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LIFETIME PREDICTION OF SMART METER

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Abstract - This paper deals with various methods to estimate the lifetime of smart meters regarding its measurement features. Shorter innovation cycles lead to additional and/or exchangeable functional components resulting in a change of the reliability. The procedure presented in this paper is a new methodical approach. It combines well-known approaches of technical reliability with a consideration of a priori knowledge. In particular, the state of measuring characteristic on several points of time is observed. The observation leads to prediction of a realistic period of utilization.

Keywords: lifetime prediction, smart meter

1. INTRODUCTION

The delivery of supply goods to the consumer, like electricity, gas, water and warmth, must be absolutely certain determined by a verified meter so that the consumer pays only for the delivered amount of those goods [3]. In particular, the measurement and calculation of the correct amount based on verified meters is economically of great importance because of rising energy and raw material costs as well as consumer-oriented handling with these costs. By using a verification procedure it can be determined whether the measurement device (here: meter) fulfils the requirements of tamper-resistance and measurement trueness for the period of verification validity. A prognosis for maintain of requirements is derived from the current measurement characteristic during the verification process as well as from the a priori knowledge over the long-term stability of the meter. In order to make conclusive statements to the period of verification validity long-term experiences of these devices are necessary. In particular, knowledge about their failure behaviour as well as experiences about procedures of life prediction are needed which consider both the current condition and the previous utilization.

Smart meter are meters with additional functions. The main goals of their application are better awareness of energy efficiency by end users and revealing potentials for energy savings. The introduction of smart meters is promoted by the European Union through different recent legislations. The European Commission has issued a mandate for the standardization of Smart Metering. The standardization process is mandated to the three European Standard Organizations (ESO) CEN, CENELEC and ETSI. More than 110 applicable technical standards are available today which cover parts of a Smart Metering application. To respond to Mandate M/441, the three ESO's work together with stakeholders in a Smart Metering Coordination Group (SM-CG) [17].

The determination of the measurement trueness can be done in two different ways. On the one hand reference measurands can be introduced or, on the other hand, reference devices may be used.

During the common utilized extension of the verification validity, the meters are removed and subjected to an inspection in state-approved testing laboratories. This represents a large logistic effort. To simplify this, the question arises if remote calibration with secure data channels can significantly reduce this effort.

2. STATE OF THE ART

2.1 Definition

Verification validities of meters are defined in regulatory documents as fixed periods and independent of the construction type. In order to minimize the economical effort sampling inspections are used. For the determination of the lot sizes following criteria are considered [18]:

- manufacturer (incl. other manufacturers, with a license to produce the same devices)
- kind or model of the supply good
- serial number and year of production
- class of accuracy
- type of approval number or - marking
- date of the initial examination or subsequent examination.

The predefined sampling procedure contains only attribute testing [5]. Therefore the results have a qualitative character – the procedure allows only well/bad and/or yes/no statements about the fulfilment of the Maximum permission error (MPE) as base for the extension of the period of verification validity of the appropriate lot.

2.2 Applied characterization

The sampling procedures for the extension of verification validity of meters were applied without considering drift features and their causes. A positive result of these sampling procedures led to an extension of the verification validity of the appropriate lot. However, no statements were made concerning to the long-term stability of the measuring devices. This could lead to the problem that an increased failure rate can occur even before the end of the extended period of verification validity was achieved.

An important advantage of this procedure is the smaller effort as with the 100% examination. Unfavourable is the limited outgoing quality.

3. MODEL FOR LIFETIME PREDICTION

3.1 Goal and benefit

The main goal is to find prediction methods for realistic periods of verification validities which consider the structure, characteristics and the possibilities of influence on their aging behaviour.

Fig. 1 illustrates the process of adjustment during the lifetime of the meter. Using advanced investigations during the period of device production (t_0, t_1) the utilization of the meter (t_1, t_2) can be estimated by for example accelerating reliability tests. Further information generated during this period (e. g. consideration of field failures) lead to an adjustment of the end of lifetime ($t_2 \pm x$) in form of a reduction or extension of the verification validity. Activities of estimation reliability should be performed during the total life cycle [12].

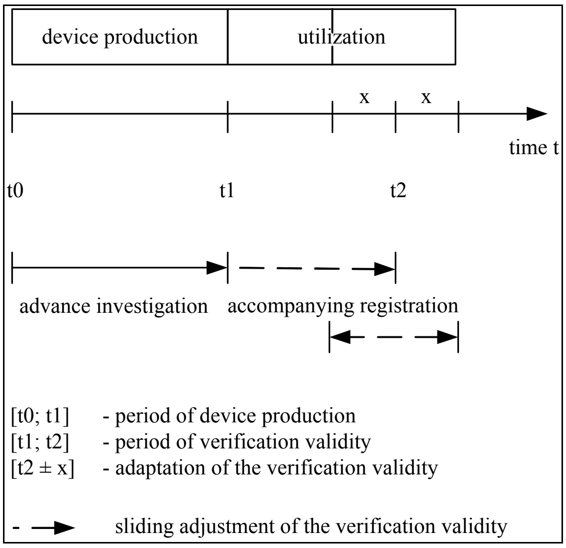


Fig. 1: Life cycle of a meter and observation points of time for lifetime prediction.

The benefits of this new procedure are:

- avoidance of increased false measuring costs by an optimal utilization period
- consideration of device-specific characteristics (previous verification validity assumed from a similar aging behaviour of supply goods)
- preventive quality assurance in order to promptly accomplish suitable measurements for reaching the reliability goals (e. g. installation of redundancies, use of error recognition concepts, use of stable measuring components, purposeful reliability pretreatments)
- uniform approach (standardization) to make the results comparable and reproductive

3.2 Options for the determination of lifetime

a.) Reliability based procedure

The possibility presented here based on the state of the art. The installed meters must be removed for the inspection.

Reliability is a summary expression of the availability and their factors of influence [11]:

- operability,
- maintainability and
- maintenance supportability.

The period of operability is important for the estimation of lifetime. It is limited by failure of function-relevant components.

In practice the lifetime t_{LD} ends if a failure in the meter occurs, which causes that the measurement result is outside of the error limits MPE or the complete functionality is fail. For dealing with both cases of quantitative and qualitative failure a combined approach was developed and presented in the following nonlinear relation (1). The downtime is determined by the temporally first occurring failure form.

$$t_{LD} = \text{Min}(\text{quantitative failure}; \text{qualitative failure}) \qquad (1)$$

A qualitative failure (e. g. failure of function) can be described as a degradation of function-relevant components. In these components internal and external stresses emerge, whose effects fluctuate randomly and are based on statistical distributions. The stresses induce damage mechanisms within the components. Therefore the distribution curves of stress B and strength BK approach to each other (see μ_B and μ_{BK} in Fig. 4). The load factor S in Fig. 4 is a function of stress B and strength BK and describes the load case. As a result of aging, fatigue and wear an increased failure rate occurs [19].

A quantitative failure happens for example if the MPE is exceeded by drift features of individual functional components.

To determine adequate periods of verification validity lifetime laws are required. These laws are described by distribution models, which are based on observations of a lot of comparable meters during a long investigation period.

The most frequent arising distribution models are:

- exponential distribution (lifetime parameter: failure rate λ)
- weibull distribution (lifetime parameter: failure slope b and characteristic lifetime T)
- logarithmic normal distribution.

The lifetime is estimated from the model parameters of the distribution by determination lifetime parameters from the downtimes of the sample.

b.) Remote calibration

In connection with reliability-based procedures would be resulted a simplify verification by reason of a lower logistic effort. In addition to reference measurements secured communication is necessary. For the supply of references two possibilities exist:

- installation of redundant measuring elements into the meter system. Redundant elements are less loaded, because they are only utilized, if it is necessary. This is ensured by a parallel measuring branch.
- impression of reference measurands

Along with the installation of redundant measuring elements comes the risk, that these elements are exposed to drifts.

The impression of reference measurands is independent of drift features. A possible approach based on the generation of a clock signal in the electricity meter with well-known frequency. This can serve as a reference for comparison-standards (e.g.: voltage and current) in the calibration procedure.

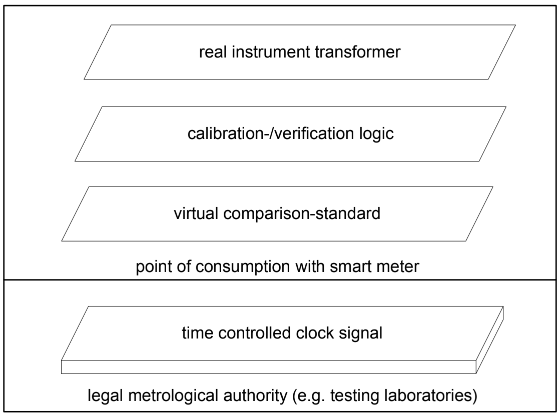


Fig. 2: Layer model of remote calibration for impressed measurands.

The presented approach of impressed reference measurands allow to predict appropriate repetition-cycles for the remote calibration as well as suitable periods of verification validities on the basis of reliability-based methods.

3.3 Process-oriented approach

Fig. 3 illustrates the procedure of lifetime prediction particularly for data acquisition by estimation of the lifetime parameters. The other points before data acquisition are explained in detail in [1].

All steps before data acquisition (number 5 in Fig. 3) are occupied through system analysis:

- functional analysis (function structure and morphologic box)
- determination of the customs and operating conditions
- reliability block diagram (in connection with the mixture of failure types)
- influence analysis.

System analysis serves the collection of functional components. A failure of one of this components leads to the ending of lifetime. Firstly a function structure of the devices has to be developed. Based on this a morphologic box is derived which serves for the modularity of the lifetime prediction concept.

Functional components will be assigned lifetime parameters by data acquisition (number 5 in Fig. 3). The derivation of the system reliability occurs by the mixture of the failure type (number 7 in Fig. 3). For the determination of the lifetime parameters the downtimes are necessary. From these downtimes the lifetime parameters are calculate with processes of estimation (e. g. Maximum-Likelihood-Estimation).

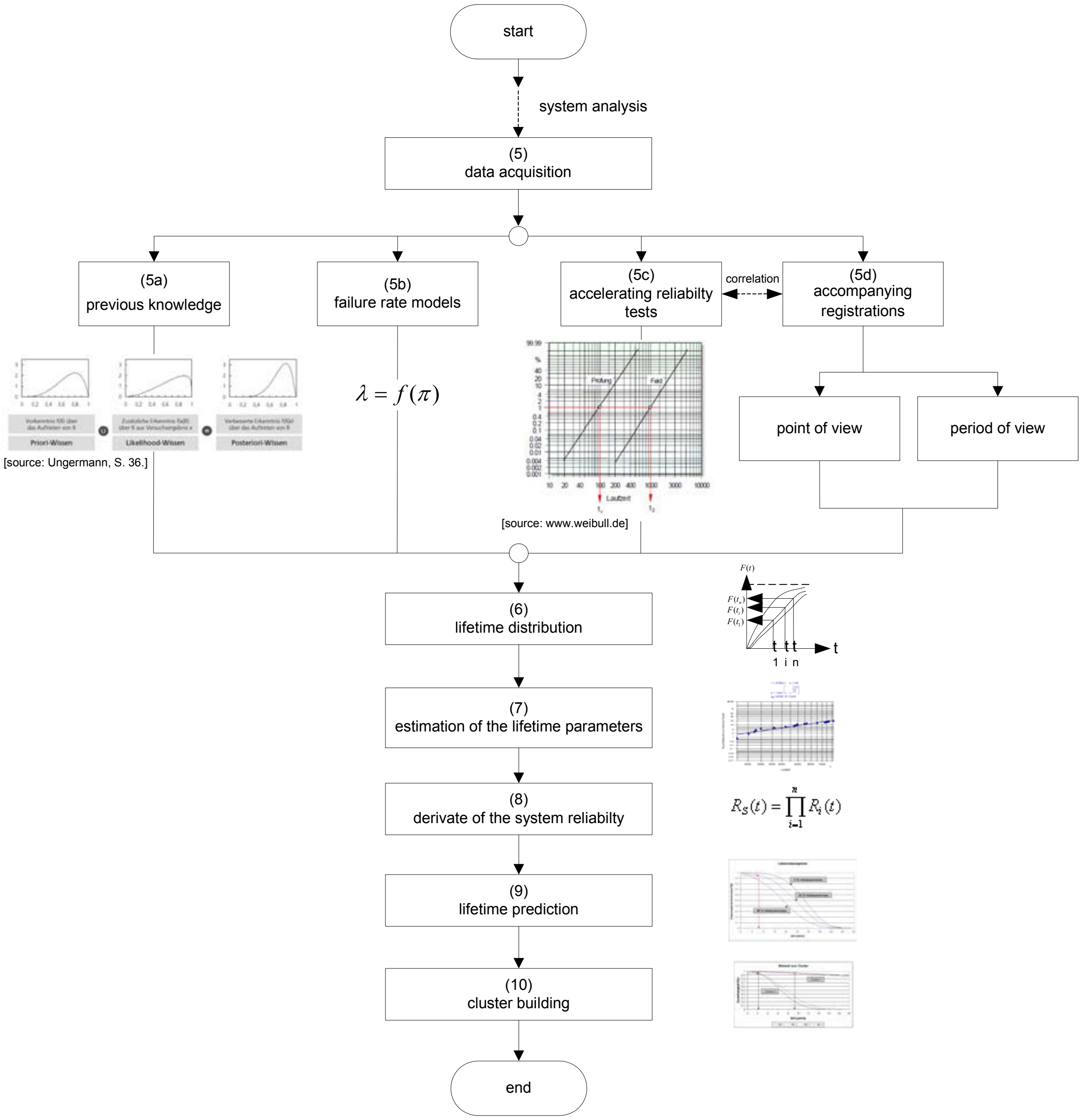
The points listed below visualize the possibilities of data acquisition.

a.) Previous knowledge

A condition for applying previous knowledge is the homogeneity of metrological relevant components. New components can generate new failure mechanism and/or accelerate well-known failure mechanism. Previous knowledge originates from:

- similar products,
- predecessor products or
- preliminary tests.

The transferability of previous knowledge can be done via similarity analyses [8] or determination of a transformation factor [13]. In [13] an extensive description for the consideration of previous knowledge for reliability tests is given (e. g. reduction of inspection time or inspection effort).



[source: Ungermann, S. 36.]

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Fig. 3: Procedure "lifetime prediction".

b.) Failure rate models [9, 15, 16]

Failure rate models describe the dependent relationship of failure rate and operating conditions. A constant failure rate is an important assumption of this model (exponential statistical distribution). In general two methods exist:

- part count method (assumption of a average load level; pessimistic results)

$$\lambda_S = \sum_{i=1}^{n} N_i * (\lambda_g * \pi_Q)_i \tag{2}$$

λ_S - failure rate of the regarded unit
N_i - number of identical components
λ_g - failure rate of the component i
π_Q - quality factor of the component i

- part stress method (consideration of specific load conditions; for calculating the stress factors appropriate load profiles are required)

$$\lambda_S = k * \lambda_b \tag{3}$$

k - lifetime-reducing influences (e. g. temperature, humidity)
λ_b - failure base rate

Failure rate models can be used during the period of device production if appropriate models for construction units are present. The application of these models is limited. Therefore no standard exists.

Tab. 1: Lifetime stress models (AF - accelerating factor; E_a - activation energy (dependent of failure mechanism); k_B - Boltzmann-constant; T_u - temperature of intended customs conditions; T_S - temperature of the severity; RH_u - relative humidity of intended customs conditions; RHS - relative humidity of the severity) [7,8].

Model Stress	factor	Mathematical description
Arrhenius – Modell	temperature	$AF = e^{\frac{E_a}{k_B}*\left(\frac{1}{T_U}-\frac{1}{T_S}\right)}$
Peck-Temperature-Humidity-Model (Eyrings-Model)	temperature, humidity	$AF = \left(\frac{RH_U}{RH_S}\right)^{-n} * e^{\frac{E_a}{k_B}*\left(\frac{1}{T_U}-\frac{1}{T_S}\right)}$

c.) Accelerating reliability tests [10]

Information about the failure behaviour can be available before the beginning of applying the meter. These tests were used for shorten inspection times. Two main models are needed:

(I) lifetime distribution model (e. g. exponential or weibull distribution)
(II) lifetime stress model (e. g. Arrhenius-Model or Peck-Temperature-Humidity-Model)

Some lifetime stress models are given in the literature (Tab. 1).

The acceleration of the failure mechanisms can be justified by the inverse-power-law (4).This means that a higher stress (B_2) within a shorter time (t_2) causes the same damage like a lower stress (B_1) within a longer time (t_1).

$$\frac{t_2}{t_1} = \left(\frac{B_1}{B_2}\right)^{k_p} \tag{4}$$

k_p - power factor

A calculation forecast on the intended use is done with the determination of AF. This allows the estimation of lifetime in good time and accomplishes a weak point analysis.

Difficulties represent the determination of suitable stress levels, so that no new failure mechanisms are activated and the availability of an appropriate lifetime stress model.

d.) Accompanying registration

The acquisition time of information corresponds to the actual failure behaviour. Accompanying registration differentiate in point of view (e. g. sampling inspection) and period of view (e. g. registration of field failures [4]). Both approaches (like accelerating tests) extrapolate the failure dates in order to derive a lifetime prediction. The following examples illustrate this thought.

<u>Example: Point of view (steps)</u>

(I) Quality attributes, like error of measurement, assign measuring values
(II) First comparative measurement has to be done before applying the meter
(III) Second point of view is placed in the application phase
(IV) The lifetime can be estimated through extrapolation of step (II) and step (III) (5) under allowance of the statistical distribution and the temporal development of standard deviation

Equation (5) is valid if a linear change of the error of measurement is assumed. The aim in (5) is to minimize the discrepancy squares of the regression line.

$$t_{LD} \le \frac{MPE - \mu_e(t_0)}{\Delta M} * \Delta t \tag{5}$$

ΔM - difference of the positional parameters of the error of measurement within $[t_n; t_{n+1}]$
Δt - difference of the observation times t_n and t_{n+1}
$\mu_e(t_0)$ - expectancy value of the combined error of measurement at the time of the first inspection.

A correction (Fig. 4) is necessary since otherwise half of the lot is failed (statistical consideration by a symmetric distribution). The reciprocal confidence interval is computed in (6) for 95 %.

$$P(x) = \int_{-MPE}^{+MPE} f(x')dx' \ge 0{,}95 \tag{6}$$

f(x') - probability density function

By using this method function and field failures are considered. The other possibilities for data acquisition (a – c) are helpful to estimate the point of views for the sample inspection. The following worked sample describes the procedure.

- assumption: normal distribution of error of measurement
- units: MPE, μ_e, σ_e units of measurement / t_{LD} units of time (e. g. years)
- MPE = ± 6
- sampling inspection before utilization (t_0): $\mu_e(t_0) = \overline{x}(t_0) = -0{,}523$; $\sigma_e(t_0) = s(t_0) = 0{,}147$ (without observation of the confidence interval as a function of the sample size)
- accelerating reliability test, previously knowledge and failure rate models

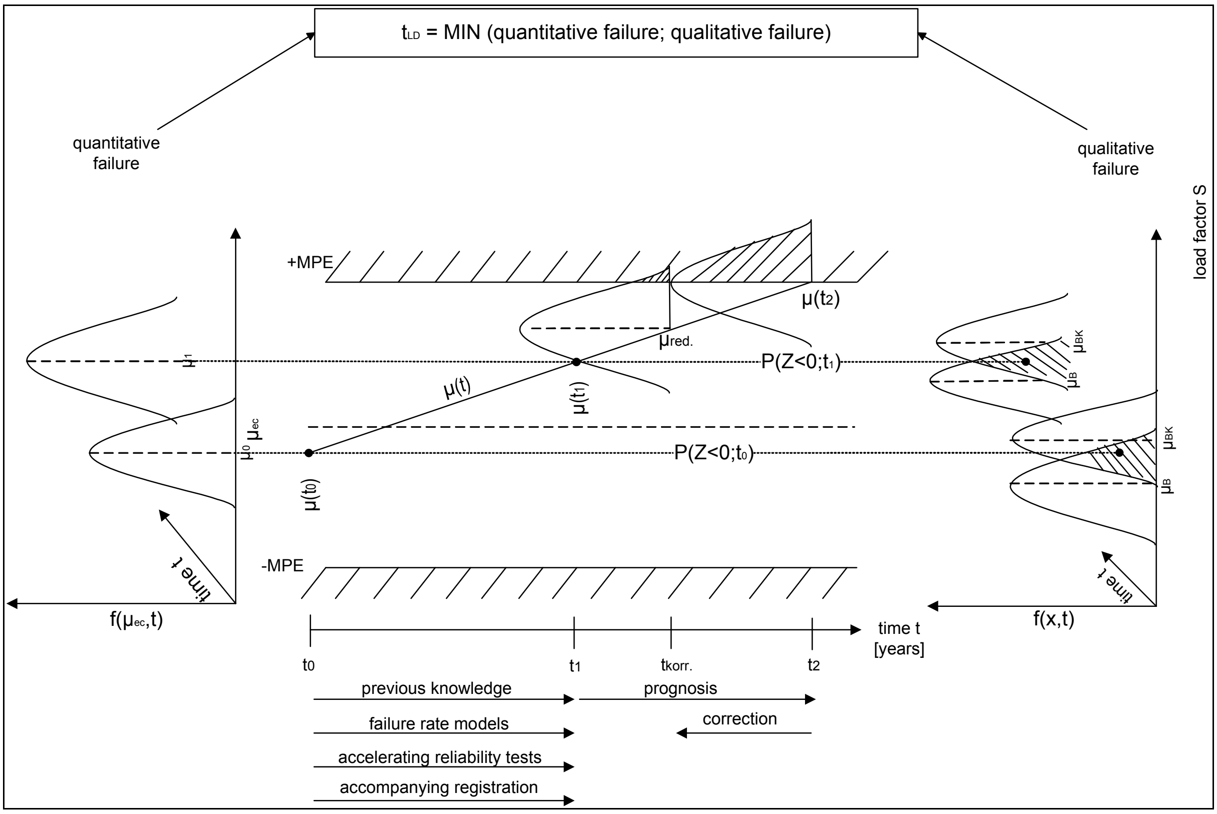

Fig. 4: Points of view for an extrapolation [2].

(pessimistically calculation) estimate the lifetime by t_{LD} = 2 years

- second sampling inspection after 2 years (t_1): $\mu_e(t_1) = \overline{x}(t_1) = 2{,}62$; $\sigma_e(t_1) = s(t_1) = 0{,}276$ (without observation of the confidence interval as a function of the sample size)
- estimation of the uncorrected lifetime (without observation of the standard deviation σ_e)

$$t_{LD} \le \frac{6\,u-(-0{,}523\,u)}{2{,}62\,u-(-0{,}523\,u)} * 2\,y = 4{,}15\,y$$

- estimation of the corrected lifetime (with observation of the chronological sequence of standard deviation σ_e) by (6): MPE = 5,354 and $t_{LD} \le 3{,}74$.

4. RESULTS

Procedures for the extension of verification validities do not consider field failures. Therefore important information about the failure behaviour get lost. The measured values from past and current measurements must be included into the long-term performance.

The lifetime prediction depends on the information basis and their confidence. Uncertainties result from different data acquisitions (e. g. failure rate models based on the fact of time-invariant failure rate or based on accelerating reliability tests where the stress expose of components increases and results in a time lapse of the failure mechanisms).

The weibull analysis [6] represents a suitable tool for the execution of the lifetime prediction. Depending on the size of the failure slope b the ranges of early failures, random failures and aging failure can be described. Further failure types of individual functional components can be analyzed.

In order to react flexibly on renewals in the meter structure (modularity) a definition of functional components in the context of a systems analysis is required by building a morphologic box and merging it into a reliability structure (reliability block diagram) of the meter system. Lifetime parameters are assigned to the functional components by data acquisitions and statistical procedures.

The procedure, introduce here, consider quantitative and qualitative failures. These make it possibility to estimate the lifetime of smart meters.

5. DISCUSSION AND FUTURE PROSPECTS

This paper showed a new approach to adequately determine verification validities by combining well-known approaches of technical reliability through a consideration of a priori knowledge. In particular the appropriate determination of points in time for sampling inspection aspire a minimum inspection effort.

A period of view considers both qualitative and quantitative failures. Through new generated information about the failure behaviour the lifetime parameters are adapted (Fig. 5). An example is the Sudden-Death-Test of field failures [20].

In order to make conclusive statements different data acquisition possibilities should be used (mixing of the methods). New expertises about the failure behaviour are used for the adaption of the lifetime parameters (Fig. 5).

A future prospect is the integration of knowledge-based methods for reliability estimation like fuzzy logic (for uncertainty-afflicted information) or artificial neural network (for the modelling of functional connections between influence factors and the failure behaviour) [14].

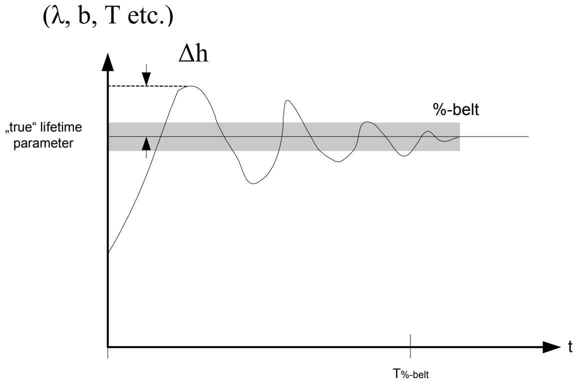

Fig. 5: Transient effect of the lifetime parameters.

6. ACKNOWLEDGEMENT

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