A New Approach To Gathering Failure Behavior Information About Mechanical Components Based On Expert Knowledge

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SUMMARY & CONCLUSIONS

This paper presents a possibility with which the reliability knowledge of maintenance employees can be used in order to receive reliability data that can be used to do simulations or further calculations. Using the presented methodology opens up a big source of information. The use of employee knowledge entails the processing of imprecise data, as the knowledge is not given in the form of a failure time plot, but in the form of verbal expressions and specific information. The paper deals with the data format and precision of expert-based information.

A methodology is presented which enables the transformation of certain employee (further called experts) information into reliability data. Apart from that the paper also shows the influence of imprecision of expert information and how to handle this imprecision in order to get applicable results. As a finishing subject the paper also provides a possibility with which the deviations of expert information from reality can be estimated dependent on the expert statement itself. With that approach one can tax the trustability of expert information.

1. *INTRODUCTION*

An essential precondition for the use of simulations (availability of production lines or determination of maintenance costs) is the existence of data. The reliability information of the components that shall be considered in the modeling and simulation must be available. Although small or middle-class enterprises cannot provide a machine- or facility focused data-collection very often, it would be useful for them to use simulation results anyhow. The key for solving that kind of problems lies represented by the employees in the enterprises themselves. The experience and knowledge of the employees comprises information about many years. The use of expert knowledge implies the processability of data revealed by experts. That means that the kind of expert data is transformable into reliability parameters. Therefore, it would be the most convenient way to gather experts' knowledge directly in the form of parameters (Ref. 1) that build up a failure behavior representing failure distribution, as for example a Weibull distribution. For many components (especially electronic ones) one can also use data out of catalogues, for example out of the Military Handbook (Ref. 2) and data banks. This described most convenient proceeding is not working in the most cases. Many catalogued values do not match the operational profile of the real product or are too imprecise and can only be used for a comparison but not for the calculation or the simulation of a real product (e.g. a production facility). Apart from that, an update has not taken place for the Military Handbook during the last decade. This decreases the accuracy of such catalogues once more (Ref. 3). Where should such information stem from elsewhere? The path that is followed in this paper bases on the use of the knowledge of employees, that already collected many experience with the machines or facilities during their working time in an enterprise. The experts have information about the failure behavior, but this knowledge is only available in the experts' speech. Using this source of information is many times more practical than assuming that an all knowing expert reveals machine- and operation dependent data in the form of direct distribution parameters. The language of employee experts is very practically oriented and is mainly based on times of failures or other events. If it is possible to translate this speech into reliability parameters and to quantify the risk of usage of these data, also small and medium-sized enterprises will be able to use simulation technique in order to optimize business processes like maintenance and spare-part strategy.

Notation & Acronyms

b	shape parameter of the *Weibull* distribution
$f(t)$	failure density function, pdf
n	amount of observed failures
i	rank of a failure time
t	time
t_{mod}	point of most observed failures
t_0	location parameter of the *Weibull* distribution
$F(t)$	failure probability, cdf
$R(t)$	reliability of a system (or component)
T	scale parameter of the *Weibull* distribution

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cdf	cumulative distribution function
pdf	probability density function
$\lambda(t)$	failure rate (hazard function)

2. *BASICS & DEFINITIONS*

2.1 *Reliability*

The reliability $R(t)$ of a system (or component) is the probability that, when operating under stated environmental conditions, the system (or component) will perform its intended function adequately for a specified interval of time t (Ref.4). The mathematical description is based on the probability density function (pdf) $f(t)$, the cumulative distribution function (cdf) $F(t)$ with $f(t) = \mathrm{d}F(t)/\mathrm{d}t$, the reliability $R(t) = 1 - F(t)$ and the failure rate (hazard function) $\lambda(t) = f(t)/R(t)$.

2.2 *The Weibull distribution*

The usual description of the failure behavior of mechanical systems or components is provided by the three-parameter *Weibull* distribution (Ref. 1), with the pdf

$$f(t) = \frac{b}{(T-t_0)}\left(\frac{t-t_0}{T-t_0}\right)^{b-1} e^{-\left(\frac{t-t_0}{T-t_0}\right)^b}, \; 0 \le t_0 \le t, \quad (1)$$

with shape parameter b, scale parameter T and location parameter t_0. For $t_0 = 0$ one speaks of a two-parameter *Weibull* distribution. The failure rate $\lambda(t)$ of a *Weibull* distribution is a function of time, it can depict all three sections of the well-known bath-tub curve depending only on the shape parameter.

3. *KNOWLEDGE OF EMPLOYEE EXPERTS*

The project on which this paper bases, has been done in cooperation with ZOLLERN ISOPROFIL, a medium-sized manufacturer of steel profiles. The enterprise has many experienced employees who are responsible for the maintenance of the machines. The project has been done in cooperation with two employees. Both of them are working already more than 13 years in the enterprise. One of the experts is responsible for an annealing furnace, the other one coordinates the maintenance activities of a sandblast unit. As the project was limited by time every expert was questioned only about one critical part of his facility, although the experts would have been able to reveal more information about other critical elements.

3.1 *The Psychological Aspect*

Gathering data from an expert is not as easy as starting an output plot. The challenge is situated in the information transfer from one person to another (Ref. 5). The asked person has to understand the question the interviewer asks him, he has to remind relevant information, he has to do judgments and ratings, and finally he has to answer the posed question. These four partial aspects must be considered and the interviewer must always be aware of them in order to get valid information. To do so, especially for the purpose of eliciting reliability information, an extensive motivation prolog took place, in which the experts have been told of what use their knowledge can be. Further it is important, that the interviewer prevents an interviewer-bias, i.e. to prevent an interviewer's misunderstanding of expert statements. Apart from that there exists the difficulty for the expert to handle the posed question. For answering a question it might be possible, that the expert has to deal with many information. If the amount of information becomes too big the expert's answer might be very imprecise (Ref. 5), because he could use very rough assumptions and simplifications to answer a question he is actually overburdened with. These and more aspects (Ref. 5) have to be taken into account, when an elicitation of expert knowledge shall take place.

3.2 *What do employee experts know?*

One of the most important assumptions that is made for the applicability of employees' knowledge in order to gather input data for purposes of simulation is that they can reveal useful data. As already mentioned above it is not likely that an employee expert can serve with certain distribution parameters. This assumption can be made (Ref. 1) but only in scarce cases. The kind of posed questions can be sorted into classes of difficulty (Table 1.).

Table 1: Difficulty classes for employee experts

Objective of a Question	**Class of Difficulty**
Failure times (first, last)	**1**
Modes (when have most of the parts failed) and Means	**2**
Probabilities	**3**
Parameters of Distribution	**4**

The interviewer started with class No. 1 and proceeded to higher difficulties if this was possible, i.e. if the expert could handle the posed question. Respective to this, the psychological aspect is of most crucial importance, as the expert shall not be rushed to give statements to questions he does not understand and as a result of that, the interviewer obtains wrong and counterproductive data. Expert No.1 chose a bearing out of an annealing furnace, as his object of consideration. The expert mentioned, that there are six identical bearings in the furnace. These six bearings have to stand the same stress. As this is given, one can suppose an identical failure behavior. During the beginning of the elicitation the expert explained that a mainly preventive maintenance strategy is applied to the annealing furnace. As a result of this almost no bearing fails in the sense of a sudden downtime, that makes the whole unit not working. In half year intervals the bearings are examined with stethoscopes. If the

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noise of a bearing exceeds a certain (subjective) level it is replaced by a new one. According to this statement one might think, that it is not possible, to develop a "real" failure distribution out of the experts´ knowledge. Two arguments are opposing this idea. First, the experts confirmed, that it is most probable, that a bearing which is not replaced although the noise level would indicate it, fails within the next half year. So one would be able to develop a time-shifted failure distribution. The second reason is that one has to ask oneself if the purpose for which the data is gathered really needs a failure-based distribution. An example therefore is the spare part strategy, which depends on the need of spare parts and thus on the real replacement behavior in the enterprise and not on the failure distribution basing on "real" failures.

In the beginning of the interview expert No.1 was asked about the shortest life-time of a bearing that he knows about. The answer was 1.75 years. This component really failed and caused a massive down-time event. Further the interviewer asked for an imprecision-band of this value. Expert No.1 gave the statement: "The early failure of this component really aggravated me. That is the reason why I know the failure time exactly." This statement of the expert can serve as a prime example for the influence of human factors into an expert´s knowledge. The expert was also questioned for the longest lifetime. This one was 5 years, also without a band. The next step of interviewing concerned mode and mean values. As shown in table 1 this kind of questions are more difficult to answer, as we leave the time-based level and enter aggregations of knowledge into values. Expert No.1 mentioned that most of the parts failed after 3 years (most of the parts have been replaced after 3 years). He was also able to give a value for the mean failure time which he assigned a value of 3.5 to.

As the correctness of the statement about the most failures is very important for the distribution that shall be built up the interviewer accomplished an example for the experts after they gave an answer to the question. A row of arbitrarily chosen failure times was given to the experts and then they were asked at what time they think most of the parts have failed.

Expert No.1 had the right understanding respective the mode of the failure behavior. So one can expect, that the information he gave about the mode of the bearing failure-behavior is very confidential.

The next step of difficulty would have been to ask for probabilities of failure. But Expert No.1 did not know how to deal with the term probability respective to failure-behavior. Here we meet the borders of employee expert knowledge.

4. *PROCESSING OF GATHERED DATA*

The knowledge of the experts must be translated into data that is compatible to simulation-tools. Therefore it would be of sense to translate these data into failure-distributions. The data-analysis bases on the three-parameter Weibull-distribution, as this one is very appropriate for modeling mechanical parts. The use of a three-parameter distribution entails the existence of three equations which enable the determination of the three parameters.

4.1 *Development of the analysis method*

The first equation bases on the knowledge about a mode (where most parts have failed). Therefore we use the equation for the failure-density (Ref.4)

$$f(t)=\frac{b}{(T-t_0)}\left(\frac{t-t_0}{T-t_0}\right)^{b-1} e^{-\left(\frac{t-t_0}{T-t_0}\right)^{b}},\ 0\le t_0\le t \tag{1}$$

and its differentiation

$$\frac{\mathrm{d}f(t)}{\mathrm{d}t}=\frac{\left(\frac{t-t_0}{T-t_0}\right)^{b}\cdot b^2-\left(\frac{t-t_0}{T-t_0}\right)^{b}\cdot b-\left(\frac{t-t_0}{T-t_0}\right)^{2b}\cdot b^2}{(t-t_0)}\cdot e^{-\left(\frac{t-t_0}{T-t_0}\right)^{b}}. \tag{2}$$

The maximum of the density-function can be determined by

$$\frac{\mathrm{d}f(t)}{\mathrm{d}t}=0 \tag{3}$$

and the subsequent simplification of Eq.(2).

$$\frac{\mathrm{d}f(t)}{\mathrm{d}t}=0=b-1-\left(\frac{t-t_0}{T-t_0}\right)^{b}\cdot b \tag{4}$$

As a result of Eq.(4) one can determine the mode t_{mod} of the failure distribution dependent on the three Weibull parameters. So the first of three necessary equations is found.

$$t_{\text{mod}}=\sqrt[b]{\frac{b-1}{b}}\cdot(T-t_0)+t_0 \tag{5}$$

As base of development of a second equation for determining the parameters the equation of the failure-probablity (Ref.4)

$$F(t)=1-e^{-\left(\frac{t-t_0}{T-t_0}\right)^{b}} \tag{6}$$

can be used.

Using this equation entails an additional information. As already mentioned expert No.1 did not give any information about any probabilities of failure. But he was able to give another information which can be helpful. The employee experts know very often how many parts they already replaced. So in a certain way the sample size of a complete sample is given. With this information one can determine the failure probability according to the longest observed life-time by using the equation for the approximation of rank-dependent failure-probabilities (Ref.4)

$$F(t_i)\approx\frac{(i-0.3)}{(n+0{,}4)}. \tag{7}$$

Expert No.1 had information about approximately 36 parts. According to Eq.(7) this means that a failure probability of 98,03 % is assigned to the 36[th] and last (5 years) failed bearing. This information applied to Eq.(6) reveals the second necessary correlation.

$$F(5)=1-e^{-\left(\frac{5-t_0}{T-t_0}\right)^{b}}=0.98093 \tag{8}$$

For the determination of the third necessary correlation we do not have a basic definition left; so an assumption must be made. The location parameter t_0 is the third parameter of the Weibull-distribution. If an infinite amount of parts is tested the location parameter is the shortest life-time of all parts. In the case of expert No.1 36 replacements have been observed. According to Eq.(7) the earliest replacement, which took place after 1.75 years, is combined with a failure-probability of 1.907 %. This means, that with a probability of 1.907 % one will observe a replacement before 1.75 years. Facing this fact it seems assumable that the earliest observed failure yields the failure-free time t_0 of the Weibull distribution. Using this assumption for the case of the bearings would mean that t_0 = 1.75 years.

Now three equations are available for the determination of three distribution-parameters.

4.2 *Application of the analysis method*

The application of the above developed methodology on the bearings of expert No.1 results in a Weibull-distribution with the parameters T = 3.44 years, b = 2.11 and t_0 = 1.75. As expert No.1 was able to give a value for the mean failure time, it is possible to control the results of the parameter determination with an expert information. Eq.(9) determines the mean of the failure-distribution (Ref.4).

$$E(t) = MTTF = (T - t_0) \cdot \Gamma\left(\frac{1}{b} + 1\right) + t_0 \tag{9}$$

Using the parameters of the furnace bearing results in a mean value of 3.24 years. The deviation from the value that was given by the expert is only 7.7 %.

Further on expert No.2 shall be dealt with. He gave information about another part. The part stems out of a sandblast unit and is again a bearing. Expert No.2 could not give a mean of failure times. He also could not handle terms like probability or parameters of a distribution. The results of the interview with him combined with the statements of expert No.1 are shown in table 2.

Expert No.2 could not give precise values. All of his information is combined with an imprecision band. If such data is given, one has to take the influence of the imprecision into account. The safest way to do this is to consider the influence of the boundary values of the imprecision bands on the Weibull-parameters. For the consideration that shall be accomplished here the imprecision of the shortest observed lifetime will not be included, as the volume of the examination would be too big.

4.3 *Determination of the parameter combinations*

We take 3 out of 4 parameter influencing variables into account; these are the longest observed lifetime, the point of most observed failures and the amount of replaced parts altogether. If 3 values are given and 2 boundary values are assigned to each one of them, this results in 2^3 = 8 possible combinations. Each of this combinations will reveal other Weibull-parameters. In doing so one can ensure, that all possible combinations are included. The starting point for the computation are Eq.(5), Eq.(6) and Eq.(7). Eq.(6) provides two subsequent equations, when - basing on Eq.(7) - the amount of observed replacements is included.

Table 2: Expert lifetime statements

Information	Expert No.1 (annealing furnace)	Expert No.2 (sandblast unit)
Shortest observed lifetime	**1.75**	**1.5 (+/- 3 months)**
Longest observed lifetime	**5**	**between 4 and 4.5**
Point of most observed failures	**3**	**between 2 and 2.5**
Mean of lifetimes	**3.5**	**-**
Observed replacements	**36**	**between 30 and 40**

$$F(t_{30}) \approx 0.97716 \approx 1 - e^{-\left(\frac{t - t_0}{T - t_0}\right)^b} \tag{10}$$

for 30 observed replacements and

$$F(t_{40}) \approx 0.98282 \approx 1 - e^{-\left(\frac{t - t_0}{T - t_0}\right)^b} \tag{11}$$

for 40 observed replacements.

Eq.(10) and Eq.(11) are now combined with the two boundary values of the longest observed lifetime and also with the information t_0 = 1.5 years (without band). This results in four equations. These equations have 2 variables, namely b and T, and are combined with two equations, that are derived from Eq.(5), namely

$$t_{\mathrm{mod}} = 2 = \sqrt[b]{\frac{b-1}{b}} \cdot (T - t_0) + t_0 \text{ and} \tag{12}$$

$$t_{\mathrm{mod}} = 2.5 = \sqrt[b]{\frac{b-1}{b}} \cdot (T - t_0) + t_0 \cdot \tag{13}$$

Combining these two equations with the four equations that were derived from Eq.(10) and Eq.(11) result in 8 possible different solutions for the Weibull-parameters which are given in table 3.

4.4 *Discussion*

The influence of an imprecision at the value of observed replacements has only few impact on the resulting parameters, as one can see in table 3. The impact is growing with a decreasing amount of observed replacements.

The deviation caused by an incorrect time of the longest lifetime (latest replacement) has a much bigger influence on the results. There is also some remarkable effect on the b-values

The most crucial influence has the time or the interval of most observed replacements, as one can see, when contemplating table numbers 1 to 4 in comparison with 5 to 8. The influence on the characteristic failure time T is comparatively low, but there exists a big gap between the values of the shape parameter.

It would also be possible, to include an imprecision of the shortest observed lifetime. This would cause the existence of 16 instead of 8 parameter sets. The influence of expert knowledge imprecision can directly be seen, when considering figure 1, which shows the two most different parameter sets (combination 3 and 8 in table 3). Are these results of use for simulation applications and an improvement of business processes?

Table 3: Weibull parameters dependent on knowledge imprecision (Expert No.2)

No.	most replacements	Observed replacements	latest replacement	*b*	*T*
1	2	30	4	1.51	2.54
2			4.5	1.42	2.68
3		40	4	1.53	2.5
4			4.5	1.44	2.63
5	2.5	30	4	2.14	2.84
6			4.5	1.89	2.98
7		40	4	2.19	2.82
8			4.5	1.94	2.96

With the knowledge of employee experts it is possible to derive a mathematical model for the failure behavior of machines and facilities. It is possible to take imprecision bands into account. The gathered data can then be used to simulate business processes e.g. the maintenance strategy.
A possible result could be, that the maintenance intervals for a certain facility are greater, than the interval boundary values, that derive from the simulation using for example combination 3 and combination 8. So, although there exists a certain imprecision in input data, the result of the simulation indicates that a shortening of applied maintenance intervals would be cost-effective.

5. *TREATMENT OF IMPRECISION*

Very often - and also in the case of this study - the experts cannot give precise information. This might be reasoned by a feeling of uncertainty and the intention not to say something precise, which might be used later to blame the expert for something that went wrong. Another reason is, that the expert really does not know a value exactly. In chapter 4 this challenge was mastered. But is there any possibility for an interviewer to get his analysis more confident?

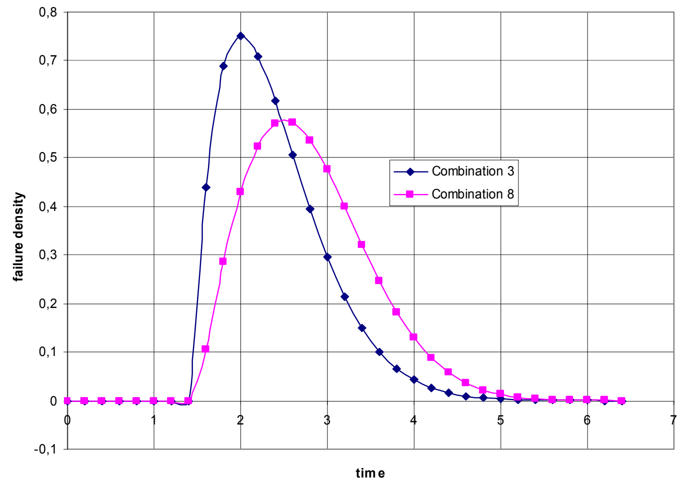

Figure 1: Failure density dependent on imprecision of expert statements

If we have only one expert for a certain part, machine or facility there will hardly be a chance to improve anything. One has only the possibility to make some reflections concerning the trustability ("good" or "bad" employee, employee's attitude towards the elicitation process) of the expert. But additionally to that, there are some theoretical aspects, that support the classification of an expert's knowledge.

5.1 *A possibility to deal with the risk of imprecise information*

Assumed there is a distribution, that exactly mirrors the failure behavior of a component. The expert can only reveal information about the time he has been working in the enterprise. As already mentioned in chapter 4, the influence of observed replacements is theoretically comparatively unimportant, if a certain experience is given. The risk of getting wrong information mainly depends on the ability of the expert to aggregate experiences into values. This risk is very important if the determination of crucial values (e.g. the shape parameter *b*) is concerned. To determine this risk of a deviation a case study was accomplished. In this case the risk is not a probability but a certain value of deviation combined with a lower and an upper boundary. The result shall show, how the amount of observed failures, the shape parameter *b*, and the difference between T and t_0 influence the deviation of an expert estimation for the mode of the failure distribution from the real mode.

5.2 *The case study*

In this case study 5 experts had to estimate the mode of several series of Weibull distributed failure times, that were given to the experts. Each expert got the same series. Thus an influence of different failure times could be excluded. The series differed respectively to the shape parameter b (2, 3 and 4), the amount of failure times (10, 20 and 40) and the difference between T (3, 4.5 and 6 years) and t_0 ,where t_0 was held constant at the value of 1.5 years. Combining these different parameters with each other results in 27 series of failure times, which were given to each expert.

As a measure for the quality of estimation the difference between the real mode and the mode that has been estimated by the experts was calculated. Therefore the sum of the deviations was calculated and divided by 5. In order to prevent, that negative deviations delete positive ones, the absolute values of deviation were used. The result was as follows:

Table 4 shows that the mean values of deviation increase with increasing differences between T and t_0. The band of values results out of varying shape parameters and varying amounts of failure times. It is possible to get more precise information out of such a case study, if certain parameter combinations are considered singly. Therefore it would be necessary to base the results on a large amount of test experts.

The analysis of the case study expert estimations also reveals, that the deviations decrease with increasing shape parameters.

Increasing amounts of failure times should lead to better estimations, as one could expect according to classical reliability analysis. The case study reveals other results. Only in the case of low values of the shape parameter the deviations sink with increasing amounts of failure times. In the cases of higher values (b = 3 or 4) the deviations increased with increasing amounts of failure times.

Table 4: Deviation of estimated mode values from real mode values

T minus t_0	Lower bound	mean	Upper bound
1.5	0.08 years	0.19 years	0.36 years
3	0.09 years	0.41 years	1.00 years
4.5	0.35 years	0.93 years	3.04 years

With information that stems from such case studies, it is possible to categorize the information that is given to an interviewer by an employee expert. Assumed, that the information, provided by the expert, is applicable and a failure distribution can be developed, one can use the resulting parameters, e.g. T minus t_0, to get a clue, which states, how big can the deviation of the mode really be. This helps to find out how trustable the expert information really is.

The case study that has been done, can not directly be compared with the process, that happens, when a real expert has to give a statement about things that happened a long time ago. The interface between the case study and reality is the fact, that in both cases a statement bases on a series of failures and failure times and the need to aggregate this knowledge in a number.

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