Karol DURCZAK[1]**, Adam EKIELSKI**[2]**, Tomasz ŻELAZIŃSKI**[2]
[1] Poznań University of Life Sciences, Institute of Biosystems Engineering, Poland
[2] Warsaw University of Life Sciences, Department of Production Organisation and Engineering, Poland
e-mail: karol.durczak@up.poznan.pl

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CALCULATION OF THE RELIABILITY FUNCTION FROM ACTUAL FAILURES RESULTING FROM THE OPERATION OF ONE MAKE OF FARM TRACTORS

Summary

Like all farming machinery, farm tractors should be characterised by high reliability, which guarantees trouble-free operation, especially during intense agrotechnical works. The knowledge of the course of reliability functions, especially the failure intensity function, is of high practical significance. It lets manufacturers lead the right overhaul policy and it lets users make the right purchase choice. Therefore, it is recommended to conduct research comparing the reliability of farming machinery. It is necessary to apply universal methodology and use a vast database providing information about failures of individual working units in various makes, models, types and variants of farming machinery. The method was validated by analysing failures of 29 components of Zetor farm tractors with the engine power ranging from 45 to 90 kW.

Key words*: reliability, farm tractor, failure intensity, exponential distribution, technical service, MTTF, Bayesian networks*

WYZNACZANIE FUNKCJI NIEZAWODNOŚCI NA PODSTAWIE RZECZYWISTYCH USZKODZEŃ EKSPLOATACYJNYCH CIĄGNIKÓW ROLNICZYCH JEDNEJ MARKI

Streszczenie

Ciągniki rolnicze, tak jak wszystkie maszyny rolnicze, powinny charakteryzować się dużą niezawodnością, która gwarantuje im bezproblemową pracę, zwłaszcza w czasie wzmożonych prac agrotechnicznych. Znajomość przebiegów funkcji niezawodności, a przede wszystkim funkcji intensywności uszkodzeń, ma duże znaczenie praktyczne. Pozwala producentom prowadzić prawidłową politykę przeglądów technicznych, a użytkownikom ułatwić dokonanie prawidłowych wyborów w procesie zakupu. Wskazane są zatem badania pozwalające na porównywanie maszyn rolniczych pod względem ich niezawodności. Do tego celu niezbędna jest uniwersalna metodyka oraz obszerna baza danych o uszkodzeń poszczególnych zespołów roboczych różnych marek, modeli, odmian i wariantów maszyn rolniczych. Walidację metody przeprowadzono na podstawie uszkodzeń 29 podzespołów ciągników rolniczych marki Zetor o mocy silników w zakresie od 45 do 90 kW.

Słowa kluczowe*: niezawodność, ciągnik rolniczy, intensywność uszkodzeń, rozkład wykładniczy, serwis techniczny, MTTF, sieci bayesowskie*

1. Introduction

Durability and reliability are the most important functional characteristics of technical devices, which determine their global quality. According to classical theory, reliability is defined as the capacity of a technical device to operate normally under specific working conditions during the time set. Reliability is measured with the probability of absence of failure in an assumed period of time:

$$R(t) = P\{T \geq t\}, \quad (1)$$

where:

T – random variable denoting the time of normal operation of a technical device,

t – time interval set.

Authors of studies in quality management and qualitology see high significance of reliability of technical devices. Hamrol [6] classified the characteristics included in the assessment of the quality of products and processes. Apart from physical, sensory, behavioural, temporal and ergonomic features, he also listed reliability. Garlin [5] proposed the following eight aspects of product quality: reliability, performance, features, conformance, durability, serviceability, aesthetics and perceived quality. According to the Independent Farmers' Opinion Poll (IFOP) – an online system developed at the Institute of Biosystems Engineering, Poznań University of Life Sciences, Poland, which is available at www.nbor.pl, there are four chief characteristics of farming machinery and vehicles, i.e. performance, reliability, ergonomics and occupational safety and health (OSH), and attractive appearance.

The problem of reliability is very complex. It comprises a large class of issues related to the physical structure of elements, their properties, surrounding conditions, types and causes of failures, assessment of reliability of appliances with a specific structure, methods of improving reliability, methods of searching for optimal systems, etc. The theoretical essentials for assessing farming machinery reliability were developed by Czeczott et al. [1], Dwiliński [4], Najafi [12] and Otmianowski [13]. The study by Michalski et al. [11] showed how different types of simulated failures of wheeled tractors resulted in varying fuel consumption. Kamiński and Kulikowski [9] prepared a mathematical model for forecasting the functional and utility properties of the pneumatic system in a tractor by means of digital simulation. Juściński and Piekarski [8] presented actions taken to maintain farm vehicles in good working order. The study presented external and internal factors affecting tractor operation. Although reliability is quantifiable as a function (1), the authors of studies discussing the economic aspect of operation of farming machinery [15] present it in a linguistic form and introduce reliability levels: high, medium and low.

The seasonal character of operation of farming machinery, diversity of its types and kinds as well as its mobile character cause the occurrence of breakdowns. These failures are an important determinant of the quality of farming machinery [14]. Durczak [3] agrees with this approach and he also classifies this characteristic as a first-order factor (minimum requirement) among the assessment criteria of farming machinery quality.

According to the rule of product, the more elements there are in a serially connected system, the less reliable it is. If we take farm tractors consisting of about 4,000 parts, manufacturers face a serious challenge to ensure adequate reliability according to farmers' expectations. The addition of new systems is in disagreement with the KISS principle (*Keep It Simple, Stupid*). If a system does not include a particular element, it will not break down. This principle does not seem to be well-known and therefore it is regularly ignored. The essence of this idea is to design simple devices so that every average-skilled mechanic can repair them in a field using simple tools.

High reliability of farming machinery is related to the need to do field and livestock works on time. Failure to do these works on time results in a loss of yield and nutritional value of crops. Farm work technology causes the need to make combinations of a few types of machines. Usually they are serially arranged and the failure of one machine breaks the technological chain. Therefore, it is so important to use machinery with highly reliable parts, components and systems. It can be achieved by regular servicing [7].

The problem can also be solved by applying parallel reliability structures. It usually involves using a larger number of identical machines, which can be hired. As far as animal production is concerned, it is necessary to increase the number of facilities and create serial systems, e.g. by increasing alternative methods of supplying power to milking equipment.

Reliability of a machine is a probabilistic value and it is a useful indicator of its quality, although manufacturers do not provide any specific numeric values. Compulsory overhauls of all groups of machinery, as is the case with field sprayers, might help to acquire data for calculation of reliability indicators. The knowledge of the farming machinery reliability function is of high practical significance both for manufacturers and potential users. Therefore, it is so important to develop universal, clear and easy methodology. The numerical form of reliability will enable rankings and analyses.

2. Aim of study

The aim of the study was to use classic reliability theory to develop universal methodology of calculation of the farm tractor reliability function, verify it logically and empirically and to indicate the usefulness of the results for farming practice.

3. Research object and methodology

The reliability function was calculated upon analysis of actual failures resulting from the operation of 70 Zetor tractors, Proxima, Proxima Power, Proxima Plus and Forterra models, with the engine power ranging from 45 to 90 kW. The data about breakdowns of 29 assembly groups (Table 1) were obtained from an authorised service station, which makes warranty and post-warranty repairs of these tractors in Poland (Table 2).

Table 1. Obligatory assembly groups at authorised Zetor service stations

Tab. 1. Grupy montażowe stosowane obligatoryjnie w autoryzowanych serwisach ciągników marki Zetor

Group number	Name of assembly group
1	Hydraulic cylinder
2	Supercharger, intercooler
3	Head
4	Electrical installation
5	Cabin
6	Engine block
7	Air-conditioning
8	Wheels
9	Heating
10	Three-point linkage
11	Front-wheel drive
12	Reverse system
13	Distributor
14	Starter
15	Clutch box
16	Compressor
17	Sprinkler
18	Two-stage clutch
19	Front axle clutch
20	Electrohydraulic transmission control
21	Clutch control
22	Glow plugs
23	Dashboard
24	Cooling system
25	Brake system
26	Hydraulics
27	Steering system
28	Pneumatic system
29	CBM hooks

Table 2. A database of Zetor tractor failures [10]

Tab. 2. Baza danych o uszkodzeniach ciągników marki Zetor [10]

Tractor number	Model/ VIN	Failure symptoms/ Assembly group	Working time before failure t_i (mth)
1	2	3	4
1	Proxima 85/…3887	Switch failure/4	2
2	Proxima 65/…2311	Shock absorber failure /5	3
3	Forterra 115/…7202	Display errors /23	3
…	…	…	…
68	Forterra 125/…2622	Display errors/23	560
69	Forterra 115/…6556	Air leak/28	580
70	Forterra 125/…2795	Oil leak/3	591
Mean time to failure (MTTF)			241

According to the proposed methodology, the farm tractor is treated as an irreparable product. This simplified approach (although farm tractors are fully renewable and reparable products) is often used for assessment of other products [6]. The tractors were observed until their first failure so as to shorten the testing time.

The following exponential dependence was proposed to calculate the farm tractor reliability function $R_c(t)$:

$$R_c(t) = e^{-\lambda t} \tag{2}$$

where λ is the failure intensity coefficient.

The function has the following characteristics:

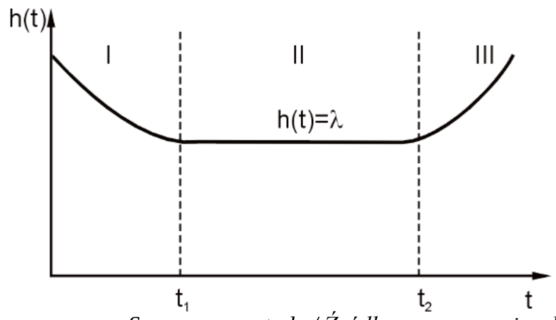
- $t = 0 \Rightarrow R_c(t) = 1$
- $t \rightarrow \infty \Rightarrow R_c(t) = 0$
- $\lambda \uparrow \Rightarrow R_c(t) \downarrow$.

The λ coefficient value in unrenewable products is:

$$\lambda = MTTF^{-1} \ (\text{mth}^{-1}), \tag{3}$$

where MTTF is the mean time to farm tractor failure measured in months.

The exponential distribution is the most frequently used in the reliability theory. It is easy to use because it has only one parameter and it is only necessary to estimate the λ coefficient value. It also makes an a priori assumption of the worst possible scenario – failures of parts, components and systems in a technical device. This distribution can be used to describe machines composed of a large number of parts and working under difficult conditions, where catastrophic failures usually occur. These failures are typical of farming machinery. If the random variable is related with the reliability of mechanical devices (e.g. the operation time of irrigation devices or a milking machine), it is a variable with exponential distribution, where the expected value is the expected time of failure-free operation of the device [2]. This distribution adequately describes the second stage of the machine life, i.e. stable operation. The period begins when typical problems occurring at an early stage of machine operation (the first stage) disappear and it ends before the period of intense wear (the third stage) (Fig. 1).



Source: own study / Źródło: opracowanie własne

Fig. 1. Stages of operation of technical devices and a failure intensity curve

Rys. 1. Etapy eksploatacji obiektów technicznych na krzywej intensywności uszkodzeń

Although the machinery operation process is continuous in time *t*, this study identifies arbitrarily logical intervals of machinery operation time, which are referred to as *i*. The empirical values of the failure intensity function $h(i)$ (aka the risk function) for individual intervals *i* can be calculated according to the following formula:

$$h(i) = \frac{\text{number of machines with failures at interval } i}{\text{number of remaining machines after interval } (i-1) \cdot \text{interval time } ti} \tag{4}$$

4. Results

The values of tractor failure times from Table 2 were allocated to six equal intervals of 100 mth each (Table 3).

Table 3. The number of failures at consecutive time intervals

Tab. 3. Liczba awarii w kolejnych okresach czasu

Number of interval *i*	Duration of interval *i* Δt (mth)	Total machine operation time *t* (mth)	Number of failures during interval *i* (-)
I	100	0-100	15
II	100	101-200	15
III	100	201-300	11
IV	100	301-400	17
V	100	401-500	6
VI	100	501-600	6
		Total	70

Source: own study / Źródło: opracowanie własne

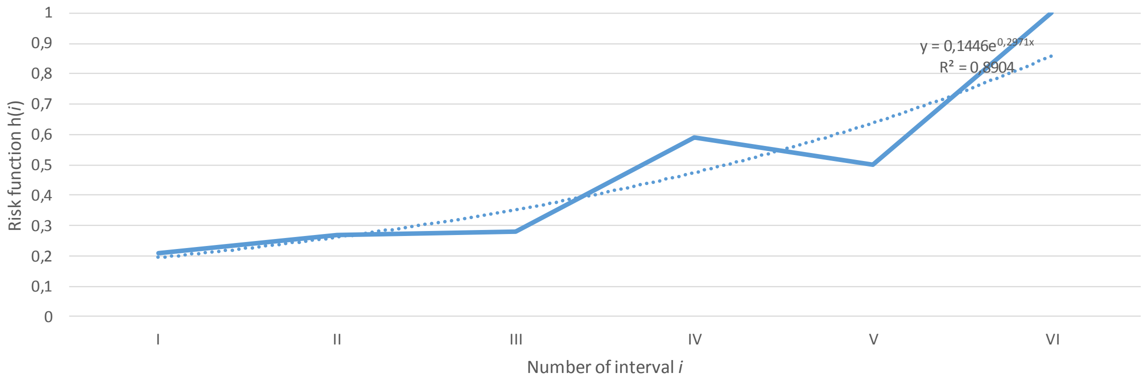
According to the research methodology and the equation (4), empirical values of the risk function were calculated (Table 4) and they were included in Diagram 2.

Table 4. Empirical data and calculation results

Tab. 4. Dane z eksperymentu i wyniki obliczeń

Total machine operation time	Duration of interval *i*	Number of failures during interval *i*	Number of failure-free machines until $(t+\Delta t)$	Risk of failure x100
i	Δt (mth)	(-)	(-)	$h(i)$
-	0	-	70	-
I	100	15	55	0.21
II	100	15	40	0.27
III	100	11	29	0.28
IV	100	17	12	0.59
V	100	6	6	0.50
VI	100	6	0	1.00

Source: own study / Źródło: opracowanie własne

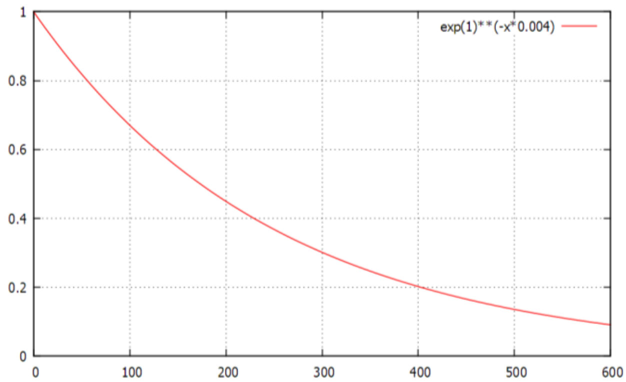


Source: own study / Źródło: opracowanie własne

Fig. 2. The course of the Zetor tractor failure intensity function and the trend line
Rys. 2. Przebieg funkcji intensywności uszkodzeń ciągników marki Zetor i linia trendu

We can approximately conclude that the group of tractors under study was characterised by constant intensity of failures. Therefore, it is justified to use the dependence (2) to calculate the probability of failure-free machine operation until time *t*.

As the average durability of all 29 assembly groups in the group of Zetor tractors under study was MTTF = 271 mth, the λ coefficient amounted to 0.004 mth^{-1}. Diagram 3 shows the theoretical course of the risk function.



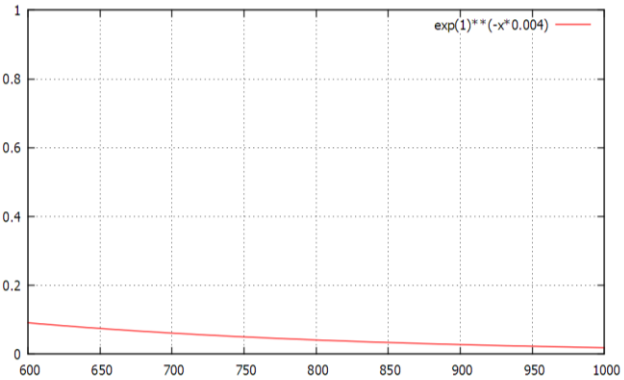
Source: own study / Źródło: opracowanie własne

Fig. 3. The theoretical course of the Zetor tractor reliability function *R*(*t*) (engine power 45-90 kW) at a time interval of 0-600 mth
Rys. 3. Teoretyczny przebieg funkcji niezawodności R(t) ciągników marki Zetor o mocy silników od 45 do 90 kW w przedziale czasu 0-600 mth

When the values are substituted in the equation (2) or when they are read from the diagram, we can see that the probability of failure-free machine operation until the end of the time interval of 600 mth (end of research) was as low as 9%. If we take a very specific point on the time axis, i.e. the average durability R_{Zetor} (271), we can see that this value amounted to 36.8%. This means that 63.2% of the group under study will have broken down by this time. It is a so-called characteristic fitness of each exponential function, which is independent of the λ coefficient value. According to the diagram, it is statistically probable that a Zetor tractor might fail (50:50 probability) as early as after 150 mth. It is not an unreal value, because it is the average annual time of operation of tractors used on Polish farms.

When we know the value of the failure intensity coefficient, we can forecast the occurrence of a failure at any time of machinery operation (Fig. 4).

In the group of tractors under study the reliability value continued to decrease after the end of the observation period. It amounted to $R_{Zetor}(1000) = 0.018$. It was impossible to compare the reliability of Zetor tractors with other tractors due to the lack of similar data.



Source: own study / Źródło: opracowanie własne

Fig. 4. Forecasting the tractor reliability after 600 mth of operation
Rys. 4. Prognozowanie niezawodność ciągników w przyszłości powyżej 600 mth

5. Summary and conclusions

The reliability of farming machinery is an important factor influencing farm work efficiency. Therefore, it is necessary to ensure optimal reliability of farming equipment both during production and operation.

The knowledge of actual failures of farming machinery enables calculation of the time-dependent reliability function. The analysis of a reliability function diagram enables highly precise prediction of the occurrence of a failure at any time. Analysis of the reliability function (or more precisely speaking, calculation of the λ coefficient) for different makes, types and models of farming machinery could be used for its ranking, like car reliability rankings prepared by ADAC, DEKRA, TÜV and GTÜ. This information would be useful for potential users of new machinery. In the future the Institute of Biosystems Engineering, Poznań University of Life Sciences, Poland could conduct tests similar to those made by the DLG Test Centre in Groß

Umstadt, Germany. The Institute has qualified staff ready to work for the public good and it has the necessary facilities to conduct such tests (laboratories, workshops, engine test stand, garage and range).

The method of measurement of farming machinery reliability described in this article is universal and it can be successfully applied to various groups of farming machinery used for plant and animal production. It is a costless method but it is time-consuming and requires good organisation of work. Manufacturers and service stations are reluctant to share data concerning failures of their products. This method is required due to the objectivity of results and a large number of machines of the same make, model and variant. However, the method does not provide information about failures of individual components of machinery. Manufacturers might use these data to modify the frequency and range of overhauls.

The researchers are working on another version of the method used for quantifying the reliability of farming machinery, which will include the reliability of individual components. Preparation of a network of probabilistic interrelations between these systems, i.e. giving machinery a reliability structure, will enable the application of conditional probability, i.e. Bayes' theorem. A Bayesian network is a modern modelling technique where the model is a product. It has a recurrent and normative character – there are specific criteria of correctness of individual components and rules of combining them into one entity.

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