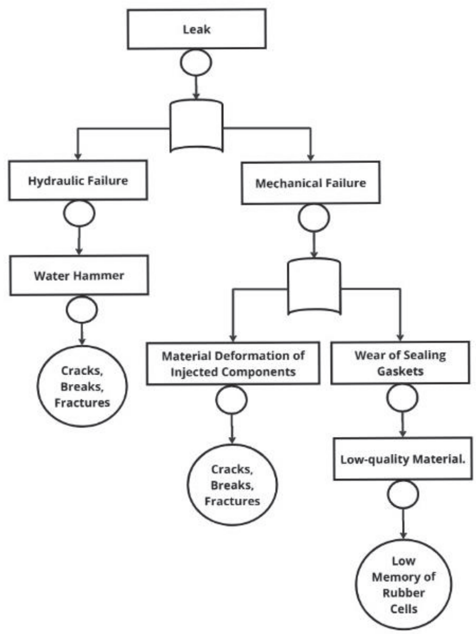

Figure 11. Example of one of the results generated in the FTA conduction.

Following the FTA, a practical FMEA analysis was conducted in preparation, execution, and completion stages (Bertsche, 2008). Using customer feedback and the team's technical expertise, potential failure modes were analyzed. The analysis identified multiple failure modes for several components (Dodson and Nolan, 1997, apud Bonetti, 2009). Preventive measures were focused on addressing the causes of these failures. The RPN prioritized critical components to enhance product reliability. Table 5 shows the three most critical components of the Pre-filter Pump, classified into four risk categories: A (High) for RPN ≥ 500, B (Medium) for RPN between 100 and 500, C (Low) for RPN between 50 and 100, and D (Very low) for RPN < 50. Table 3 displays the three most critical components of the Pre-filter Pump.

Table 3 - Classification of the components with the greatest impact on the product Pump with prefilter

	Component	Failure mode*	RPN	Classification
1°	**11**	1	196	B
2°	**1**	2	160	B
3°	**10**	3	150	B

Fault Mode Legend*: *1 - Cracks, crevices / 2 - Broken or torn power cable / 3 - Unbalanced rotor*

5. Main results and discussions

The study analyzed time-to-failure (TTF) data from 507 warranty claims to calculate reliability indicators, using both parametric and non-parametric methods to address multi-censoring and uncertainties (Falcetta, 2000; Oliveira and Turrioni, 2016). The Anderson-Darling test compared Weibull, Exponential, and Lognormal distributions, with Weibull chosen due to its lowest AD value. The analysis revealed that less than 40% of pumps were operating after 180 days, highlighting low reliability and performance inconsistent with the manufacturer's reputation. The Failure Rate analysis showed two behaviors: the Weibull model suggested a slight decrease in Failure Rate (early lifecycle phase), while the Kaplan-Meier model indicated an increase in the rate (aging phase). This divergence reflects the empirical nature of Kaplan-Meier, in contrast to the parametric Weibull model (Dillenburg, 2005). The results highlight the challenges in fitting statistical distributions to real data, emphasizing the need for better data collection and treatment for more robust analyses.

Recommendations include: (a) Improving traceability and organization of warranty data: Implementing systems that allow for more detailed tracking of individual failures. (b) Including post-warranty information and individual failure modes: Expanding data collection beyond the warranty period to capture more comprehensive information about product reliability. (c) Adopting fuzzy logic to handle uncertainties, using methods that incorporate variability and uncertainties inherent in the data. (d) Applying Bayesian and non-parametric methods, such as Kaplan-Meier, which are better suited for handling censored and variable data. € Investing in advanced tools for statistical analyses: Software like MINITAB® and RStudio proved effective for conducting complex statistical modeling in an accessible and replicable manner.

In the study of FTA and FMEA, critical components, such as the pump body (leak prevention) and the rotor, were prioritized for attention. The combined use of FTA and FMEA, complementing the models, optimized intervention strategies and highlighted opportunities to reduce costs and increase customer satisfaction.

6. Conclusions

This study used field failure data derived from warranty claims to estimate the reliability of hydraulic centrifugal pumps, which is rarely seen in this type of analysis due to the uncertainties associated with such data. The gap in companies that launch products without reliability parameters, due to a lack of resources, motivated the research. The data, collected by Customer Service, pointed to opportunities for improvement. "Pumps with prefilter" from a manufacturer in Rio de Janeiro with 50 years in the market were evaluated using both qualitative and quantitative modeling. The Weibull and Kaplan-Meier distributions were used: the Weibull distribution presented limitations but was deemed adequate by the Anderson-Darling test; the Kaplan-Meier distribution, more robust for multicensored data, showed similar results, proving effective in handling data with many uncertainties and censoring, as in the case of failure data recorded through warranty claims.

With the help of MINITAB® and RStudio, a survival probability of 40% at 180 days was estimated, revealing inconsistencies in the records due to censoring and data limitations.

The application of FMEA and FTA identified critical components—Pump Body, Motor, and Impeller—guiding improvements in design and manufacturing. Actions such as traceability, record standardization, and database organization are recommended to the manufacturer. Future research could explore fuzzy methods, Bayesian analysis, and post-warranty data integration to enhance reliability assessments.

The results of this research scientifically contribute to the understanding that, although underestimated, reliability based on real field data offers valuable insights into the practical operation of products. Studies applying or developing methods—or combinations of methods—that help reduce or diminish the uncertainties associated with failure data from warranty claims could contribute significantly to the adoption of a reliability-focused culture. Investments in improving this approach could make it more efficient and accessible, benefiting both industry and society.

Finally, the research also demonstrates that the use of tools like MINITAB® and RStudio facilitated statistical modeling, making advanced analytics accessible to companies of all sizes and promoting continuous improvements in products and processes.

Acknowledgement
We would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) and the National Council for Scientific and Technological Development (CNPq) for funding this research.

References

Associação Brasileira de Normas Técnicas (ABNT). 1994. *NBR 5462: Reliability and Maintainability.* Rio de Janeiro, Brazil.

Bertsche, B. 2008. *Reliability in Automotive and Mechanical Engineering.* Springer Berlin Heidelberg.

Bonetti, L. V. 2009. *Warranty Data and Expert Qualitative Analysis as a Basis for Reliability Study in the Agricultural Machinery Sector.* Dissertation, Federal University of Rio Grande do Sul.

Dillenburg, M. R. 2005. *Product Reliability Estimates from Monthly Sales and Failure Counts Over the Warranty Period.* Porto Alegre: Federal University of Rio Grande do Sul.

Falcetta, E. F. 2000. *Product Reliability Analysis Based on Warranty Usage Data.* Master's Dissertation in Production Engineering, Federal University of Rio Grande do Sul, Porto Alegre.

Fogliatto, F. S., and J. L. D. Ribeiro. 2011. *Reliability and Industrial Maintenance.*

Guimarães, U. V. 2002. *Modeling for the Reliability Analysis of Products under Warranty.* Master's Dissertation, Federal University of Rio Grande do Sul.

Julio, C. V. J. C. de A. 2024. *Evaluation of the Reliability of Centrifugal Pumps Using Warranty Claims Data as Field Failures.* Master's Thesis, Federal University of Itajubá, Postgraduate Program in Production Engineering, Institute of Production Engineering and Management. Available at: https://repositorio.unifei.edu.br/jspui/handle/123456789/4121.

Kronthaler, F., and S. Zöllner. 2022. *Data Analysis with RStudio: An Easygoing Introduction.*

Oliveira, G. S., and J. B. Turrioni. 2016. "Reliability Modeling Using Warranty Data: An Alternative to Address Limitations in Working with Field Data." *Produto & Produção* 17 (2).

Pasetto, S. de C. 2002. "Failure Prediction During the Warranty Period from Customer Perception: A Case Study at a High Technology Company." Master's Dissertation, Federal University of Rio Grande do Sul.

Santos, G. T. dos. 2008. "Reliability Model Combining Warranty and Post-Warranty Data to Three Failure Behaviors." Doctoral Thesis, Federal University of Rio Grande do Sul, August.

Santos, G. T. dos, F. Sanson Fogliatto, L. Duarte, and M. Rausand. 2008. "Application of a Competing Risks Model in the Reliability Analysis of Warranty Data." *Produto & Produção*.

Santos, J. C. dos. 2011. "Reliability Analysis of a Centrifugal Pump: Application in Water Injection for Oil Recovery." Master's Dissertation, Federal University of Rio Grande do Norte, Natal.

Santos, A. F. C. dos, M. A. Bovério, and D. P. da Silva. 2023. "Technical Analysis of Corrective Intervention in Centrifugal Pump." SITEFA VI.

Schneider, R. G. 2001. "Methodology for Feedback of Product Development Cycle with Reliability Data from Field Use." Master's Dissertation, Federal University of Rio Grande do Sul, Porto Alegre.

Souza, R. A. de. 1999. "Reliability and Field Failures: A Methodology for Design Support." Master's Dissertation, Federal University of Santa Catarina, Florianópolis.

Turrioni, J. B., and C. Henrique Pereira Mello. 2012. *Research Methodology in Production Engineering.*

Vesely, W., M. Stamatelatos, J. Dugan, J. Fragola, and J. Minarick. 2002. *Fault Tree Handbook with Aerospace Applications.* Washington, DC: U.S. Government Printing Office.