MODELLING OF NETWORK-COMPONENT-TECHNOLOGY CHANGES IN RELIABILITY-CENTERED MAINTENANCE PLANNING

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Abstract – A methodology for forecast of the influence of technology changes on reliability of electrical network components is presented. The approach in based on renewal theory. Component lifetime is modeled by lifetime distributions changing with time in dependence of technology development. Lifetime distributions are used for the computation of the renewal density function delivering an image of the time series of component outage frequency. A risk function is constructed by combination of renewal density with maintenance- and societal outage costs. Risk function serves as object function for maintenance optimization. Feasibility of the methodology is demonstrated by case studies performed with real-life data.

Keywords: Asset management, Maintenance planning, Reliability, Renewal processes, Risk assessment.

1 INTRODUCTION

Network companies underlie increasing pressure to reduce operation cost by simplification of facility and network structure, by reduction of maintenance frequency and by higher exploitation of network components. As a consequence, within next few years reduction of supply reliability to a degree visible by consumers has to be expected. To prevent a degradation of the network as well as to justify investments in the presence of regulation authorities, methods of reliability-centered maintenance planning become important tools for future assessment of the reliability of supply.

In literature different approaches to deal with this topic can be found. In [1] computation of a weighted list of facility importance forms the basis for maintenance activity planning. By inclusion of information on component health-state this concept allows for a combination of importance- and condition-based maintenance planning methodologies [2]. These approaches do not necessarily require reliability calculations, since importance-screening can be based on network structure and consumer data.

However, for the assessment of the influence of suspended maintenance on future system reliability the interaction between maintenance intensity and outage frequency has to be modeled in a realistic way.

Models of that type are presented in [3], [4] and [5]. In [3] outage rate is formulated as a combination of a constant and a time-dependent part, the second one representing aging. The authors of [4] and [5] propose Markov models with operation states for different levels of wear-out. Maintenance is taken into account by maintenance states and maintenance rates which form links between operation and maintenance states.

Instead of modifying outage rate, maintenance can be simulated by appropriate modifications of lifetime distribution [6], [7]. The same type of approach is applied in this paper. The method is based on renewal theory applicable to network-component lifetime distributions of deliberate shape. A recursive procedure processing lifetime distributions delivers the time series of renewal density function which serves as an image of outage frequency. The effect of future technology development is taken into account by changing lifetime distributions during observation period.

The combination of renewal density with event-based societal outage costs results in a risk function applied to forecast the costs of component outages during the simulation period. Event-based outage costs can be evaluated by conventional reliability computations. Effects of maintenance are introduced as additional parameter into the renewal and risk function. The sum of risk- and maintenance-cost-function constitutes the object function for maintenance planning. Minimization is performed by variation of maintenance intensity. Maintenance measures taken into account are: preventive maintenance performed to increase lifetime and exchange of worn out components.

Feasibility of the presented concepts will be demonstrated by processing real-life data for wood poles of a 20-kV- network.

2 FORMULATION OF RENEWAL DENSITY FUNCTION

Assuming that repair times are much smaller than operation times, outage and succeeding renewal can be treated as one related event.

Renewal density is the statistical expectation of the number of renewals (outages) per time interval dt [7]. Under the assumption that lifetime density f(t) remains unchanged during time period t, renewal density r(t) can be computed by the recursive equation (1) which is valid for discrete time steps dt = 1 year [7].

$$r(t) = f(t) + \sum_{\tau=0}^{t} r(t - \tau).f(\tau) \qquad (1)$$

Improvement of technology manifests itself by an increase of lifetime expectation expressed by an appropriate lifetime density. If in a certain year j components with new technology are put into operation, lifetime density f(j,t) of these components will be different from the lifetime density of components put into operation in the year before j; lifetime density for year j-1 is designated as f(j-1,t) in (2).

$$f(j-1,t) \neq f(j,t) \qquad (2)$$

With this formulation the generalized equation of renewal density is given by (3).

$$r(t) = f(0,t) + \sum_{\tau=0}^{t} r(t - \tau).f(t-\tau,\tau) \qquad (3)$$

Equation (3) is valid for condition f(0,0)=0. A more general expression is presented in [8]. A formulation with repair times being taken into account is presented in [8], too.

Successive commencement of component operation is taken into account by the "operation-commencement" function e(t) defined for an operation period tb. As soon as the end of tb is reached no new locations for additional components are established. Instead, failed components are replaced at their existing locations. Function e(t) is of the type of a statistical density function. Thus, condition (4) holds.

$$\sum_{t=0}^{tb} e(t) = 1 \qquad (4)$$

Combination of e(t) with the renewal density (3) leads to a new formulation [8]:

$$r(t) = \sum_{\tau=0}^{t} f(t-\tau,\tau).re(t - \tau) \qquad (5)$$

with

$$re(t) = e(t) + \sum_{\tau=0}^{t} f(t-\tau,\tau).re(t - \tau) \qquad (6)$$

r(t) and re(t) are linked together by (7) [8].

$$re(t) = r(t) + e(t) \qquad (7)$$

Thus, re(t) is a renewal density like r(t). However, in re(t) not only outages but also commencement of operation are taken into account.

3 AGE DENSITY FUNCTION

The age density function fa(t,τ) is a measure for the percentage of components that have reached the age τ at time instant t [8]. This percentage is related to the sample number of observed components. Mathematically, age density at time instant t can be formulated as the product of the survival-probability for time span τ and the number of renewals during the foregoing time t-τ. Survival-probability R(τ) is expressed by the lifetime distribution F(τ):

$$R(\tau) = 1 - F(t-\tau,\tau) = 1 - \sum_{j=0}^{\tau} f(t-\tau,j) \qquad (8)$$

Combination of (7) and (8) yields the equation for the age density function (9).

$$fa(t,\tau) = (1 - F(t-\tau,\tau)).re(t-\tau), \quad 0 <= \tau <= t \qquad (9)$$

4 RENEWAL DENSITIES FOR RENEWAL EVENTS OF DIFFERENT TYPE

The following events leading to component renewal will be considered:

- Severe faults caused by aging processes which cannot be influenced by maintenance (irreversible aging).
- Severe faults caused by aging processes which can be slowed down by maintenance (reversible aging).
- Exchange when a predefined operation period has been reached.

All these events lead to substitution of failed components by new ones. Other less severe events which can be cleared by repair can be taken into account in a similar way like the faults mentioned above [8].

Each event type is represented by a special lifetime distribution. Since aging processes are proceeding in parallel, survival time is given by the minimum of the survival times due to the parallel processes. Thus, probability of survival is governed by the product rule. Keeping in mind that survival probabilities are expressions of the type [1 - F(t)], the combined lifetime distribution can be formulated by (10).

$$F(t) = 1 - [1 - F_{Ln}(t)][1 - F_{Lr}(t)])][1 - F_{Ex}(t)] \qquad (10)$$

$F_{Ln}(t)$, $F_{Lr}(t)$, are the lifetime distributions for irreversible and reversible aging, $F_{Ex}(t)$ is the exchange function.

Differentiation of F(t) results in the combined lifetime density function (11) which can be separated into the terms (12) and (13).

$$f(t) = f_l(t) + f_{ex}(t) \qquad (11)$$

$$f_l(t) = f_{Ln}(t).[1 - F_{Lr}(t-1)].[1 - F_{Ex}(t-1)] + \\ + f_{Lr}(t).[1 - F_{Ln}(t)].[1 - F_{Ex}(t-1)] \qquad (12)$$

$$f_{ex}(t) = f_{Ex}(t).(1 - F_{Ln}(t)).(1 - F_{Lr}(t)) \quad (13)$$

$f_{Ln}(t)$, $f_{Lr}(t)$, $f_{Ex}(t)$ are the densities belonging to $F_{Ln}(t)$, $F_{Lr}(t)$ and $F_{Ex}(t)$. As a consequence of discreteness of time-axis, shifts by one time unit dt=1 have to be performed in (12). Expressions (12) and (13) are valid for t>0, expressions for t=0 can be found in [8]. In the special case when exchange is strictly performed at a predefined component age the exchange function is modeled by a step function and the exchange density by an impulse function with time delay being equal to the time instant of exchange.

Substitution of (11) into (5) results in renewal density-expressions for the events described above:

Outage (end of life):

$$r_l(t) = \sum_{\tau=0}^{t} f_l(t-\tau,\tau).re(t - \tau) \quad (14)$$

Exchange:

$$r_{ex}(t) = \sum_{\tau=0}^{t} f_{ex}(t-\tau,\tau).re(t - \tau) \quad (15)$$

5 MAINTENANCE MODELS

The maintenance model presented in [7] was based on the assumption that maintenance times are of deterministic nature and that the system can be fully restored to its initial condition (perfect maintenance). For the simulation of imperfect maintenance the model of [7] was modified by introduction of the time-shift parameter tv by which the density function is shifted towards the left after each maintenance action, see Fig. 1.

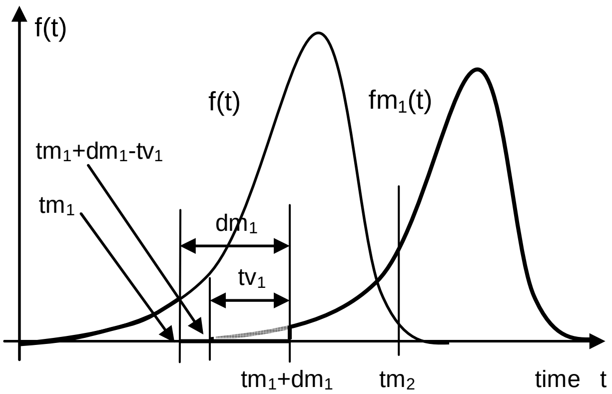

Figure 1: Lifetime density function for one maintenance action, imperfect maintenance

By that way immediately after having finished maintenance, (time-dependent) outage probability starts with values greater than 0 thus representing a degradation residue which cannot be eliminated by maintenance. In the figure tm and dm are maintenance time and maintenance duration respectively. If the degradation parameter tv is smaller than the maintenance interval (tm_i - tm_{i-1}), then maintenance results in an increase of lifetime expectation, otherwise lifetime expectation is decreased. If tv is equal to the maintenance interval, maintenance has no effect. To relieve the effect of deterministic maintenance intervals and to introduce an additional stochastic aspect into the model, inspection can be taken into account. The concept is described in more detail in [9].

6 OUTAGE AND MAINTENANCE COST FUNCTIONS

6.1 Total cost

Total cost Ct(t) is the sum of outage cost O(t), maintenance cost M(t) and exchange cost E(t).

$$Ct(t) = O(t) + M(t) + E(t) \quad (16)$$

Cost expressions given in the following paragraphs are related to one single component. To evaluate cost for a sample of similar components, results have to be multiplied by the number of sample members.

6.2 Outage cost, risk index

Costs of component outages are given by the product of outage frequency with the sum of repair costs and event-based societal outage costs. Representing outage frequency by renewal density [7], outage costs per component for a time interval of 1 year at time instant t can be formulated by (17). This expression can be interpreted as risk index.

$$O(t) = (s(t) + b(t)).r_l(t) \quad (17)$$

s(t) Mean value of societal costs caused by one single outage of a component belonging to a collective of members with similar attributes.

b(t) Repair cost. In the case of life end: Cost of component replacement

Event-based outage costs are evaluated by reliability computations of the observed system. Because of network structure and network technology changes which occur during the observation period, s(t) is dependent on time.

6.3 Maintenance cost

For a certain component, maintenance is performed as soon as it has reached the age for which maintenance activities have been assigned by the actual maintenance concept. The mathematical formulation of the maintenance concept is given by the time series of maintenance cost wk(t,τ). E.g., if a component was put into operation in year t and maintenance has to be performed every τ=5 years then wk(t,τ) consists of cost values-per-maintenance in distances of 5 years whereas positions between these time intervals are occupied by zero values. Component age is represented by the age-density function $fa(t,\tau)$ which is a measure for the percentage of components that have reached the age τ at time instant t, see chapter 3. Taking these remarks into account, maintenance cost for components with age τ at time instant t is the product of $fa(t,\tau)$ and $wk(t-\tau,\tau)$. Maintenance cost for the entire component age spectrum is given by the cost sum (18) expanded over all possible component ages.

$$M(t) = \sum_{\tau=0}^{\tau_{max}} fa(t,\tau).wk(t-\tau,\tau) \quad (18)$$

τ_{max} Maximum reachable component age

6.4 Exchange cost

Exchange cost E(t) is the product of the exchange part of the renewal density (15) with cost per component exchange ep(t):

$$E(t) = ep(t).r_{ex}(t) \quad (19)$$

6.5 Minimization of total cost

Since lifetime densities are formulated as functions of maintenance- and exchange- interval, maintenance intensity becomes an independent parameter of renewal density and outage cost respectively. Thus, total cost minimum can be found by variation of maintenance and exchange intervals.

7 ASYMPTOTIC BEHAVIOR OF RENEWAL DENSITY AND COST FUNCTIONS

Asymptotic values of renewal densities are of special interest for cost minimization applications. For a large observation period ($t \to \infty$) and an extensive class of life time distributions, renewal density (1) converges to an asymptotical value which is given by [7]:

$$r(\infty) = 1/E(tl) \quad (20)$$

with lifetime expectation

$$E(tl) = \int_0^{\infty} t.f(t).dt \quad (21)$$

Equation (20) is also representing the outage frequency for general renewal processes. This equivalence was used for derivation of (17).

For derivation of the asymptotic value of the generalized renewal density function (3) the assumption has to be made that changes of lifetime distribution occur within a finite time period. Thus, for $t \to \infty$ changes of lifetime distribution become irrelevant for the asymptotic behavior and (20) can be applied to the generalized renewal density, too. A similar consideration performed in context with the operation-commencement function e(t) which is defined within the finite time interval 0 to tb, leads to the result that (20) is also applicable to renewal density functions of type (5).

A modification of (20) is necessary if renewal density has to be split up into portions according to (11). It could be shown in [8] that the asymptotic value of (14) is given by:

$$r_l(\infty) = F_l(\infty)/E(tl) \quad (22)$$

with

$$F_l(\infty) = \int_0^{\infty} f_l(t).dt < 1 \quad (23)$$

The asymptotic renewal density for exchange can be evaluated by an equivalent formula.

Cost functions converge to finite values only in the case that finite values do exist for the specific costs s(t), b(t), ep(t) and $wk(t,\tau)$. Under these assumptions asymptotic behavior of costs can be expressed by formulae (16) and (17) omitting time parameter t in specific cost terms and substituting renewal densities by asymptotic formulations like (22).

Asymptotic maintenance cost is given by [8]:

$$w(\infty) = \sum_{\tau=0}^{\tau_{max}} fa(\tau).wk(\tau) \quad (24)$$

with

$$fa(\tau) = (1 - F(\tau))/E(tl) \quad (25)$$

For computations presented in this paper, asymptotic values of specific costs were set equal to present-time cost values.

8 RESULTS

8.1 Influence of technology changes on renewal density and age density function

Technology changes are modeled by modifying lifetime expectations at a certain time instant of the observation period. To demonstrate convergence of renewal densities towards their asymptotical values, simulation is performed for a large observation period of 70 years. During this period one single technology change takes place.

For demonstration purposes synthetic densities with shapes similar to a normal distribution are used. Parameters of these densities are given below.

Base case lifetime density parameters (E(T): expectation, σ: standard deviation):

Irreversible aging: E(T)=45 years, σ=6 years.

Reversible aging: E(T)=14 years, σ=6 years.

Effect of technology changes are demonstrated by performing the following density-parameter modifications:

Case 35/10: Irreversible aging: E(T)=35 years, reversible aging: E(T)=10 years (deterioration)

Case 65/20: Irreversible aging: E(T)=65 years, reversible aging: E(T)=20 years (improvement)
Case 75/25: Irreversible aging: E(T)=75 years, reversible aging: E(T)=25 years (improvement)

For all cases standard deviations of σ =6 years are used. Simulations are performed for technology change time instants (Tv) of 10, 20 and 30 years. In the base case, lifetime densities remain unchanged during the entire observation period.

In Fig. 2 and 3 the effects of technology changes according to the cases described above are demonstrated for a fixed time Tv=20 years. No preventive- maintenance activities are simulated.

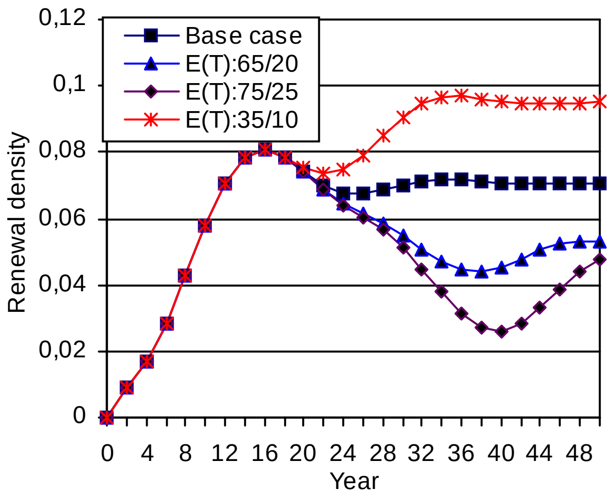

Figure 2: Renewal densities; technology change at year No. 20.

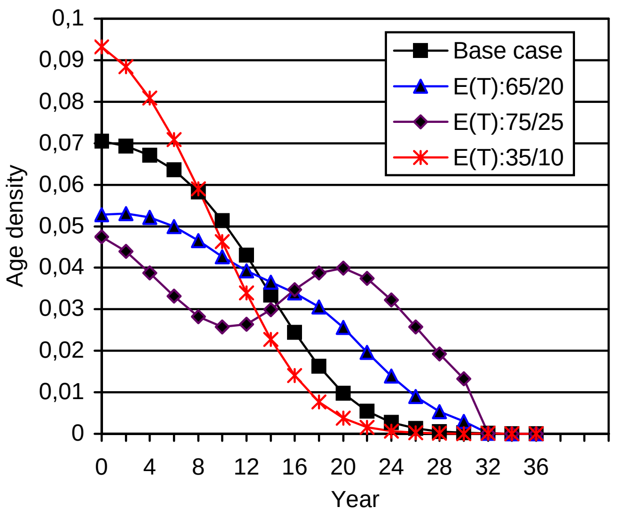

Figure 3: Age densities; technology change at year No. 20.

It can be observed in Fig. 2 that the renewal densities split up as soon Tv has been passed and begin to progress by different time series. For a large time horizon the curves approach to different time-invariant values. Renewal densities of cases with larger lifetime expectations tend to lower asymptotic values. According to (17) financial expenses for component renewal are proportional to renewal densities. Thus, gains which can be reached by technology improvement can be evaluated and compared using the results of Fig. 2.

Age density serves as an indicator for the exploitation time increase gained by technology improvements. It is demonstrated by Fig. 3 that technology improvements lead to a shift of "mass" represented by the age density function towards larger age values.

In Fig. 4 the effects of preventive maintenance are illustrated. Maintenance takes place in intervals of 10 years. Additionally, function e(t) is taken into account. It spreads component operation-commencements equally distributed over a time period of 10 years. It can be observed in Fig. 1 that maintenance activities introduce a peak into lifetime density at each maintenance time. These peaks are responsible for the wave- shapes of the curves of Fig. 4.

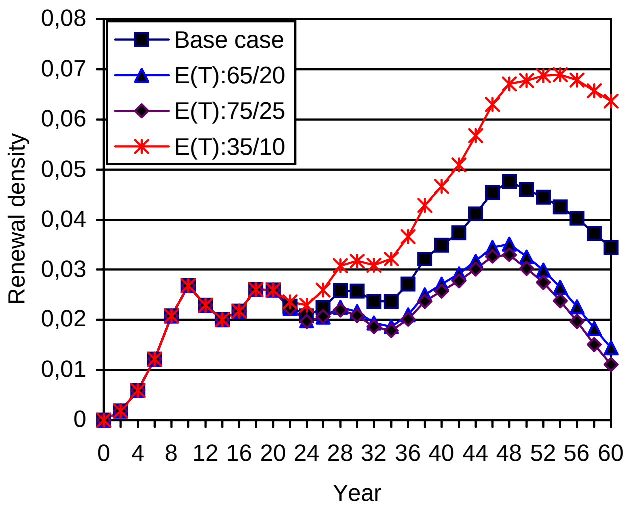

Figure 4: Renewal densities with maintenance effects; technology change at year No. 20.

As a result of maintenance activities, renewal densities tend towards lower asymptotic values thus indicating increase of lifetime expectations, compare Fig. 4 and 2. In this test case, 4 maintenance actions are performed during the first 40 years of component lifetime. After that time lifetime density progresses according to its "natural" shape. The consequence of this modeling feature is a distinct increase of renewal densities after year No. 40.

In reality, maintenance of 20-kV network components like wood poles would rather not lead to such a large increase of lifetime as reached in this test case. Thus, for practical application purposes a more careful adaptation of maintenance-model parameters would be necessary.

In Fig. 5 results of variations of technology change time Tv for lifetime densities of type E(T) = 60/20 are illustrated and compared to base case results. The renewal densities for E(T) = 60/20 converge to the same asymptotic value irrespective of time Tv, which is a consequence of the statements of chapter 7. Convergence speed of renewal density is dependent on the time of technology change. Lower Tv values lead to faster convergence.

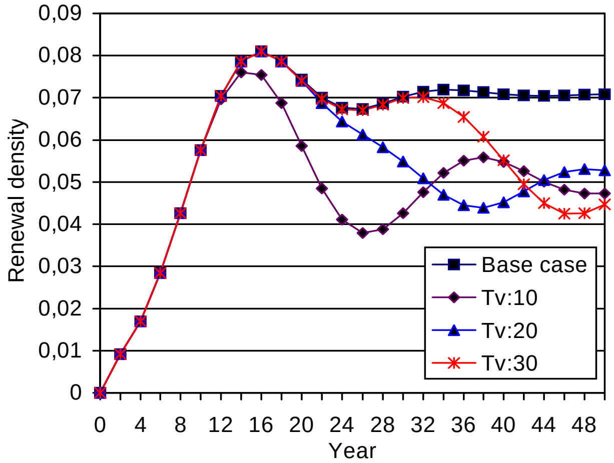

Figure 5: Renewal densities; technology change at different time instants Tv.

8.2 Examples for maintenance optimization

8.2.1 Wood-poles

A sample of 13600 20-kV-wood poles constitutes the basis for the evaluations. Parameters of the lifetime density function were evaluated by application of a parameter estimation procedure with the lifetime histogram used as input data for the estimation software. The resulting density is a normal distribution with an expectation of 26 years and a standard deviation of 9.9 years [10].

Since the raw data material did not contain any information about the reasons for which components were taken out of operation it is not possible to distinguish between internal effects (aging) and external influences (e.g. adverse weather, security considerations). In addition, the effects of maintenance are included in the density function. Thus, by applying maintenance models, maintenance will be taken into account twice, implicitly by the original density function and explicitly by the maintenance model. Consequently, the presented results are applicable for demonstration but not for planning purposes.

For simulation of irreversible aging a second lifetime distribution is used. With reference to [6] it is formulated as normal distribution with an expectation of 50 years and a standard deviation of 11 years. The ratio of event based societal outage costs, component replacement/exchange costs and maintenance costs amounts to 8.8 : 2 : 0.2.

In Fig. 6 the development of cost units per component and year with respect to variation of maintenance intervals is shown. Components are exchanged after a lifetime of 42 years irrespective of their health-condition. While maintenance costs decrease with increasing maintenance intervals, outage costs increase due to decrease of lifetime expectation. Total cost function reaches a minimum at maintenance intervals of 5 years. Exchange costs reduce slightly with increasing outage costs since in the case of large outage frequencies only a small number of components reach the age specified for exchange.

In Fig. 7 total costs for variable exchange intervals and different lifetime expectations E(T) are shown. No preventive maintenance is simulated in this case. The unrealistic low optimal exchange interval of 20 years for the base case with lifetime expectation of 26 years indicates that lifetime expectation is evidently too low. Possible reasons for the incorrect estimate were already discussed at the beginning of the chapter. Lifetime expectations in the region between 30 and 40 years seem to be more realistic estimates.

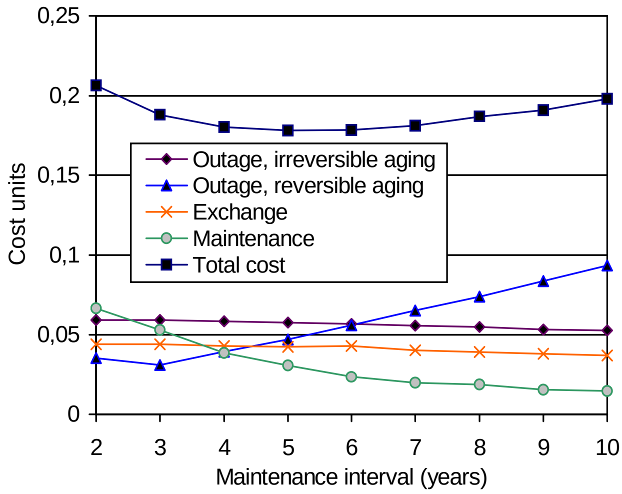

Figure 6: Societal outage costs and maintenance costs per year, variation of maintenance intervals

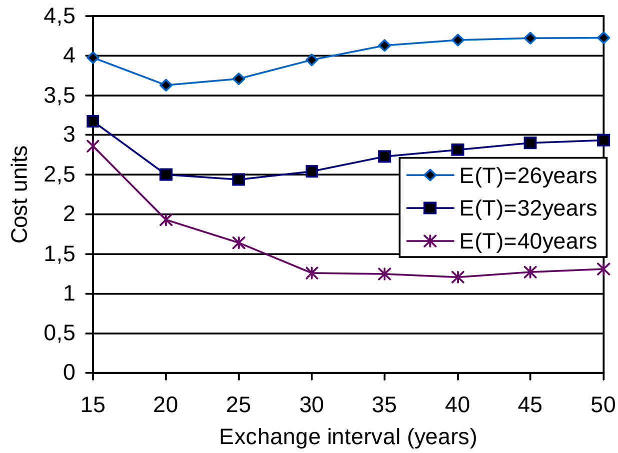

Figure 7: Total costs per year, variation of exchange intervals

8.2.2 Line sections

Parameter estimations performed for a sample of 20-kV line sections with a mean length of approximately 0.5km resulted in a normal distributed "lifetime" density with a rather low expectation of 27.6 years and a standard deviation of 8.5 years [10]. Due to similarity of this density with that of wood poles, maintenance-optimization procedures deliver qualitatively similar results [11].

9 CONCLUSIONS

The influence of technology changes on reliability of electrical network components and on maintenance costs can be evaluated by a method based on generalized renewal theory. The output of this methodology is a total-cost function consisting of an outage- (risk-) cost and a maintenance cost term. This function serves as object function for maintenance planning. Important input parameters are component lifetime distributions. Technology changes are taken into account by appropriate modification of the parameters of lifetime distributions. For simulation of technology improvement, parameter "lifetime expectation" is increased. Maintenance is taken into account by modification of the shape of the lifetime distribution.

Case studies were performed for samples of 20-kV wood poles. It could be demonstrated that substitution of failed components by new ones with improved technology can lead to considerable total-cost reductions. Reduction of exploitation time by substituting healthy components by new ones with improved technology will be profitable only in the case when a distinct reduction of operation cost can be reached by this measure. The time of introduction of new technology is only relevant for short- or medium-term planning.

Cost functions converge during a large observation period to time-invariant asymptotic values which can be computed without the need of performing time consuming simulations. Asymptotic indices are especially useful for purposes of cost optimization by variation of maintenance intensity.

It could be demonstrated that reduction of total cost is possible by optimization of preventive-maintenance as well as exchange intervals. However, a distinct optimization gain can be reached only if the ratio of outage cost to maintenance cost is large. This is the case when societal outage costs are used for the valuation of outage effects. The position of the optimum is sensible with respect to component lifetime expectation. Thus, before applying the presented methods special attention has to be focused on correct estimation of lifetime distribution parameters.

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