URN (Paper): urn:nbn:de:gbv:ilm1-2011iwk-040:0

56TH INTERNATIONAL SCIENTIFIC COLLOQUIUM
Ilmenau University of Technology, 12 – 16 September 2011
URN: urn:nbn:gbv:ilm1-2011iwk:5

LIFETIME PREDICTION OF SMART METER – ESTIMATION OF LIFETIME PARAMTERS

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ABSTRACT

This paper deals with various methods to estimate the lifetime of smart meters based on lifetime distribution and determination of their lifetime parameters. Focal points in this article are accelerated reliability tests and accompanying registrations in order to describe and quantify failure behaviour. It combines well-known approaches of technical reliability by the consideration of a priori knowledge. It is shown that the Weibull analysis represents a helpful method for the lifetime prediction due to its universal character. To modularize this procedure regarding to product variety and shorter innovative cycles, it is necessary to identify the functional components (reliability structure) and to assign lifetime parameters with the aid of a morphological box.

Index Terms - lifetime prediction, lifetime parameters, smart meter

1. INTRODUCTION

The delivery of supply goods to the consumers, like electricity, gas, water and warmth, must be absolutely certain determined by verified meters at the interchange points [5], because the consumer should only pay for the delivered amount of those goods.

The physics of meters and their manufacturing tolerances cause *Maximum Permission Errors* (MPE). The value of MPE depends on the consumer protection level and the economic effort of the state regulated inspection.

Rising energy costs as well as consumer-oriented handling with various energy sources (energy efficiency) strengthens the importance of a correct measurement of the delivered amount.

Smart Meters are meters with additional functions like communication with other devices or evaluation modules to illustrate the actual consumption. Since 1th January 2010 operators of measuring facilities are compelled to insert such measuring systems, if it is technically feasibly, financially justifiable and the comparison with the potential conservation of energy is appropriate [4]. Furthermore nothing is described about the construction and structure about such measuring systems, its main task is to reflect the energy consumption. In addition to the identification of energy saving possibilities, the purpose for introducing such measuring systems is the imposition of variable tariffs for energy supply. This allows the power suppliers a better utilization of their power station infrastructures and it avoids peak loads.

Disadvantages of the utilization are higher internal consumption based on additional functions, like communication, and a questionable protection of privacy.

To determine the conformation of meters, they are verified by authorized institutions. With the verification procedure is inspected whether the measurement device (here: meter) fulfils the requirements of tamper-resistant and measurement trueness during the period of verification validity. A prediction for the adherence of requirements is derived by the momentary admission during the verification process as well as by the a priori knowledge about the long-term stability of the measuring device. In order to make conclusive statements about the period of verification validity, long-term experiences of these devices are necessary. In particular, knowledge about their failure behaviour as well as procedures of life prediction are needed, which consider both the current condition and the previous utilization [3].

2. STATE OF THE ART

2.1. Definition

Verification validities are periods in which measurement trueness is assured on the assumption of an intended use. Such periods are fixed, independent of the construction type and regulated nationally [3]. They only differ on the consumption type and physical measuring principle. For Germany, verification validities are specified in [6] annex B. They are divided in two different testing processes [1]. If the manufacturers confirm the conformity assessment procedures, which can be selected [24], its meters can be introduced on the market (first verification validity) and are provided with CE - European conformity marking (Fig. 1) [24].

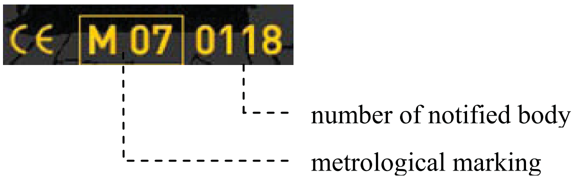

Fig. 1: Example for CE-conformity marking [31].

A renewed testing is necessary, if the meters conformity expired (extended verification validity). Meters occur in large numbers, so that in order to minimize the economical effort, sampling inspections are used. For the determination of the lot sizes following criteria are considered [27]:

- 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.

Different quality features are determined by an attribute testing [11]. Therefore the results have a qualitative character – the procedure allows only well/bad or yes/no statements about the fulfilment of the MPE, as base for the extension of the period of verification validity of the appropriate lot.

2.2. Applied characterising

A positive result of these sampling procedures leads to an extension of the verification validity of the appropriate lot. This extended period is shorter than the first verification validity.

Drift features and their causes are not considered. Also no statements about the long-term stability as quality feature of the measuring devices are made. This could lead to the problem that an increased failure rate can occur even before the end of the extended period of verification validity [3].

For the conventionally used electricity meters, with electromagnetically measuring principle (*ferraris meter*), long-term experiences over their measuring behaviour were sufficient available, in order to be able to make conclusive statements about their measuring stability. The new and often used smart meters are lacking from such long-term experiences. Therefore conclusive statements of measuring stability are not given. Based on shorter innovation cycles, new components are added and/or exchanged. Whereby the failure behaviour of measuring devices is variable and new laws of lifetime prediction are necessary.

As with each sampling inspection is expected a statistic uncertainty, which lead to a manufacturer and customer risk.

3. LIFETIME AND ITS DISTRIBUTIONS

3.1. Goal and benefit

The main goal is to determine adequate verification validities of statistical information which consider the structure, characteristics and the possibilities of influence on their aging behaviour [3]. To minimize economical effort it is necessary to find an optimal sample size as well as certain periods for comparative measurements.

Analyses about the failure behaviour should be performed during the total life cycle of the meter [22]. At beginning it can be applied previous knowledge, failure rate models or accelerated reliability tests to estimate lifetime parameters. In the course of time, the knowledge about the failure behaviour and lifetime parameters increase and it approach to its true values. In combination with accompanying registration can be generated further information during the utilization of the meter.

Via estimation of lifetime parameters, to determination the lifetime, can occur predictions about the future failure behaviour. This makes it possible to consider meter-specific ageing characteristics. The accomplishment of reliability measurements has the advantage, in addition to estimate the lifetime, that weak points are uncovered early and appropriate measures for an increased reliability can be introduced. This can lead to competitive advantages for the manufacturer by products with higher quality (quality leadership with a long-term benefit).

3.2. Failure Forms

The lifetime t_{LD} can be determined by the temporally first occurring failure form. Failure forms of measuring devices, in general, can be divided in quantitative (exceeding MPE border by drift features) and qualitative failures (failure of function). The combined approach of quantitative and qualitative failure is presented in the following nonlinear relation (1) [3].

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

A qualitative failure can be described by the degradation of function-relevant components. In the components emerge internal and external stresses, whose effects fluctuate randomly and are based on statistical distributions (Fig. 2). 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. 2). As a result of aging, fatigue and wear an increased failure rate occurs [7]. To identify such failure forms during the operating time, destructive inspections or analyses of field failures are necessary. Smart meters can already register this failure forms.

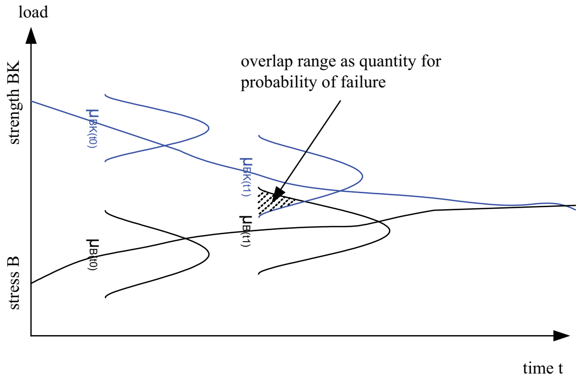

Fig. 2: Chronological sequence of stress B and strength BK.

Quantitative failures can be registered only, on current state of the art, by comparative measurements (e. g. sampling inspections). Necessary is the consideration of the appropriate numerical values, in order to be able accomplish discrepancy conditioned lifetime estimation via extrapolation of the data values (Fig. 3 and (2)). For the prediction of the lifetime the confidence intervals of expected value and variance must be considered (as function of the sample size) as well as the prognosticated probability density function of the appropriate lot. This leads to a correction of the predicted lifetime [1].

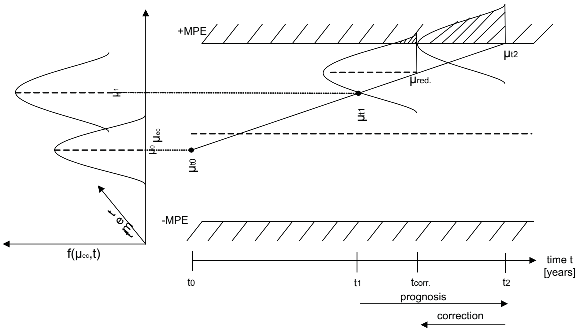

Fig. 3: Extrapolation of the data values.

$$t_{LD} \leq \frac{MPE - \mu_e(t_0)}{\Delta M} * \Delta t \qquad (2)$$

ΔM - difference of the positional parameters of the error of measurement within $[t_n; t_{n+1}]$
Δt - difference of the view times t_n and t_{n+1}
μ_e (t0)- expected value of the combined error of measurement at the time of the first inspection.

3.3. Lifetime distributions and its parameters

Lifetime parameters are necessary to predict the lifetime. Dependent on the statistical distribution (lifetime distribution) various parameters are possible. Important lifetime distributions are (with their parameters):

- exponential distribution (λ) and
- weibull distribution (b, T)

Fig. 4 illustrates typical characteristics of failure rate λ. The bathtub curve is built up of early (e. g. construction failures), random and late failures (e. g. wear).

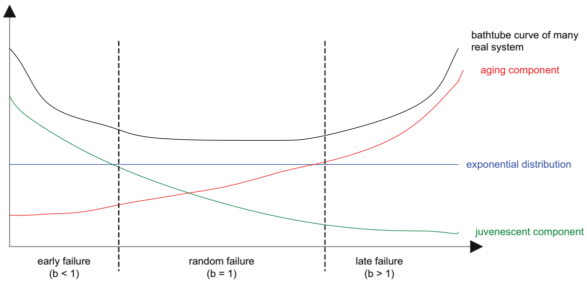

Fig. 4: Characteristics of failure rate λ.

Exponential distribution describes the failure behavior of (sub-) assemblies with constant failure rate λ (b=1). All assemblies have the same probability of failure, independent of the assemblies age. The probability of survival R(t) is determine by (3).

$$R(t) = e^{-\lambda * t_{LD}} \qquad (3)$$

The Weibull distribution [8] is a universal function and describes, depending on the value of failure slope b, early-, random- and late failures. The characteristic lifetime T is the time where 63,2 % of the units are failed. For various main failure modes (e. g. failure of microcomputer) can be defined different values of failure slope b and characteristic lifetime T. The probability of survival R(t) is determined by (4).

$$R(t) = e^{-\left(\frac{t_{LD}}{T}\right)^b} \qquad (4)$$

If no information are available about the failure behaviour at system level (e.g. new products like smart meter), it is helpful to estimate the lifetime parameters at component level (TOP-DOWN-approach).

4. ESTIMATION OF LIFETIME PARAMETERS

4.1. Previous knowledge

Previous knowledge can be helpful, if still no information about new products are available.

A condition for applying previous knowledge is the homogeneity of metrological relevant components [3]. This can be occurred previously for example through accelerated reliability tests, to determine whether itself the same failure modes with the appropriate lifetime parameters are given. New components can generate new failure mechanism and/or accelerate well-known failure mechanism. To reduce the inspection effort previous knowledge can be used. It originates from [3]:

(1) similar products,
(2) predecessor products or

(3) preliminary tests.

The transferability of lifetime parameters of similar or predecessor products can be made via similarity analyses [10] or the determination of a transformation factor [23]. The similarity analysis is divided in products with high degree of similarity and with low degree. The effectiveness of this procedure resulted in the discovery of the characteristic differences. Those can arise from the following factors:

- physical (expected lifetime, electrical load, weight etc.)
- process (FMEA, material composition/quality etc.)
- environmental (use environment, duty cycle etc.)

For example component levels, draft and manufacturing processes to be a part of physical models.

The varieties of environmental conditions affect the reliability of technical products (meter). These environmental influences must be considered at the planning of tests to validate the reliability. Often can not be considered all relevant environmental influences, because only less information of the new unit, concerning their effect on factors of influence, are available. This takes the risk that the required reliability in the field is not complied. For example, by field observations in the later phase, new relations could be won over relevant factors of influence. Preliminary tests in form of a transformation factor φ_V (5) can be transferred for reliability assessment (e.g. in form of a reduction of the inspection effort) [23]. The verification of the transformation factor must occur via a proof test.

$$\varphi_V = \frac{\sum_i K_{\text{prüf}}(UW_i) * T_{\text{bed}}(UW_i) * P_{\text{auf}}(UW_i)}{\sum_i P_{\text{auf}}(UW_i)} \quad (5)$$

UW_i - field working environmental condition i
$K_{\text{prüf}}$ - test accomplished (0: no; 1: yes)
T_{bed} - test conditions (0: reduced; 1: tightened)
P_{auf} - probability of occurrence in the field

In order to apply this method, for the estimation of lifetime parameters, it is necessary to have knowledge about the system structure of the "old" and "new" (sub)-assembly. The results must be treated with attention and should be verified by a proof test.

4.2. Failure rate analysis and models [12],[25],[26]

These procedures are based on the fact of a constant failure rate over the life cycle - only random failures are described. The models describe the dependency relationship between failure rate and operating conditions. Generally, two kinds of failure rate prediction models are applied:

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

$$\lambda_S = \sum_{i=1}^{n} N_i * (\lambda_g * \pi_Q)_i \quad (6)$$

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 the calculation of the stress factors are appropriate load profiles necessary)

$$\lambda_S = f(\pi, \lambda_b) \quad (7)$$

π - lifetime reducing influences (e. g. temperature, humidity etc.)
λ_b - failure base rate under intended use

In the following are introduce the most frequently used databases and methods for failure rate models [28].

The *Military Handbook: Reliability Prediction of Electronic Equipment* (MIL-HDBK-217F) is the most frequently used reliability prediction method of electronic components and was primarily developed for military electronic components. The failure rate based on pessimistic assumptions due to the outdated standard (last update 1995) and its application in the military sector with oversized components and redundancies. Values included in this database originate on statistical analysis of actual field failures [28].

NPRD-95 is the most frequently used reliability prediction method of non-electronic components. Data values are originated from long-term monitoring of the components in the field by the collection of historical failure data of numerous mechanical devices (1970 - 1994). Only field data are available, mathematical models do not exist [28].

Further databases and methods are for example IEC 61709 [37], IEC 62380 [38], FIDES [14] or Prism [30].

Each failure rate model has its own advantages and disadvantages. By mixing these models in the context of lifetime prediction, the accuracy of the prediction can greatly improved [26]. The application of these models is limited. Therefore no standard exists [3].

4.3. Accelerated reliability tests

The main goal of accelerating reliability test is the reduction of testing periods based on higher load of influence quantities. The conversion of the accelerate test results on the intended customs conditions occur with the accelerating factors (AF).

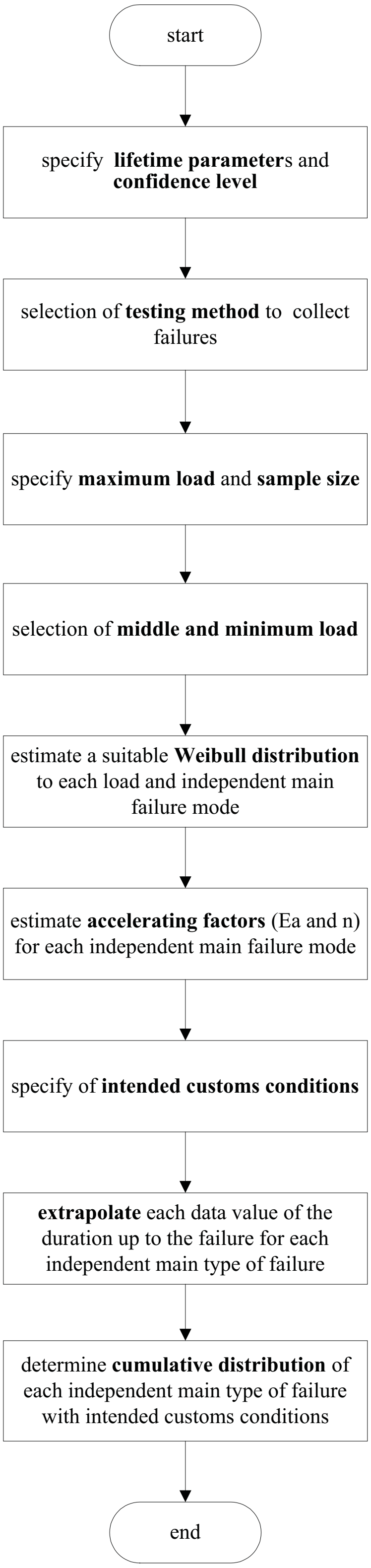

Fig. 5: Flow-chart accelerated reliability tests to determine the lifetime [9].

For the accomplishment of accelerated reliability tests two calculation models are needed:

(1) lifetime distribution model and
(2) lifetime stress model.

Common lifetime stress models are [7, 8]:

- Arrhenius-Model (4) for temperature as stress factor

$$AF = e^{\frac{E_a}{k_B} * \left(\frac{1}{T_U} - \frac{1}{T_S}\right)} \tag{8}$$

AF - accelerating factor
k_B - Boltzmann-constant
T_u - temperature of intended customs conditions
T_S - temperature of the load

- Peck-Temperature-Humidity-Model for temperature and humidity as combined stress factors (5)

$$AF = \left(\frac{RH_U}{RH_S}\right)^{-n} * e^{\frac{E_a}{k_B} * \left(\frac{1}{T_U} - \frac{1}{T_S}\right)} \tag{9}$$

RH_u - relative humidity of intended customs conditions
RH_S - relative humidity of the severity

Fig. 5 illustrates the process to determine the lifetime under assumption by a proven weibull distribution.

Initial point is the load modelling (Fig. 6). It is important to understand the operational and environmental stresses that generate the failure mode based on physics of failure [13]. In cases where two or more stresses (multiple stress acceleration methodology) are the cause of reactions affecting the component or product life (reliability), the test acceleration is done by increasing each individual stress using models appropriate for those stresses. In these cases failure rates, which stand for each individual failure mechanism, are accelerated individually, afterwards the complete probability of survival (R) or probability of failure (F) have to be estimated separately [13].

$$R = \prod_{i=1}^{S} R_i \tag{10}$$

R_i - influence of the type of load i on the probability of survival of the test item, for n from each other independent loads.
R - probability of survival of the test item

In addition to reduce test times, weak point analysis can be realized if are not enough long-term experiences exists. The results must be handled carefully, because higher loads can be activate other failure forms, which not exists if the intended custom conditions are applied. The lifetime distribution can be changed, if accelerated reliability test are done, especially if the loads are too high.

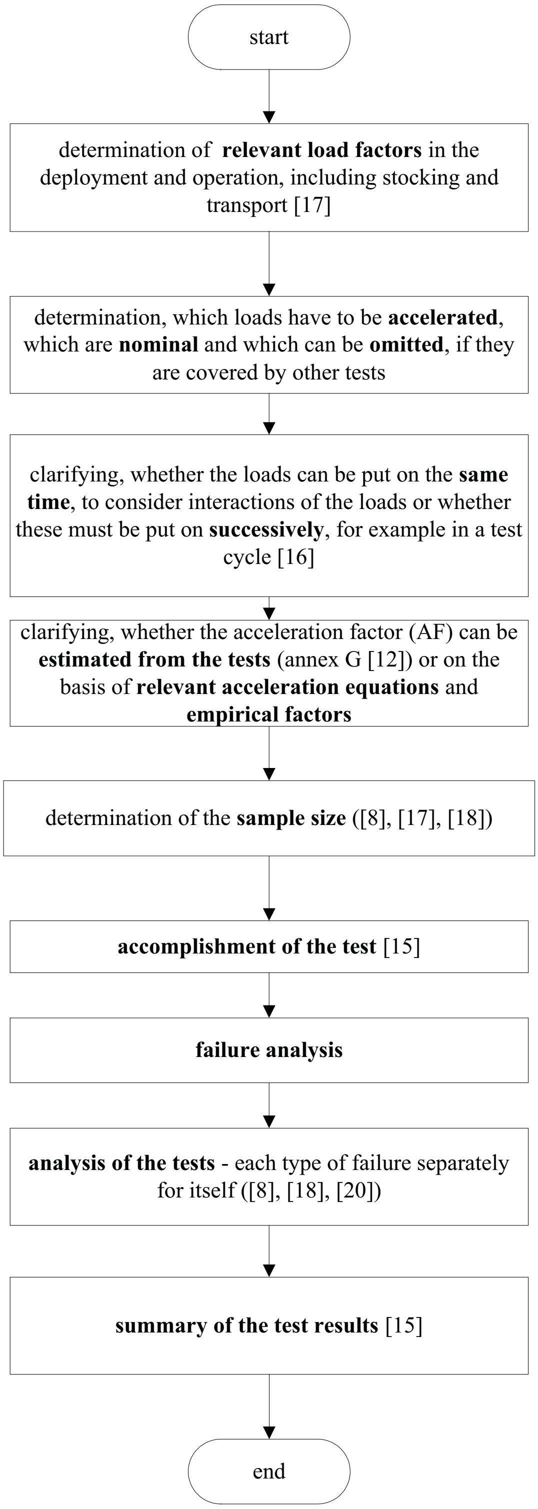

Fig. 6: Flow-chart to modularize the load [13].

4.4. Accompanying registration

Accompanying registration can be occurring in two forms:

(1) point of view or
(2) period of view.

For the points of view measurements on defined deadlines are done. This can be realized for example in form of sample inspections (Fig. 3). Therefore no field failures are considered so that important information about the failure behaviour are lost. Quantitative failures between defined deadlines are uncertain, with regard of their downtime (Fig. 7).

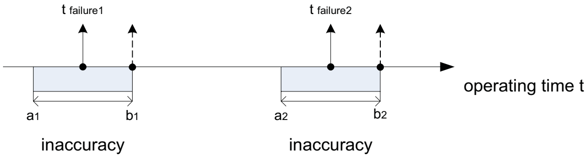

Fig. 7: Inaccuracy of failure time [7].

In the worst case scenario is used a rectangular distribution for the description of inaccuracy. From the given dispersions, which appear realistic for the downtime, can be determined limit values of the lifetime parameters.

With period of views field failures can be considered. With the additional function of smart meter qualitative failures can be determined. For quantitative failures comparative measurements are necessary. Up to now no remote functions for the calibration of smart meter are possible. A suitable tool for analysing field failures is the Weibull analysis in connecting with sudden death testing.

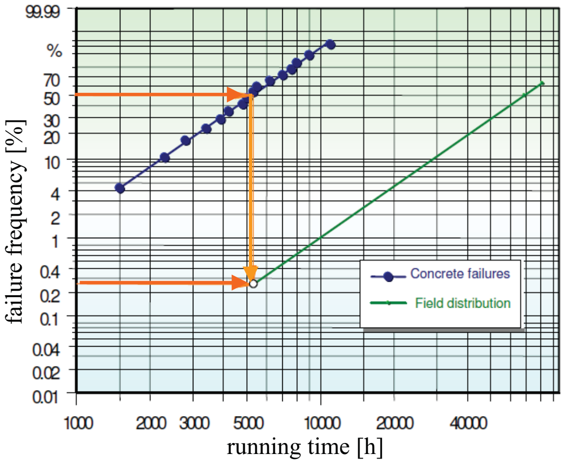

Fig. 8: Lifetime law prediction with sudden death testing [29].

The lifetime of the first point of the field distribution in the Weibull diagram is gained from the intersection of the concrete failures with median rank 50 % and the plumb line to the x-axis (Fig. 8). Every new failure adds up to a new lifetime parameters. For the estimation of lifetime parameters, under assumption of Weibull distribution, various methods are possible (numerical like Maximum-Likelihood-Estimation or graphical procedures). The goal is to receive a good fitting as possible into the measured values.

The connection of qualitative and quantitative failure (1), by the accompanying registration, represents a practicable approach for lifetime estimation of smart meter. Failure data from field utilization should be available by the appropriate market participants.

5. MORPHOLOGICAL BOX

The morphological box is a creative technique from mechanical-design. The product is divided into its functions. To these functions are different variants possible. The goal of morphological box is to generate many variants as possible for same the functions. It should be represent a support, to modularize the procedure of lifetime prediction.

The procedure, to use morphological box, might appear as following:

- failures are assigned to the appropriate functional module (variants) and registered into a data base with its lifetime parameters
- if new components are added into the system structure, then an inspection is done of how these new components influences the failure behaviour (e. g. accelerated reliability tests)
- if in smart meters are integrated already available elements, the lifetime parameters and their values can be taken from data base.

Sampling inspections should be done, if interacting effects occur, in order to determine whether the lifetime law has changed.

6. RESULTS

Procedures for the extension of verification validities do not consider field failures and drift features with their causes [3]. The new approach, introduced in this paper, considers both field failures and drift features.

By the determination of lifetime parameters for different components and failure modes, it is possible to analyse the failure behaviour in a more efficient way. Weak points can be eliminated by appropriate methods (installation of redundancies, reliability stress screening to avoidance of early failures or installation components with higher reliabilities), if reliability-aims are not reached. By the application of accompany registration, qualitative and quantitative failures are detectable for the lifetime prediction.

A combined procedure of various methods to estimate lifetime parameters improve the accuracy of the lifetime prediction. If several methods are available, they should be used, to receive appropriate verification validities.

The application of the morphological box modularizes the present approach. It allows the possibilities to fall back on well-known experiences of the failure behaviour in form of their lifetime parameters.

7. DISCUSSION AND FUTURE PROSPECT

A suitable possibility to estimate lifetime parameters is the accompanying registration. The utilization of the meters corresponds to the intended customs conditions. Therefore, there are no simulated test conditions used, contrary to the other methods, but the information, about the lifetime parameters, are available later.

For smart meters exists frequently not enough long-term experiences over its failure behaviour to make conclusive statements to reachable verifications of validity. This difficulty is compounded by the fact, that shorter innovation cycles and product varieties make it more problematic to find general statements over lifetime prediction of smart meter. The application of the TOP-DOWN-approach is helpful. Acquired knowledge about the failure behaviour of individual components or assemblies may be used for lifetime prediction. To hold the effort within economic reasonable limits it may be helpful to build cluster of appropriate lifetime parameters and/or – lifetime laws.

For mechanical components it is more difficulty to predict lifetime. They are subject frequently wear effects, so failure rate is not constant in time. But such symptoms of failure can be described with Weibull-analysis.

For Meters such as water meters, the measuring medium is a significant lifetime-reducing factor of influence and is partly subject to high regional differences in quality (water hardness). This accelerated impact of failure effects can be described by field tests. In addition, for example, meters of the same construction type have to be built in different water hardness ranges. On the assumption, that no further different factors of influence exists and the same interactions predominate, conclusions on the accelerating effect of this kind of failure effects can be made.

8. ACKNOWLEDGEMENT

The research work is the result of cooperation between Thuringian state authority of metrology and verification (LMET), Technical University of Ilmenau, PTB Braunschweig and Agentur für Messwertqualität und Innovation e. V (AMI e. V.). We thank them for the financial and expert knowledge support.

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