Engineering Asset Management – a Foundation for Sustainable Development

Proceedings of the 3rd World Congress on Engineering Asset Management and Intelligent Maintenance Systems Conference

(WCEAM-IMS 2008)

27 – 30 October 2008
Beijing International Convention Center, Beijing, China

Editors
Gao Jinji, Jay Lee, Jun Ni, Lin Ma and Joseph Mathew

Published by

Springer-Verlag London Ltd

PAPER SEARCH

PRODUCT RELIABILITY AND AVAILABILITY IN FIELD DATA

Nevavuori L

Service Development, KONE Corporation, Myllykatu 3, Hyvinkää 05801, Finland

KONE is one of the world's leading elevator and escalator companies. It provides customers with industry-leading elevators and escalators and innovative solutions for maintenance and modernization. KONE was established 1910 in Finland. Currently the company has approximately 32,500 employees.

Demands for the dependability have risen in the elevator industry during the recent years. The aim of the paper is to introduce a case study that was performed by KONE's reliability and maintenance departments in the beginning of year 2007. The case is about products' perceived dependability follow-up. Moreover, a target is to present how reliability data was collected as well as utilized in reliability centered maintenance planning. In this case the starting point for a dependability follow-up was the back reported field data from maintenance actions.

One of the main objectives of the case was to construct a new method for modeling the lifetime of a component based on the failure data. In the first phase of the case study, a reliability function was modeled for the studied component by utilizing the Kaplan-Meier estimation method. Both complete and censored lifetime observations were exploited. In the second phase, the cost factors of corrective and preventive maintenance were evaluated. Then, by utilizing the modeled reliability function and simulation software the most suitable maintenance strategy for the component was optimized.

The paper summarizes the experiences collected from the methods of the case study. As the second conclusion, requirements and advantages for a systematic dependability follow-up process are outlined. It is generally clarified which are the main challenges to utilize field data, and how back reporting procedures and follow-up tools can be developed in the industry.

Key Words: Field data, Reliability engineering, RCM

1 INTRODUCTION

Customers expect reliable products. The reputation of a company can be lost in a short time, if a product fails dramatically. KONE has researched reliability many years as a part of product development and adopted several methods to increase the degree of durability of products. However, the designed reliability of elevators is not the only factor relating to finally perceived dependability. Also manufacturing, transportation, installation, and maintenance as well as operational environment have effects on dependability [1]. To understand previous effects a large number of different field data studies were performed for MonoSpace elevators, the one of KONE's global volume products. The first release of MonoSpace was introduced in 1996. It was the world's first affordable and efficient "machine-room-less" elevator concept. It is operated by a disc-shaped KONE EcoDisc™ hoisting machine which fits inside a standard elevator hoist way.

The performed field data analyses have identified that elevator cabin lighting failure is one of the most frequently reported call-out root cause in MonoSpace elevators. A term call-out is defined by: "Any request for an intervention coming from a customer or a remote monitoring system, which triggers a repair visit to equipment by a service technician". KONE aims to

minimize call-outs by performing appropriate maintenance, which is an important financial issue, and increases customer satisfaction. This paper introduces a case study that aimed to find out the most suitable maintenance strategy for a certain type of elevator cabin lighting. A maintenance strategy was optimized based on the information that the reliability data provided.

2 DEPENDABILITY DATA HANDLING

2.1 Data Requirements

Reliability and maintenance engineering require several types of qualitative and quantitative data. Figure 1 illustrates needs for a dependability research. To understand the functions and requirements of a system, technical data is required for its every component. Technical characteristics are obtained usually from manufacturers, standards or handbooks. The date of manufacturing, installation and commission are important to define clearly the begin-point of a life. Maintenance and service data is important to determine system's dependability. Moreover, plenty of failure data is needed. Failure data should generally consist of failure modes, root causes, performed actions to correct the failure, and the time of the failure occurrence. Maintenance and repair actions should also include spare part data. Spare part information is for example the number of parts in the stock. [2; 3]

For dependability simulation, cost information is needed from all materials and functions related to the studied system. A failure always incurs direct and indirect expenses. Operational and environmental information is necessary to establish component and system models. It includes characteristics describing operational and environmental conditions. [3]
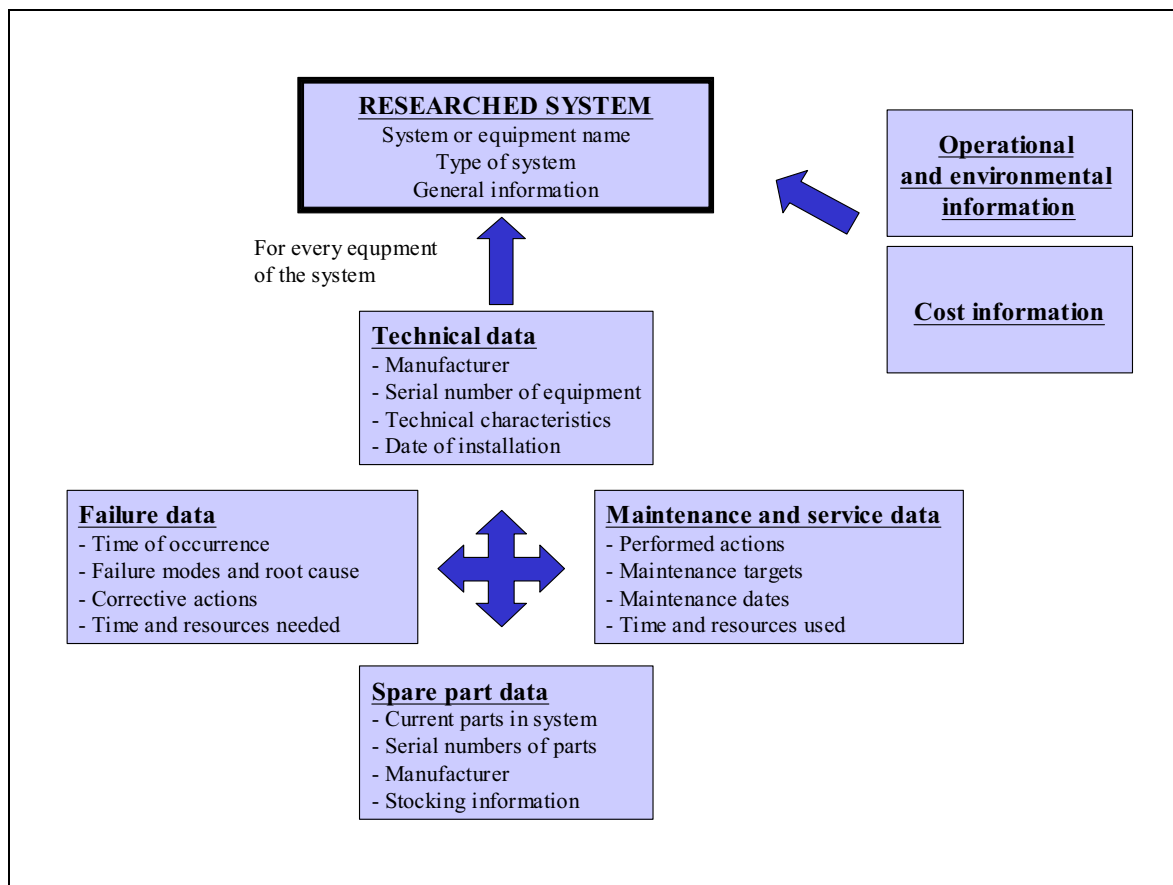

Figure 1. Required data for dependability studies.

2.2 Censored Data

Reliability data that contains uncertainty, which restricts ability to observe exact failure times, is termed censored data [4]. Censoring is typically related with field data. In many cases censoring causes considerable practical difficulties to reliability

tests and failure data analyses. There are three main types of censored field data: Right-censored, interval-censored, and left-censored. [3]

Concentration is now targeted to right-censored data that is utilized in the case study. Right-censored (suspended) data is the most common type of censored data. The origins of the lifetimes are known. Uncertainty arises because some of the items have not failed during the tracked analysis time. A right-censored data set is shown in Figure 2. There are five units on a field. Three of those have experienced failure events that are marked as black squares. The term right-censored can be used for the units 1 and 4. [2; 3; 4]
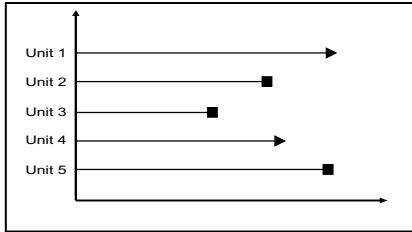

Figure 2. A right-censored data set.

2.3 Kaplan-Meier Estimation

Kaplan-Meier estimation procedure (K-M) provides quick and simple estimates of the statistical reliability distribution based on censored failure data. The method is normally unbiased. Suppose that a sample of units starts operating at time $t = 0$. Operating time is divided into m intervals $(t_{i-1}, t_i]$, where $i = 1,…,m$. An unit that does not fail in interval i is either censored at the end of interval i or it continues into interval $i+1$. [4]

Let d_i denote the number of units that failed in the interval $(t_{i-1}, t_i]$. In contrast, r_i denotes the units that survive interval i and are right-censored at t_i. The number of units that alive at the beginning of interval i is n:

$$n_i = n - \sum_{j=0}^{i-1} d_j - \sum_{j=0}^{i-1} r_j , \qquad\qquad i = 1,…, m. \tag{1}$$

where m is the number of intervals, Moreover, $d_0 = 0$ and $r_0 = 0$.

An estimator of the conditional probability of failure in interval i can be written:

$$p_i = \frac{d_i}{n_i}, \qquad\qquad i = 1,…, m \tag{2}$$

Furthermore, the estimator of the survival function is:

$$S(t_i) = \prod_{j=1}^{i} (1 - p_j), \qquad\qquad i = 1,…, m. \tag{3}$$

Finally, the corresponding non-parametric estimator of cumulative distribution function point $F(t_i)$ is:

$$F(t_i) = 1 - S(t_i), \qquad\qquad i = 1,…, m. \tag{4}$$

The K-M estimation is non-parametric method. More information can be found from the reference 4. A simple method to fit the statistical distribution to estimated points is introduced in the next chapter.

2.4 A Method to Estimate Parameters for Weibull Distribution

The Weibull distribution is a general-purpose reliability distribution model. By adjusting parameters it can be made to fit many life distributions of components or systems. Failure rate can be increasing, decreasing, or constant.

The probability density function of the two parameters Weibull distribution is written:

$$f(t) = \frac{\beta}{\sigma} \cdot \left(\frac{t}{\sigma}\right)^{\beta-1} \cdot \exp\left[-\left(\frac{t}{\sigma}\right)^{\beta}\right] \qquad \text{for } t \geq 0 \qquad (5)$$

where the shape parameter $\beta > 0$ and the scale parameter $\sigma > 0$. [5; 6]

Ahead is shown a simple estimation method of the Weibull distribution parameters. The fitting of distribution is done by the mean and standard deviation of the observations. Source values can be calculated from the observed data sample. The mean (MTTF) and standard deviation (*stdev*) of the Weibull distribution can be written [6]:

$$\text{MTTF} = \sigma \cdot \Gamma\left(1 + \frac{1}{\beta}\right) \qquad (6)$$

$$stdev = \sqrt{\sigma^2 \cdot \left[\Gamma\left(1 + \frac{2}{\beta}\right) - \Gamma\left(1 + \frac{1}{\beta}\right)^2\right]} \qquad (7)$$

where σ is the scale parameter and β is the shape parameter of the Weibull distribution. Γ is the gamma function that is defined:

$$\Gamma(a) = \int_0^\infty y^{a-1} e^{-y} dy \qquad \text{for } a > 0 \qquad (8)$$

By utilizing the functions (6), (7) and (8), the parameters σ and β can be solved. Hereby, this method can be used to calculate mathematical function for failure distribution.

3 PREVENTIVE COMPONENT REPLACEMENT OPTIMIZATION

Particular planning of preventive maintenance can reduce failures that are age related. According to reliability centered maintenance (RCM) methodologies, a preventive replacement interval might be found for components that have wear-out characteristics. The frequency of the scheduled component replacement is governed by the age at which the component shows a rapid increase in the conditional probability of failure. [7]

An economical dependence between corrective and preventive maintenance strategies can be seen in Figure 3. The horizontal axis represents preventive maintenance frequency and the vertical axis refers to maintenance costs. Corrective maintenance costs decrease if preventive replacements are performed more frequently. In an ideal case there can be found optimum area where total costs are minimal.[7]
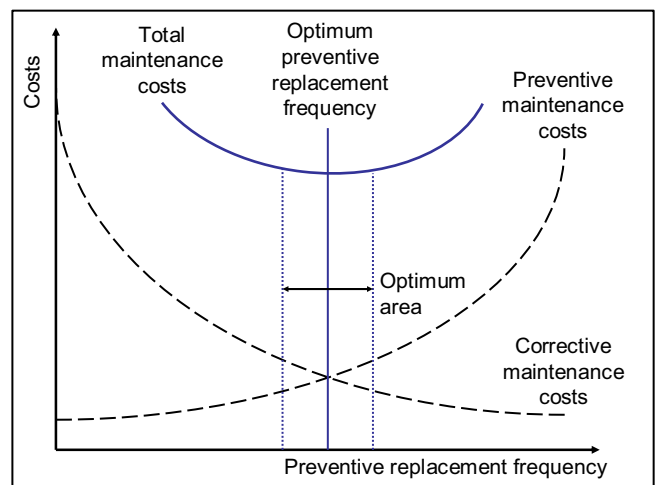

Figure 3. Principles of preventive replacement interval optimization.

4   ELEVATOR CASE STUDY

To optimize a preventive maintenance interval for the particular elevator cabin lighting, back reported field data was collected from two KONE frontline units. KONE supply line delivery data was utilized to define the group of 2000 MonoSpace elevators that had the identical cabin lighting. The followed elevators were installed from year 2004 to 2006. All call-outs occurred to those elevators were filtered out from the field data that was available from maintenance recording system. Then, compilation of statistics on the periods of time between commission date and possible first call-out date was performed. Similarly, time periods that elevators had been on field without call-out were also added to statistics. Hence, the statistical methods of censored data were possible to use.

A problem was encountered when cabin lighting related failure data was collected. The target elevators had three identical fluorescent tubes in a cabin. Generally, a call-out may occur when at least one of the three fluorescent tubes will fail. However, it is more possible that a call-out occurs not until all the three tubes are failed. Call-outs, caused by cabin lighting, were reported by a specific component code by a maintenance technician. Back reporting didn't systematically take position how many of the three tubes were failed. This made the modeling of reliability function for one individual fluorescent tube impossible. Thus, the reliability function was modeled for call-out occurrences. Actually this was a good approach for this case. Concentration was focused into problems that elevator users and owners see on field. Therefore, customer perspective was really taken account.

4.1 Lifetime Distribution Modeling

The calculations of this section were performed with the Mathcad engineering calculation software. The used calculation formulas were developed by cooperating with the reliability engineering experts of Tampere University of Technology in Finland.

The lifetime of cabin lighting is meant here a time from elevator's commissioning until a call-out occurs. The collected lifetime observations were handled as right-censored, because large number of elevators suffered none call-outs during the follow-up. The cumulative distribution function $F(t)$ of the lifetime was modeled by using the method introduced in Section 2.4. The modeled Weibull distribution is shown in Figure 4, and it had the following statistics: MTTF = 1430, standard deviation = 870, shape parameter $\beta = 1{,}7$ and scale parameter $\sigma = 1600$.
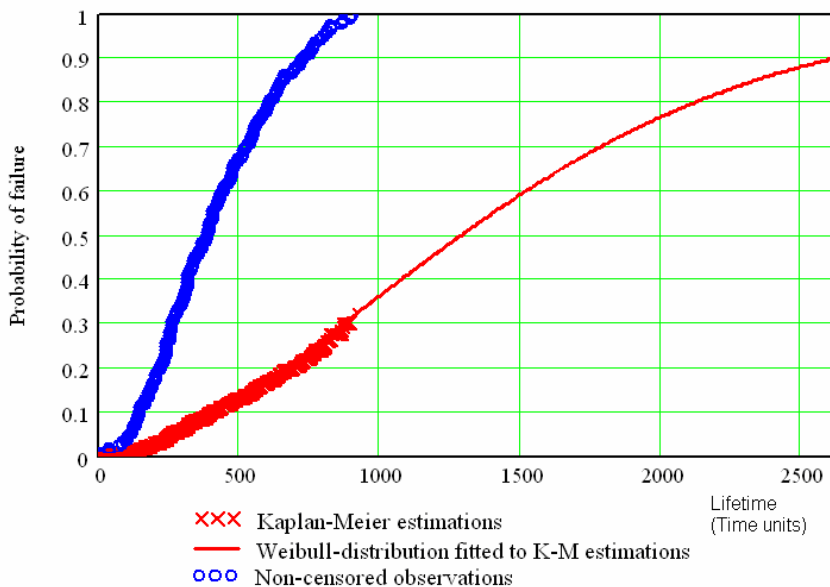

Figure 4. The lifetime model by Kaplan-Meier estimation method and the example of cumulative lifetime distribution that is modeled only from non-censored observations.

From the cumulative distribution function could be derived the failure rate function that defines the conditional probability of a failure per time unit. In all, 19% of the field data observations were non-censored (failed) and 81% were censored. Figure 4 also demonstrates the extensive impact of large amount of censored data. The blue points represent the sample version of

cumulative distribution function that is modeled straight from non-censored observations. As a result, without taking account the information that censored observations provided, the modeled lifetime distribution would have been extremely pessimistic.

4.2 Cost Elements of Corrective and Preventive Maintenance

Preventive replacement costs elements were calculated for the maintenance optimization. It was decided that a new separate maintenance visit to an elevator would not be created for the replacement of cabin lighting. Possible preventive component replacements could be included in already scheduled maintenance visits. Thus, the extra costs of preventive replacements would come mainly from spare parts and labor costs.

Corrective maintenance costs, i.e. call-out costs were generally derived from used spare parts and a maintenance technician's working time. In addition, there exist several hidden costs that are the consequences of a call-out. Hidden costs are difficult to quantify. In elevator industry hidden costs consist for instance of the following aspects:

Table 1

- Lost resource from planned maintenance actions	- Invoicing working time
- Travel time costs	- Stocking and handling of spare parts
- Call-centre costs	- Cost of product's downtime (customer satisfaction effect)
- Supervisor working time	

For maintenance optimization, the values of previous cost elements were estimated. The costs of spare parts and labor could be easily evaluated by book values, expert judgments, and field data studies. An assumption was that labor costs are directly proportional to a time used on field. A time on field consist of actual work, back reporting, and customer contact. Travel time costs included all cost factors that were caused by traveling to a failed elevator. A maintenance technician's salary and all costs related to a car used are the most substantial. A time spent to traveling depends for example a lot on city and density. A maintenance technician is obliged to interrupt planned preventive maintenance actions when a call-out dispatch is ordered, and due to that the costs of lost resource had to be estimated. A call-out dispatch causes direct work to KONE call-centre. It also increases the workload of work supervisor and invoicing. The costs of spare part stocking and handling are higher in corrective maintenance than in preventive maintenance.

The role of customer satisfaction aspect was quite highly considered in the case study. The cost of downtime basically is the lost of reputation towards KONE's products and services. It is clear that some customers are interested in the availability of their elevator. On the other hand, for some customers availability is not so crucial. Customer satisfaction obviously affects directly to new equipment and maintenance contract sales. The issue is especially crucial in certain customer segments like shopping centers, hotels, airports, or public transportation.

The costs of labor and hidden costs vary a lot inside KONE's global business environment. Therefore, the case study was performed with a couple of different starting values. Those represented countries where price level is completely unequal as well as different customer segments.

4.3 Inputs to Dependability Optimization

RAMoptim is software for optimizing system's reliability, availability and maintainability (RAM). It was utilized in this case study. The stochastic simulation methods behind the solution are developed by Tampere University of Technology. Ramentor has commercialized the software. Further information about software can be found from www.ramentor.com. RAMoptim produces predictions of how the system will behave during its entire life cycle. For instance the following issues can be optimized:

Table 2

- System's reliability and availability	- Costs caused by maintenance actions
- Need of maintenance resources	- Components failure probability influence to system's
- Costs caused by failures	dependability

RAMoptim utilizes several starting values for simulating system's dependability. Estimation of all those was not needed in this case. Altogether, the following starting value topics are considered in RAMoptim:

Table 3

- Repair time in case of unexpected failure	- Needed resources
- Time used in preventive maintenance	- Cost factors of unexpected failure
- Failure tendencies of components	- Cost factors of preventive maintenance
- Simulation time and restrictions	

First, the repair time caused by a call-out was determined. A repair time function was defined by an approximated mean, standard deviation, and delay time. The delay time was a time that is spent before the actual repair work is started. The second step before simulations was determining the failure tendency of basic events (call-outs). It was done by the MTTF and standard deviation of the modeled cumulative distribution function. Figure 5 shows the input sheet of failure tendency.
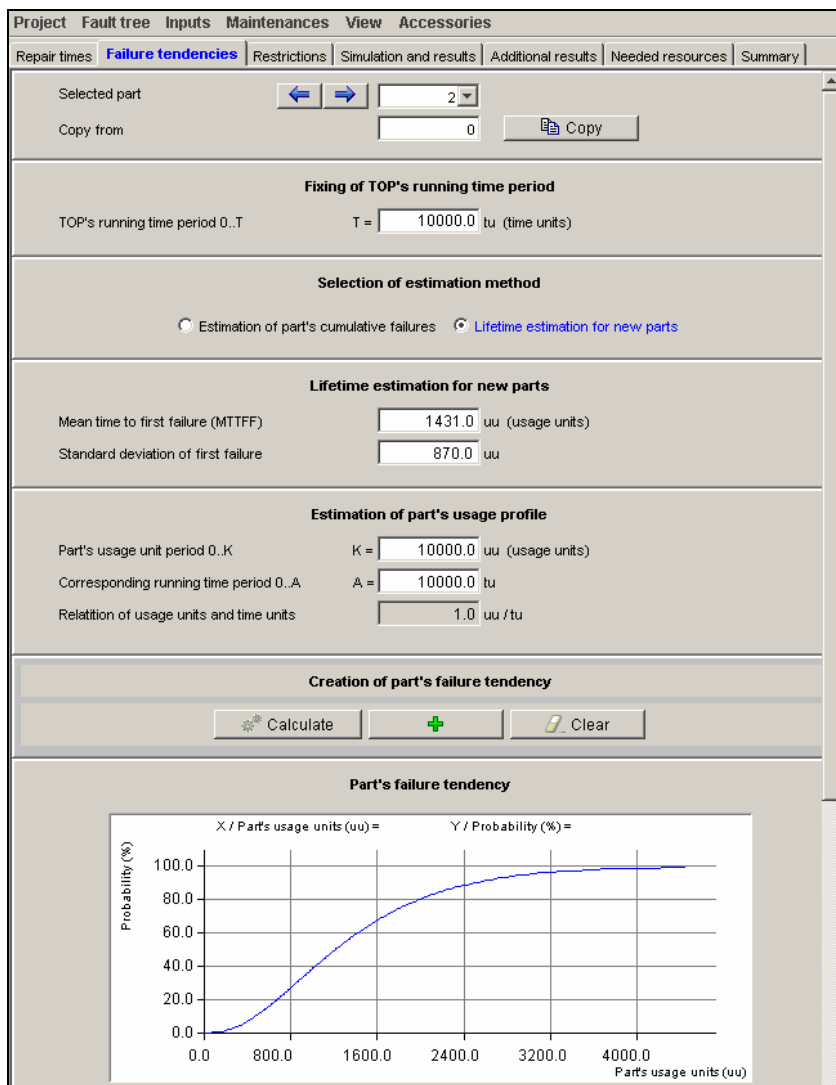

Figure 5. An example of user interface of RAMoptim: Basic events' failure tendency was input by MTTF and standard deviation of the cumulative distribution function.

The software allows user to determine some restrictions on behaviour between the TOP-event and the basic events of the fault logic. For example, how the TOP-event (call-out) will influences to the lifetime basic parts (fluorescent tubes), and can a part be repaired if the TOP runs. In this case, whole cabin lighting was expected to be as a new after a call-out.

The next step was to determine needed human resources and the losses of a call-out. Time dependent as well as time independent costs related to a maintenance technician's work and used spare parts were defined. In addition, a loss of call-out (hidden costs) was input in the software by one time independent value. The value consisted of all the factors that were presented in Section 4.2.

The last input was defining of costs and a time spent on preventive component replacements. A maintenance time was filled in with one value. That time affected straight to the TOP-event's availability in simulation. The costs consisted of resources and spare parts that are used for a preventive maintenance visit.

4.4 Simulation and Results

When all needed starting values were filled into RAMoptim the final dependability analysis could be performed. The first step was to find out optimal preventive maintenance interval. Figure 6 shows the example of an optimization result in RAMoptim. There is graphically illustrated total maintenance costs dependence on the length of preventive replacement interval. The red plot illustrates the costs caused by call-outs, and the green one signifies the costs of preventive maintenance actions. Moreover, the blue curve represents the total costs of maintenance.

The final result of the simulation was that the most cost effective solution would be to perform preventive component replacements as a part of normal preventive maintenance roughly at the interval of one year. Dependability simulation could be performed for different time scenarios as typical customer warranty period and whole elevator's lifetime. RAMoptim software provided many detailed results related to the availability, maintenance costs, and needed human resources. The results actually clarified that total working time needed in maintenance was even a bit more when cabin lighting was replaced once a year. However, unexpected failures caused almost 75% less work.
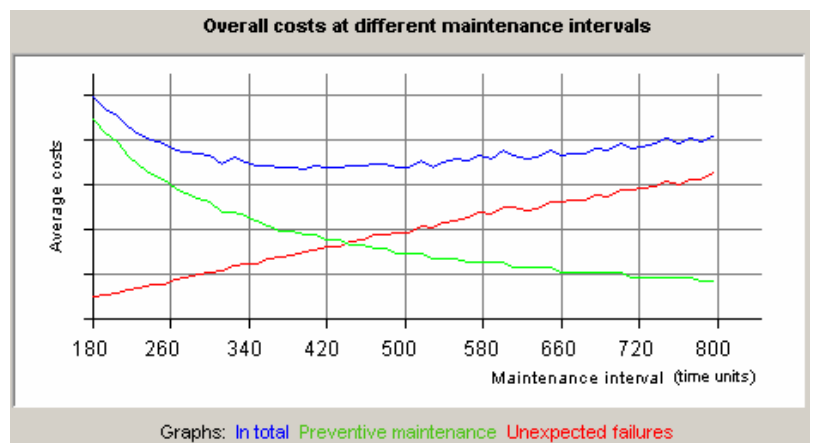

Figure 6. Optimization of appropriate preventive replacement interval.

5 CONCLUSIONS

5.1 Experiences from the Case Study Methods

In the dependability case study, the cumulative distribution function was modeled with commercial Mathcad software. The price-quality ratio of the software is good and software itself is easy to use. The modeling case in question needed quite large mathematical knowledge because all functions and equations were created manually. However, when the mathematical model is once generated it can be used in the future.

RAMoptim software was used in maintenance optimization. The program is logical and user interface is good. RAMoptim provided convenient method to optimize preventive replacement intervals. A lot of cost information was required before simulation could be performed, but it provided the interesting results about dependability and cost effectiveness.

A practical example how to increase product dependability was the introduced case study about elevator cabin lighting. Experiences from the methods were good. Preventive maintenance planning can be boosted by information on the lifetime of the components. The similar way of planning can be used for number of elevator components. Naturally, time-based maintenance planning is not the best solution for every elevator component. The similar method can be applied for example to start-based maintenance planning. In this case, preventive replacement recommendations can be given after a particular number of starts, instead of calendar time.

5.2 Requirements and benefits for Systematic Dependability Follow-up Process

There is several requirements for dependability follow-up, until actual reliability function of a component is available. Firstly, the follow-up must be done for the pre-defined set of equipments that are operating in similar conditions. Moreover, all corrective and preventive maintenance actions that have affected to the studied components must be saved in the maintenance reporting system, and taken into account in lifetime analysis. Traceability of the failures is important. Thus, back reporting must be performed so that it clearly clarifies the root cause of the failure and performed repair actions. As the case study showed, the difficulties arose just when back reporting was not defining the exact root cause of a failure.

A follow-up period should theoretically last until all the components are failed. Often, this is not possible in practice. The lifetimes of components are long and study results are needed in the early phase of products' life to ensure a proper maintenance. Censored observations can also be utilized; however, the amount of censored data decreases the confidence of the produced reliability function. Generally, results in a dependability follow-up are as good as the source data available. A systematic follow-up process consists mainly of correct back reporting, up-to-date databases, and automated collection and analyzing processes.

The starting point for a dependability follow-up is back reporting that is performed by maintenance technicians. In several industries the most suitable method to provide systematic back reporting is to report failure modes by standardized codes. It is beneficial to utilize similar codes around a global company. The codes have to define exact enough a component that was the object of a failure. Codes for failure root causes as well as performed actions make data analyzing more efficient.

After all, the weakest link in back reporting is a person who performs it. Thus, people's way of thinking has an influence on selecting the appropriate code. These factors must be reduced to a minimum. Logical codes reduce the possibility of misunderstandings. The most important thing to achieve an error-free reporting is to give proper instructions to people about how to choose a right code. Moreover, all automated functions that reduce people involving themselves in field data collection process improve the quality of data. On the other hand, all automated functions typically cost a lot. Complex systems also require maintaining. The first step in automated data collection is the use of PDA-devices. A paper free data handling reduces the possibility of processing errors because the information is transferred electronically. In addition, an electronic reporting procedure normally motivates technicians to report correctly. Automated data collection can be developed also by the utilization of bar codes. This is possible when there is a bar code scanner in the PDA-device. For example, bar codes that are printed in spare parts can be used easily to identify the target component of inspection, repair, or replacement.

The second basis of the dependability follow-up which cannot be without mention in this paper is the technical information of followed products. Exact technical characteristics are required to compare for example elevator models, revisions, properties, etc. Therefore, at KONE the technical database of maintained elevators is updated continuously.

6 REFERENCES

1 Blischke WR & Murthy DNP. (2000) Reliability Modelling, Prediction and Optimization. New York, Wiley.

2 Rausand M & HØyland A. (2004) System Reliability Theory: Models, Statistical Methods and Applications. Second Edition. Canada, John Wiley & Sons, Inc.

3 International Standard 60300-3-2. (2004) Dependability management – Part 3-2: Application guide – Collection of dependability data from the field. Second Edition. Geneva, Switzerland, IEC.

4 Meeker QM & Escobar LA. (1998) Statistical Methods for Reliability Data. United States of America, John Wiley & Sons, Inc.

5 O'Connor P. (2002) Practical Reliability Engineering. Fourth Edition. Chichester, England, John Wiley & Sons, Ltd.

6 Ebeling CE. (1997) An Introduction to Reliability and Maintainability Engineering. United States of America, McGraw-Hill Companies, Inc.

7 Moubray J. (1997) Reliability-centred Maintenance. Oxford, Great Britain, Butterworth-Heinemann.