STATISTICAL METHODS AND MODELS WITH ANALYSIS OF SUITABILITY FOR PREDICTION OF THE END OF LIFE OF EQUIPMENT

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Outline of the presentation

- Review of most common statistical and analytical methods for analysis of failure data and calculation of the remaining life of equipment
- Demonstration of a simple, Excel-based tool to perform such analysis

Statistical methods can be divided into two categories

- Methods based on the analysis of historical data
  - Weibull analysis,
  - Lognormal analysis,
  - Kaplan-Meier survival estimation,
  - Life-table method,
  - Crow-AMSAA-Duane reliability growth method
- Mathematical models
  - FEMA and Fault Trees
  - Markov Models
  - Life curve and failure rate trending

Preliminaries

- Lifetime of electrical equipment
  - Physical lifetime - preventive maintenance can prolong physical lifetime by slowing deterioration
  - Technical lifetime - usually when spare parts are no longer available
  - Economic lifetime – either capital depreciation to zero value or operating and maintenance costs become excessive.

Estimating remaining life – different approaches

- **Based on constant monitoring of the deterioration state of equipment.**
  - In principle, this allows to justify maintenance / replacement decisions by knowledge of the real state of equipment.
  - However, Some pieces of equipment simply cannot be monitored. For instance, it is almost impossible to monitor the aging process of an underground cable since sampling a section of cable cannot represent the status of the whole cable. For a power transformer, although oil sampling can be performed to partially monitor the status of its condition, there are many other mechanisms of transformer deterioration that are normally not monitored.

Estimating remaining life – different approaches

- **Based on estimation of mean remaining life of equipment**
  - Using this idea, some utilities have developed a common practice to set a retirement age at around the estimated mean life of equipment.
  - The problem for this policy is the fact that any specific piece of equipment may die before or after the specified retirement age. If it can survive longer, its early retirement will result in a waste of capital.

Estimating remaining life – different approaches

- **Based on probabilistic analysis for making decisions about retirement of aged equipment**
  - The basic idea is to quantify the expected system risk cost and capital savings due to delaying the retirement of aged equipment
  - The approach uses probability distribution to obtain the probability of equipment end-of-life failure.

The probability of equipment end-of-life failure

- Available data can be used to obtain “life” probability distribution.
- Depending on how historical data was collected regarding equipment performance, lifetime data used for estimation of equipment reliability measures can be *complete* or *censored*.
- Two methods can be used: (1) parametric (one of the standard distributions is used), and (2) nonparametric (no assumption on the life distribution is used.

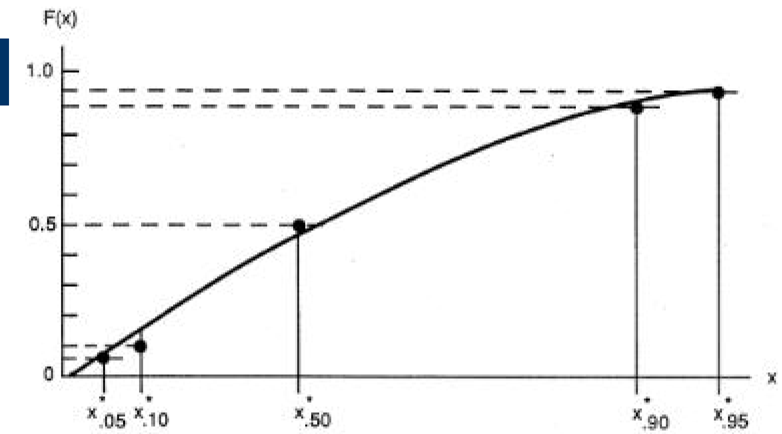
Random variables and probability distributions

- Using the language of the theory of probability, times to failure observed for some pieces of equipment will be considered a *sample* from a *random variable* representing time to failure
- The fundamental property of a random variable is its distribution, which describes probabilistic behavior of a random variable (i.e., specifies probabilities of the random variable for each of its possible value / outcome).

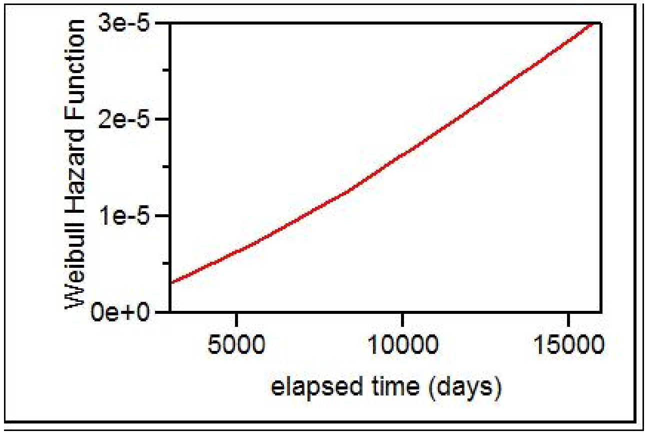
Representation of a random variable

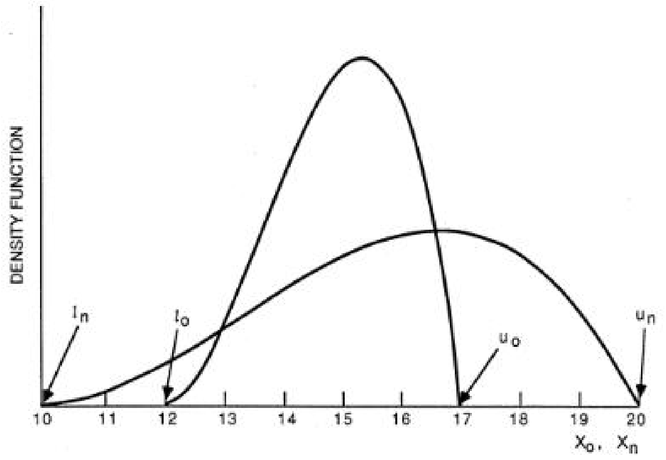
- Random variable distribution can be expressed using one of the following equivalent concepts:

Cumulative Distribution Function (CDF)



Hazard function





Density Function (PDF)

Parametric analysis – three most common distributions

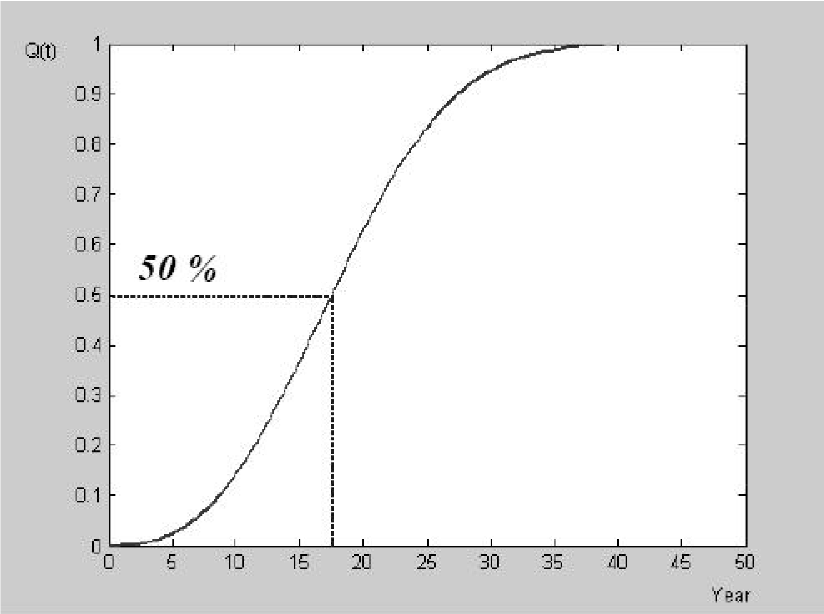
Weibull

$$F(t) = 1 - \exp\left[-\left(\frac{t - t_0}{\eta}\right)^{\beta}\right]$$

$$h(t) = \frac{\beta}{\eta}\left(\frac{t - t_0}{\eta}\right)^{\beta - 1}$$

Lognormal

$$f(t) = \frac{1}{t\sigma\sqrt{2\pi}} \exp\left(-\frac{(\log t - \mu)^2}{2\sigma^2}\right)$$



Exponential

$$f(t) = \lambda e^{-\lambda t}$$

Demonstration of an Excel-based tool for the estimation of parameters of the distributions

Nonparametric methods of estimation of a survival function $S(t) = 1 - F(t)$

- Kaplan-Meier survival estimation
  - This method (also known as product-limit method) produces an estimate of the survival function based on complete or censored data

$$\hat{S}(t_i) = \prod_{j=1}^{i}\left(1 - \frac{d_j}{n_j}\right)$$

- Life Table Method
  - the method allows to estimate survival, probability density and failure rate functions from complete or censored data

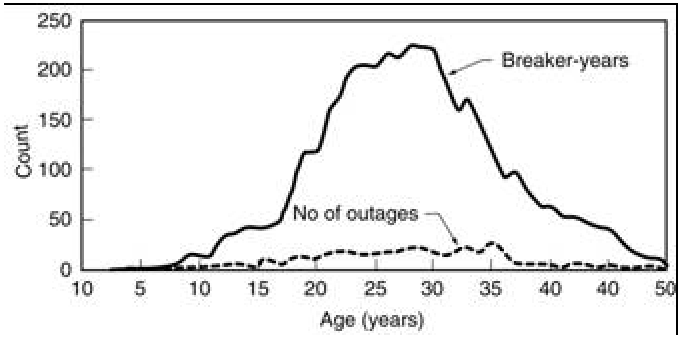
$$\hat{S}(t_i) = \begin{cases} 1 & i = 0 \\ \hat{S}(t_{i-1})\hat{p}_{i-1} & i > 0 \end{cases}$$

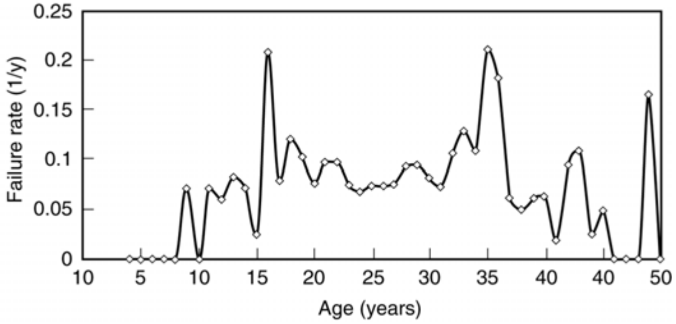
$$\hat{h}(t_{mi}) = \frac{2\hat{q}_i}{b_i(1 + \hat{p}_i)}$$

Demonstration of an Excel-based tool for the estimation of creation of survival functions using nonparametric methods

Analytical methods-Examples

- Deterministic methods
  - The most common approach to the analysis of the life of the equipment that does not involve explicit probability concepts is based on the evaluation of the trends in the equipment failure rate.



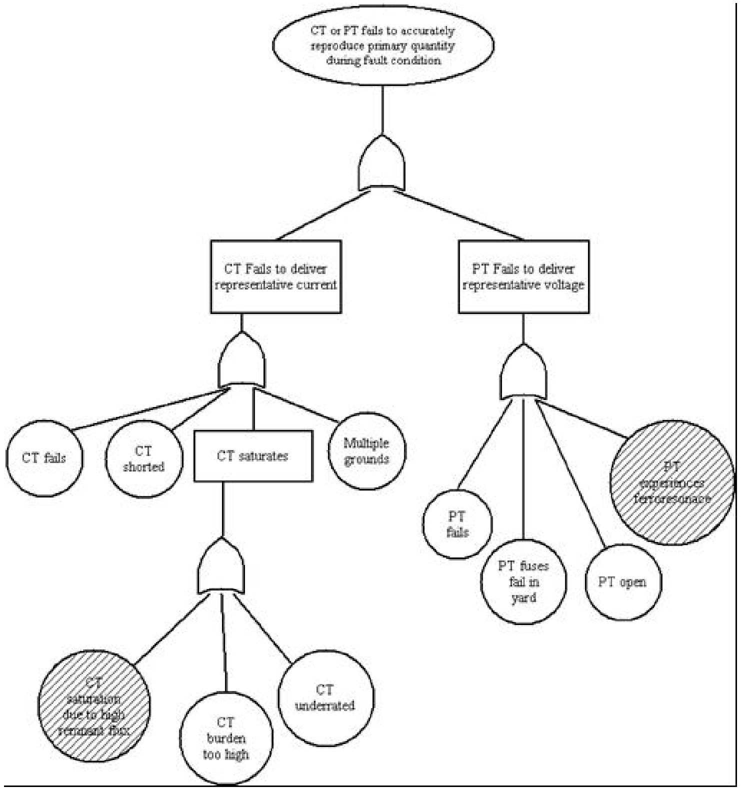


$$\lambda_t(c) = \frac{\sum_y n_{t,y}(c)}{\sum_y N_{t,y}(c)}$$

Each sum is for years y=1 to k

Analytical methods-Examples

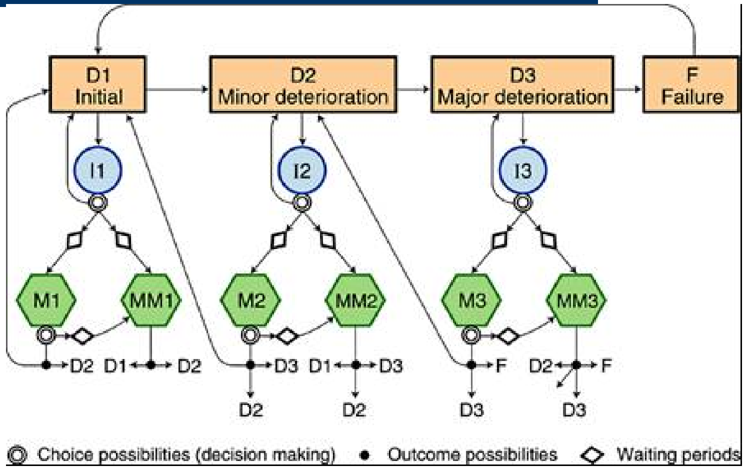
- Fault trees
  - Fault Tree Analysis (FTA) is one of the most important logic and probabilistic techniques used in the Probabilistic Risk Assessment (PRA) and system reliability assessment today
  - It is used to compute a probability of a top event

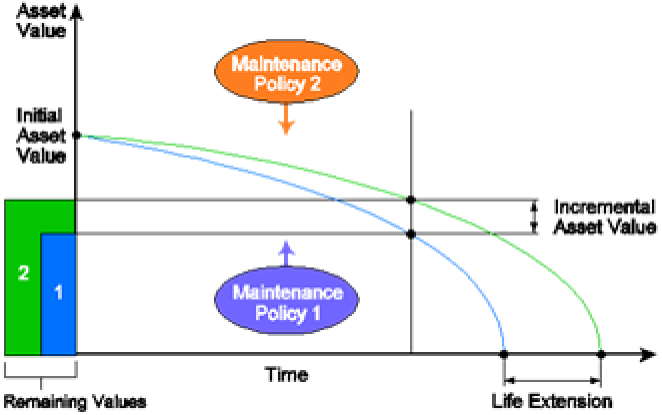


Example of a fault tree for an instrument transformer block for a protection system

Analytical methods-Examples

- Markov models
  - Markov models are a special type of stochastic processes.
  - approach can be used to solve a problem of estimation of hazard rate of equipment.
  - This approach is based on a model of equipment deterioration over time
  - Can be used to produce “life curves”





Summary

- Several techniques are available to perform "end of life" analysis. The most common are:
  - *Classical Weibull analysis*.
  - *Classical lognormal analysis*
  - *Kaplan-Meier Survival Estimation*
  - *Life-table method*
  - *Crow-AMSAA-Duane reliability growth method*
  - *Markov model for life estimation*
  - *Life curve and failure rate trend curves*

Summary

- When data is available the standard procedures can be used to estimate the equipment/system life.
- When data is not readily available, or when additional information is required, analytical methods such as Fault Tree Analysis or Markov models can be used.

Summary

- Some of these methods can be used to obtain a more realistic (then sample mean) estimate of mean expected life of equipment (since censored observations are used for estimation of life expectancy).
- End of life can be estimated from fitted survival or hazard functions.
- **Parametric models cannot be used if observed failure data does not follow specific distribution** (however, the Weibull assumption often proves valid for the failure data of technical equipment).

Summary

- The procedures are well amenable to a simple Excel-based development. There are commercial programs for each type of calculations but they are quite expensive and often difficult to use.
- The presentation demonstrated that is is possible to construct a very simple to use tool that will simultaneously perform all types of parametric and nonparametric analyses.

Thank you for your attention

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