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# USING THE WEIBULL ++ SOFTWARE IN WATER SUPPLY NETWORK FAILURE ANALYSIS

The water supply network is a basic element of the water distribution subsystem and its task is to provide consumers with water of appropriate quality, in the required quantity, under appropriate pressure, at any time and at an acceptable price. To fulfil these tasks, the water supply network should have an appropriate level of operational reliability. The paper presents an analysis of the causes of water pipes failures using the Weibull++ software. The analysis was based on the operational data from 2018 obtained from the water supply company. The data included the failure book specifying the date and place of the failure, the cause of the failure, diameter and material of the damaged pipe. The probability density function for the failure of water pipes and its cumulative distribution function have been determined. The impact of individual types of failure causes on the failure of the water supply network was determined. The results provide information about the probability of failures of the water supply network depending on their cause. These results can be used in further analyses of the reliability and safety of water supplies to consumers.

**Key words:** failure, reliability, water supply, Weibull++

## 1. Introduction

The basic element of the water distribution subsystem is the water supply network with utilities, therefore the reliability and security of water supply to the consumer depends mainly on its operation [1,2,3,4,5,6]. The distribution subsystem should be able to provide water of the right quality, in the required quantity, under the right pressure, at any time and with an acceptable price [1,3,6,7]. The biggest threat to the performance of the above tasks are failures of the water supply networks, which may cause interruptions in the water supply or affect water quality, which reduces the reliability and security of water supply to consumers [7,8,9,10,11,12,13,14,15,16]. The causes of water supply network failures may be internal (errors at the stage of design, construction or operation) or external (random failures resulting from the impact of the natural environment

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or human activity) [2,17]. Water supply companies should strive to reduce the number of breakdowns through appropriate management of the water supply network, carrying out renovation and repair plans, the use of modern operational tools (GIS applications, hydraulic models) and monitoring of the water supply network operation [3,5,7,8,11,12,14,18]. The main purpose of the work is to present the possibilities of using the Weibull ++ software for water supply network failure analysis. The paper attempts to describe the probability distribution model of a water supply network failure by means of a statistical probability distribution. The causes of the water supply network failure were identified and their impact on the failure of the distribution subsystem was examined. An application example was made for real data provided by a water supply company operating in a voivodeship city located in south-eastern Poland. The results of the work will complement the research conducted so far and will provide valuable information for water supply system operators.

## 2. Research methodology

The Weibull ++ software is a tool for testing the reliability of individual parts, complex machines or entire systems [19]. Input data for the program are operational data such as time between failure (TBF) or time to failure (TTF). These data are described by units of time: minutes, hours, days, but can also be described by other units, e.g. the number of work cycles performed, kilometres travelled, etc. Then the program selects the probability distribution model for the entered data with the assumed method of parameter estimation and the given confidence level. The adjustment and selection of the distribution to the description of the real data is based on the ranking created on the basis of: the result of the Kolmogor-Smirnov test, the normalized correlation coefficient (rho-Spearman) and the logarithmized value of the distribution probability function for the estimated parameters. The matching results may vary depending on the method used to estimate the distribution parameters, i.e. the least squares method, the rank regression method or the maximum likelihood estimation method (MLE). The program has the ability to describe the input data using the following probability distributions: 1-parameter exponential, 2-parameter exponential, normal, logarithmic normal, gamma distribution, g-gamma distribution, logistic, Gumbel or Weibull distribution 1, 2 or 3 -parameter [19]. On the basis of the obtained model, the program gives us the possibility to determine the reliability function R(t) (describing the probability that the object will not be damaged in time t), the failure function F(t) (describing the probability of object damage in time t), the average working time of the object to failure MTTF (Mean Time To Failure), the average object operation time between subsequent failures MTBF (Mean Time Between Failures) and the failure rate function $\lambda(t)$. For each of these functions you can specify confidence limits of a given level, which are calculated using the methods: FM (Fisher

Matrix) or LRB (Likelihood Ratio Bounds). Based on the operational data, the program also allows [19]:

- testing the reliability of the object under varying load and strength conditions,
- comparative analysis of the causes of failures,
- post-warranty data analysis,
- economic analysis for a specified level of object reliability.

The paper attempts to describe the distribution model of the probability of water supply network failure based on data on failures in 2018 and analysis of their causes. In the first step, water supply failures were classified in terms of their cause. Based on the available data, 4 basic types of causes of water supply failures in the analysed Collective Water Supply System (CWSS) are specified: corrosion, unsealing, brake and crack. After the initial analysis, the data were introduced into the Weibull ++ software, in which a probability distribution model describing the failure of the water supply network was created. The described random variable is the network operation time until the failure occurs. After performing preliminary calculations, the program selected the Weibull probability distribution closest to the input data. The estimation of the distribution parameters was performed using the MLE method, which is recommended for use with a large amount of collected data [19]. The 2-parametric Weibull distribution implemented for the analysed data is described by the probability density function (density of the random variable T) taking the form [19,20]:

$$f(t) = \frac{\beta}{\eta} \cdot (\frac{t}{\eta})^{\beta-1} \cdot e^{-(\frac{t}{\eta})^{\beta}} \tag{1}$$

where: β - distribution shape parameter,
η - distribution scale parameter,
t - variable described by the distribution,
e – the Euler number.

Then the program determined the failure function F(t), which characterizes the probability of water supply network failure. It is the distribution function of the random variable T. It is given by the formula [19,20]:

$$F(t) = 1 - e^{-(\frac{t}{\eta})^{\beta}} \tag{2}$$

Similarly, the failure functions of water supply network, characterizing the probability of failure related to a given type of cause, were determined.

For the failure function F(t) confidence limits were set at 99% using the FM method. This means that the numerical value F(t) will be between these limits with a probability of 99%.

## 3. Research object

The analysis was carried out for the collective water supply system (CWSS) of a voivodeship city located in south-eastern Poland. The total length of the pipes of the examined water supply network is 1025.7 km. The main network (55.1 km) is made of cast iron, steel and polyethylene pipes; the distribution network (605.0 km) is made of cast iron, steel, asbestos-cement, PE and PVC pipes; Water supply connections (365.6 km) are made of steel, PE and PVC pipes. The age structure of the pipes is shown in Figure 1.

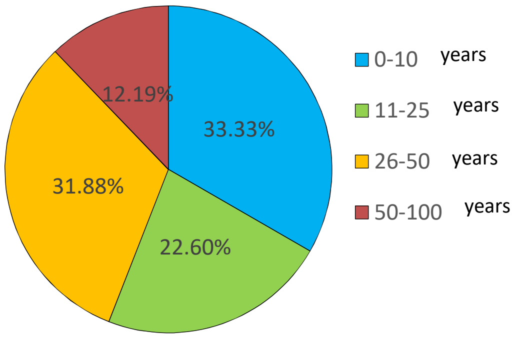


Fig. 1. The age structure of the water supply network pipes.

The analysis was performed for real operational data made available by a water supply company. The data included the age structure of the network and the failure log detailing the date of the failure, the location of the failure, the cause of the incident, the diameter and material of the damaged pipe. The network diagram of the analysed CWSS is presented in Figure 2.

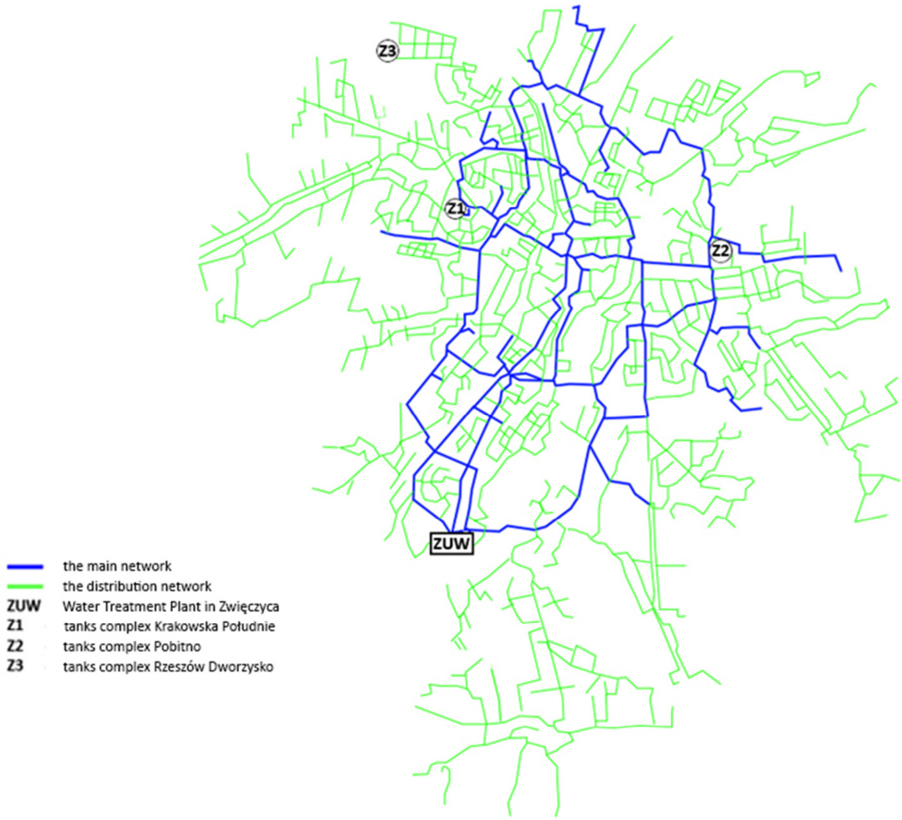


Fig. 2. Scheme of the analysed water supply network

## 4. Results

During the analysed year 2018, 216 water supply network failures occurred. In the failure log kept by the water supply company the following causes of failure were specified: corrosion, unsealing, cracking and breaking of the pipe. The number of failures due to corrosion of the pipe was 103, which constituted 47.7% of all failures, unsealing was the cause of 83 failures, which corresponded to 38.4% of failures, 22 failures were due to a broken pipe - 10.2%, and failures caused by pipe crack occurred only 8 times, which accounted for 3.7%.

Figure 3 presents the density probability function of the water supply network in the analysed year 2018 described by equation 1, for which the Weibull distribution parameters were calculated, i.e. the shape parameter $\beta = 1.55301$ and the scale parameter $\eta = 229.090797$. The function describing the density of the probability distribution takes the form:

$$f(t) = \frac{1{,}55301}{229{,}090797} \cdot \left(\frac{t}{229{,}090797}\right)^{1{,}55301-1} \cdot e^{-\left(\frac{t}{229{,}090797}\right)^{1{,}55301}}$$

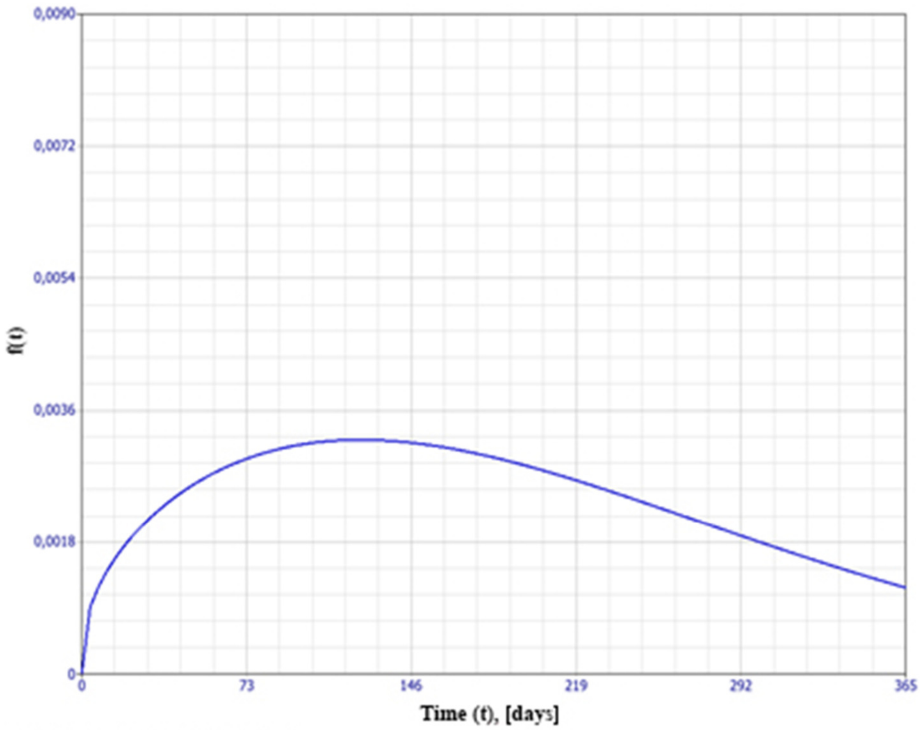


Fig. 3. Probability density function describing the failure of the water supply network.

The density function of the probability distribution describes us a random variable, which is the working time until failure. The field below the graph determines the probability of a water supply network failure. We can calculate it as the integral of f(t) in the range (0,t). At the end of the analysed period (t = 365 days) it was 0.8876791.

Figure 4 presents the cumulative distribution function of random variable t, so we can determine the probability of network damage at a given time t. It is described by equation 2, which after inserting the calculated parameters took the form:

$$F(t) = 1 - e^{-\left(\frac{t}{229{,}090797}\right)^{1{,}55301}}$$

The cumulative distribution function (blue) is limited from above and below by dashed lines (red) which are the limits of confidence intervals at 99% level. This means that with 99% probability the value of the function F(t) will be between these lines.

Figure 4 also presents the graphs of the failure function F(t) describing the probability of a water supply network failure related to individual types of causes, the equations of which took the form:

- the network failure function related to pipe corrosion:

$$F(t)_C = 1 - e^{-\left(\frac{t}{357,390582}\right)^{1,748704}}$$

- the network failure function related to unsealed pipes:

$$F(t)_U = 1 - e^{-\left(\frac{t}{445,433037}\right)^{1,413579}}$$

- the network failure function related to pipes break:

$$F(t)_B = 1 - e^{-\left(\frac{t}{1586,524704}\right)^{1,135663}}$$

- the network failure function related to pipes crack:

$$F(t)_C = 1 - e^{-\left(\frac{t}{686,716892}\right)^{3,446719}}$$

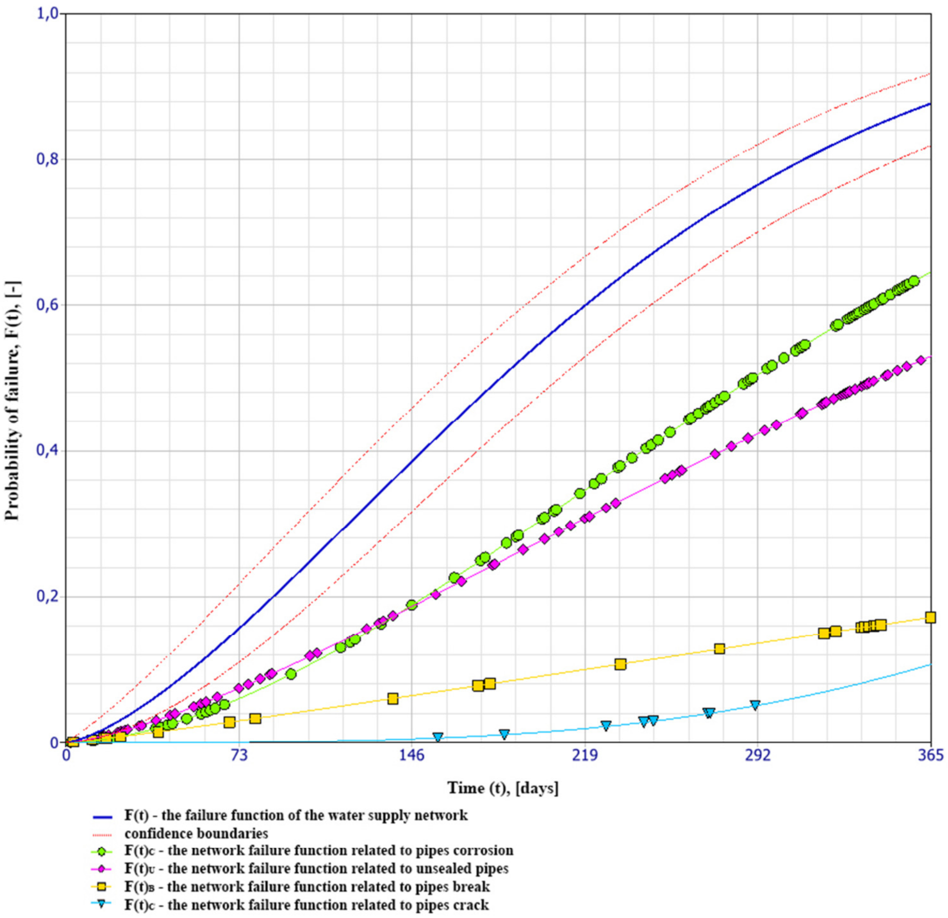


Fig. 4. Graph of the failure function F(t) of the water supply network due to the causes of the failure

The function of network failure due to corrosion ($F(t)_C$) is described in green, due to unsealed pipes in violet ($F(t)_U$), due to pipes break ($F(t)_B$) in yellow and due to pipes crack ($F(t)_C$) light blue. Failures due to corrosion and unsealing had the greatest impact on the water supply network failure function F(t). It was observed that in the first half of the year failures caused by unsealing had a dominant impact on the shape of the graph of the network failure function F(t), while in the second half of the year the shape of the graph was more dependent on corrosion-related failures. Due to the small number of failures associated with broken and cracked pipes, they had a negligible impact on the water supply network failure function F(t).

## 5. Summary

The paper presents the possibilities of using the Weibull ++ software in the analysis of water supply failure. This program allows testing reliability and failure rates based on statistical probability distributions. The program describes the density probability function of the water supply network based on actual operational data. The developed probability model was based on a 2-parameter Weibull distribution that was matched to real data using the MLE method. On its basis, the failure function of the water supply network F(t) was determined, the value of which determines the probability of failure at a given time t. Based on the data, the causes of the failure include: corrosion of pipe, unsealing, break or crack of pipe. Then, using the program, the failure functions were determined, depending on the cause of the failure ($F(t)_C$, $F(t)_U$, $F(t)_B$, $F(t)_C$), thanks to which it is possible to determine the probability of failure occurrence at time t due to a given cause. These results can be used in further analyses of the reliability and security of water supply to consumers. To assess the failure rate of the water supply network which is a linear object, the failure rate index λ is used, which specifies the number of failures that occur in a unit of time per length of the network. The Weibull ++ software only allows to determine the failure rate function λ (t), which determines the conditional probability of failure occurrence in the time interval Δt, if at the beginning of this interval the tested object was in working order. Further research should explore other options for using the Weibull +software in analysing the reliability and failure rate of collective water supply systems.

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