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Field-Based Reliability Assessment of Agricultural Machinery Using the Weibull Distribution: A Case Study in Northern State, Sudan

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ABSTRACT

Agricultural machinery reliability is critical for ensuring timely field operations, minimizing downtime, and improving machinery utilization. This study aimed to develop and evaluate an operational efficiency-based model to support maintenance planning and improve operational efficiency under Sudanese farming conditions. Five-year repair and maintenance records were obtained from the Northern State Agricultural Services Corporation, Sudan, for four machines: Belarus tractor, John Deere tractor, Camco tractor, and combine harvester. The collected data included operating hours, failure occurrences, and failures of major machine subsystems. A reliability model was developed using Microsoft Excel and Visual Basic for Applications (VBA), and the failure data were analyzed using the two-parameter Weibull distribution. Weibull parameters (shape β and scale α were estimated using probability plotting and linear regression, and reliability-life measures were determined for both machine and subsystem levels. At the machine level, the estimated shape parameter (β) ranged from 0.61 to 1.02, indicating different failure-rate patterns among the investigated machines. At the subsystem level, β values ranged from 1.18 to 2.25, indicating predominantly increasing failure rates consistent with wear, ageing, and component deterioration. The estimated reliability-life measures for the major subsystems ranged from 209 h for the combine harvester fuel system to 689 h for the Belarus brake system. The results demonstrate that Weibull-based reliability analysis can provide useful quantitative information for identifying failure patterns, prioritizing maintenance activities, planning spare parts, and supporting machinery replacement decisions. The developed model provides a practical approach for applying field failure data to reliability assessment and maintenance planning of agricultural machinery under Sudanese operating conditions.

KEYWORDS:

Agricultural machinery reliability, Weibull distribution, failure analysis, maintenance planning, operational efficiency, machine subsystems, Sudan

1. Introduction

Effective machinery management is essential for improving farm productivity, reducing operating costs, and maintaining reliable equipment performance. Proper selection, operation, maintenance, and timely replacement of agricultural machinery can extend machine life, reduce repair costs, and improve farm profitability. On most farms, the cost of owning and operating machinery exceeds all other costs except land use; in some cases, it is the most expensive part of the business. Efficient selection, operation, and maintenance of this machinery are critical to the viability of the farm. (Van Loon & Flores Rojas, 2022).

Timely agricultural operations are essential for achieving high crop yields. Machinery breakdowns during critical field operations can cause delays, reduce productivity, and increase downtime. Therefore, reliability assessment and adequate maintenance and spare-parts planning are essential for minimizing failures and ensuring timely operations (Paman et al., 2024).

Reliability engineering provides quantitative methods for evaluating the probability that machinery will perform its intended function under specified operating conditions for a given period. Reliability indicators such as failure rate, mean time between failures (MTBF), availability, and downtime are widely used to support maintenance planning, optimize replacement decisions, and improve machinery performance (ISO, 2024; ASABE, 2023).

Advances in computer-based decision support systems have further enhanced machinery management by integrating reliability analysis, maintenance scheduling, and economic evaluation. These tools assist farmers and managers in selecting appropriate machinery, planning maintenance activities, and minimizing operational risks. However, the adoption of such systems remains limited in many developing countries, including Sudan, where machinery management decisions are still largely based on experience rather than analytical methods. This highlights the need for locally applicable reliability assessment models that support efficient maintenance planning and improve machinery utilization under Sudanese farming conditions (McCampbell, 2022; Ahmed, 2022).

The objective of this study is to develop and evaluate a reliability-based algorithm for agricultural machinery to support maintenance planning, reduce equipment downtime, and improve operational efficiency under Sudanese farming conditions.

2. MATERIAL AND METHODS

2.1 Data Collection and Analysis:

The required input data for the reliability model were collected from relevant records and reports found in the Northern for Agricultural Services (a corporation shared between the Northern State Government and the Dongola for Agricultural Inputs and Services Corporation). It was collected for several types of tractors and machines. The data include the number of tractor types, the type of machine, working hours per season, the number of breakdowns during the working season for tractors and machines, and the number of breakdowns of specific parts of tractors and machines during the working season. For data analysis, simple descriptive tools (regression, t-test, and standard deviation) were used in Microsoft Excel.

2.2 Reliability Model Development:

A machine reliability model was developed in Microsoft Excel using Visual Basic for Applications (VBA). The model technical specification is shown in Table 1. It provides a graphical user interface for entering failure data, selecting the reliability analysis, performing regression analysis, and presenting the results in tabular and graphical forms. The model workflow is shown in Figure 1.

Table (1): Reliability Model Technical Specification

Item	Description
Program language	Excel and Visual Basic
Program type	Button menu-driven and Spreadsheet user
Program flexibility	Inherited from Excel 2010 and later versions, as well as from Visual Basic
Program adaptability	Work under Window
Program interface	One main menu and Spreadsheet
Units used	SI system
Space required on hard disk	424 kbit

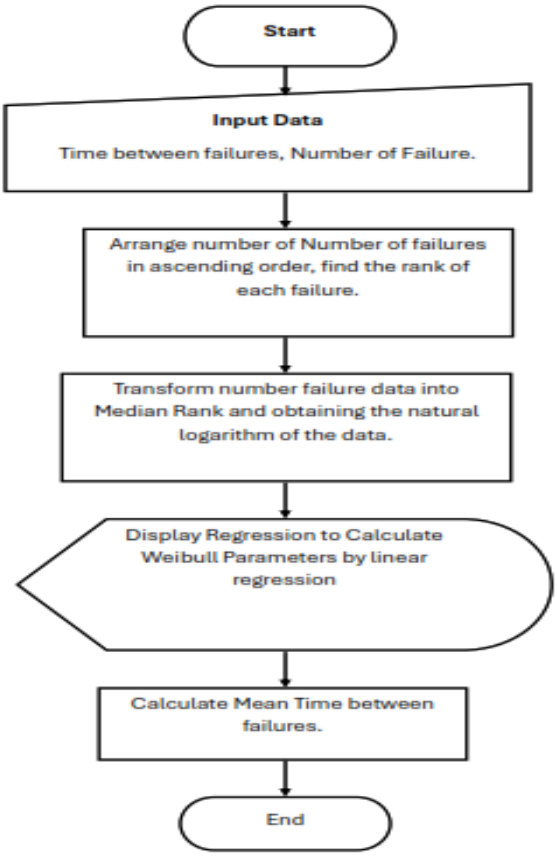


Figure 1: Reliability flowchart.

2.3 Reliability Analysis Using the Weibull Model

Machine reliability was evaluated using the Weibull probability distribution, which is widely applied in reliability analysis because of its flexibility in representing different patterns (decreasing, constant, and increasing failure rates). The Weibull model is particularly suitable for mechanical and agricultural machinery because its shape parameter can describe decreasing, approximately constant, and increasing failure rates.

In general, the reliability function of a component or machine can be expressed in terms of the hazard or failure rate function as stated by (Shao *et al.*,2021) using equation 1.

$$R(t) = \exp\left[-\int_0^t \lambda(u)\,du\right] \quad \text{.....(1)}$$

Where R(t) :is the probability that the machine operates without failure up to time (t)
and λ(t):is the instantaneous failure rate.

For the three-parameter Weibull distribution, the probability density function (PDF) is expressed as reported by (Kumar *et al.*, 2022) utilizing formula 2.

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t-\gamma}{\alpha}\right)^{\beta-1}\exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right], \qquad t \geq \gamma \quad \text{.....(2)}$$

where α: is the scale parameter, β is the shape parameter, and γ:is the location or lower-bound parameter.
The corresponding cumulative distribution function (CDF) is calculated using formula 3.

$$F(t) = 1 - \exp\left[-\left(\frac{t-\gamma}{\alpha}\right)^{\beta}\right] \quad \text{.....(3)}$$

The three-parameter Weibull model provides flexibility in describing different failure-life distributions. However, for the agricultural machinery considered in this study, failures may occur from the beginning of machine operation. Therefore, the lower-bound parameter was assumed to be zero (γ=0). The model consequently reduces to the two-parameter Weibull distribution.

The probability density function for the two-parameter Weibull distribution is computed using equation 4.

$$f(t) = \frac{\beta}{\alpha}\left(\frac{t}{\alpha}\right)^{\beta-1}\exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right] \quad \text{.....} \quad (4)$$

The corresponding cumulative distribution and reliability functions are given by utilizing formula 5 and 6

and $$F(t) = 1 - \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$$ ..... .(5)

$$R(t) = \exp\left[-\left(\frac{t}{\alpha}\right)^{\beta}\right]$$ .....(6)

The shape parameter β\beta indicates the failure-rate pattern of the machinery. When β<1, the failure rate decreases with operating time, which may indicate early-life or initial failures. When β≈1\beta\approx1, the failure rate is approximately constant, indicating predominantly random failures. When β>1, the failure rate increases with operating time, which may be associated with ageing, wear, or deterioration of machine components.

2.4 Estimation of Weibull Parameters:

The Weibull parameters were estimated using the Weibull probability plotting method and linear regression. The cumulative distribution function can be transformed into a linear relationship by taking the natural logarithm twice using formula 7.:

$$\ln[-\ln(1 - F(t))] = \beta \ln(t) - \beta \ln(\alpha)$$ .....(7)

Thus, a plot of $ln[-\ln(1 - F(t)]$ against $ln(t)$

produces an approximately linear relationship. The slope of the fitted regression line provides an estimate of the shape parameter β\beta, while the intercept is used to estimate the scale parameter α. The adequacy of the Weibull model was assessed from the linearity of the probability plot and the corresponding regression results.

2.5 Mean Life and MTBF

Following estimation of the Weibull parameters, the characteristic life and mean operating life of the machinery were determined. For the two-parameter Weibull distribution, the mean life is given by utilizing equation 8.:

$$MTBF = \alpha\Gamma\left(1 + \frac{1}{\beta}\right) \times 100$$ .....(8)

where T denotes the gamma function.

For repairable agricultural machinery, the mean time between failures (MTBF) was determined from the observed failure and operating-time records. Where MTBF is derived directly from the fitted

two-parameter Weibull distribution, the corresponding Weibull mean-life expression in Equation (8) was used. These reliability measures provide useful information for maintenance planning, spare-parts management, machine utilization, and replacement decisions.

3. RESULTS AND DISCUSSION

The developed reliability model was applied to five years of repair and maintenance records for four agricultural machines: Belarus, John Deere, Camco, and a combine harvester. The failure data were analyzed using the two-parameter Weibull distribution to estimate the shape parameter **β**, scale parameter **α**, and reliability-life measures at both machine and subsystem levels.

At the machine level, the estimated β values were 0.61, 1.02, 0.83, and 0.98 for the Belarus, John Deere, Camco, and combine harvester, respectively, with corresponding α values of 3.24, 2.59, 2.46, and 2.43. The results indicate different failure-rate patterns among the machines. The Belarus and Camco tractors, with β values, exhibited decreasing failure rates, suggesting a greater contribution of early-life failures. The John Deere and combine harvester, with β values close to unity, showed approximately constant failure rates. These differences indicate that maintenance strategies should be adapted to the observed failure behavior of each machine.

The estimated Weibull parameters and MTBF values for the major machine subsystems are presented in Table 1. The MTBF values ranged from 209 h for the combine harvester fuel system to 689 h for the Belarus brake system, indicating considerable variation in subsystem reliability. The Belarus tractor recorded the highest MTBF for the steering system (637 h) and brake system (689 h), while the John Deere showed the highest MTBF for the electrical system (578 h). The lowest MTBF values were observed mainly in the combine harvester, particularly for the fuel system (209 h).

At the subsystem level, all estimated **β** values ranged from 1.18 to 2.25 and were greater than one, indicating increasing failure rates associated with wear, aging, and component deterioration. The higher **β** values observed for the steering systems of the Camco tractor and combine harvester indicate a more pronounced wear-out failure pattern. These results demonstrate that subsystem-level analysis provides additional information that may not be evident from overall machine reliability.

Table1: Weibull reliability parameters and estimated reliability-life measures for the investigated agricultural machinery

Subsystem	Machine	β	α	Standard Error of β	MTBF (h)
Steering	Belarus	1.21	6.789	0.135	**637**
	John Deere	1.31	4.719	0.254	**435**
	Camco	2.15	5.162	0.345	**457**
	Combine H.	2.25	4.162	0.445	**369**
Fuel	Belarus	1.30	5.987	0.564	**553**
	John Deere	1.21	3.577	0.765	**336**
	Camco	1.78	4.215	0.589	**375**
	Combine H.	1.18	2.215	0.289	**209**
Electrical	Belarus	1.29	4.560	0.458	**422**
	John Deere	1.42	6.354	0.215	**578**
	Camco	1.41	5.687	0.215	**518**
	Combine H.	1.51	3.687	0.315	**333**
Brake	Belarus	1.40	7.564	0.346	**689**
	John Deere	1.49	4.598	0.426	**415**
	Camco	1.49	4.598	0.426	**415**
	Combine H.	1.46	3.598	0.526	**326**

Overall, the Weibull analysis showed substantial differences in failure behavior and reliability among the investigated machines and subsystems. The estimated MTBF and **β** values provide a quantitative basis for prioritizing maintenance activities, scheduling inspections, planning spare-parts requirements, and determining appropriate preventive maintenance and replacement intervals. Subsystems with lower MTBF and increasing failure rates require closer monitoring and greater maintenance attention to reduce unexpected failures and machine downtime.

4. RECOMMENDATIONS:

1. The developed reliability model successfully estimated the reliability and MTBF of agricultural machinery using actual field failure data.
2. The model provides a practical approach for maintenance planning and machinery management under farm operating conditions.
3. The method allows the use of actual field data, without any modifications, for estimation of parameter values for reliability functions.

4. The study confirms that the Weibull distribution is suitable for reliability analysis of agricultural machinery and can effectively support preventive maintenance and replacement planning.
5. Future improvements should focus on expanding the database to include additional machinery types and operating conditions, integrating predictive maintenance techniques, and developing a more user-friendly software interface to improve practical application.

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