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Unreliability costs in Life Cycle Cost Analysis (LCCA) – comparison of calculation methods

Keywords

Life Cycle Cost (LCC), operation and maintenance phase, unreliability costs, failure rate, discounting

Abstract

The paper describes aspects related to the reliability and its influence on life cycle cost analysis performance. The emphasis is on the unreliability costs, caused by failures, which are incurred over an entire object's useful life. Later, there are characterized three methods, i.e. exponentially distributed failure rate, the determined failures frequency, and Weibull distributed failure rate, which allow to quantify the economic impact of the costs associated with reliability in the Life Cycle Cost Analysis. Applications of these approach to predict the unreliability costs of railbus electrical system are presented as well.

1. Introduction

Every object goes through several phases of its anticipated life cycle, i.e. from its conception, subsequent design and production processes, through its practical use lifetime, with maintenance support to wear-out stage [12]. In the paper the term of an object is used, which corresponds to the name of a whole system, its subsystems or elements. Each life-phase covers actions, which contributed to the appearance of costs.

According to IEC [14] the ownership costs of an object, which are incurred during the operation and maintenance phase are the highest. As a result, these costs are the main component of Life Cycle Cost (LCC). This type of cost occurs throughout an entire lifetime of an object (i.e. recurring cost) and for that reason, discounting must be used in order to compare those economic values that appear in different time periods. The discounting technique used in LCC method is considered in very wide literature, for instance in [3], [6], [8], [9], [17], [18], [20].

The objects are unreliable, ones have failures, which can appear during the entire objects' useful life. Hence, costs of system non-reliability are one of the important components determining the total cost of ownership. Reliability analysis performed to calculate the system characteristics (i.e. failure rate, Mean Time Between Failure - MTBF) can be used to help estimating life cycle cost.

The aim of this paper is to highlight the meaning of the most common reliability parameter which is the failure rate in Life Cycle Cost Analysis (LCCA).

The paper covers six sections. After the introduction, i.e. in the sections 2 and 3, there are discussed issues concerning the definition and classification of reliability costs and also the concept of life cycle cost. The next section presents the aspect of reliability in LCCA. In this section author focuses on the costs that are incurred in the operation and maintenance phase of an object, in particular the costs resulted from its failures. Methods taking into account the failures frequency of a system, which allows to assess the present value of future system unreliability-related costs within its useful life are characterized in the section 5. Later, there is provided a practical example of these methods and briefly summary.

2. Reliability cost definition

In the literature, one can find different meanings of term "*reliability cost*". Generally this term refers to all of the costs that are incurred to prevent defects or that result from defects in product. K.K. Aggarwal [1] and B.S. Dhillon [7] defined the following reliability cost categories:

- prevention cost,
- appraisal cost,
- internal failure cost,
- external failure cost.

Prevention and appraisal costs are incurred to keep an object into an operational state.

Prevention cost can be defined as: costs of reliability planning (reliability plan includes also the preparation of specialized procedures), costs of reliability engineering associated with the launching of new design, costs of evaluation and training personnel, costs of preventive maintenance performance, costs of suppliers evaluation and cost of prototype construction.

Appraisal costs, which are sometimes called inspection or review costs, are the costs incurred to determine the degree of conformance to quality requirements. The appraisal cost includes such costs as: costs of inspection and test objects, costs of document review, costs of audits and costs of monitoring.

The other two groups of costs are known as internal failure costs and external failure costs. Internal and external failure costs are incurred because defects are occurred despite efforts to prevent them.

Internal failure costs result from identification of product defects before they are shipped to customer. These costs include costs associated with scrap, reworking, failure analysis, retesting, changing (modifying) manufacturing or service processes and unplanned downtime.

Instead ***external failure costs*** are costs associated with defects that are found after product is received by the customer. These costs are associated with such issues as: warranty, servicing and handling complaints, repairs and replacements or returns.

Note, that these above-mentioned costs are carried in the entire life cycle of an object. The phases occurring in the life cycle are helpful to classify reliability costs which may occur. Consequently life cycle cost is considered.

Used in the paper the term of reliability costs means all reliability-related costs, which are incurred by a system's user only in its operation and maintenance stage, i.e.:

- current operation costs,
- maintenance-related costs (both preventive, and corrective).

3. Life Cycle Cost concept

Many of the Life Cycle Cost definition can be found in the literature. As defined by the Department of Defense of United States of America [5] Life Cycle Cost is *the total sum of the direct, indirect, recurring, non-recurring and other related costs incurred, or estimated to be incurred in the design, research and development (R&D), production, operation, maintenance, and support of a product over its life cycle, i.e. its anticipated useful life span. It is the total cost of the R&D, production, O&S and, where applicable, disposal phases of the life cycle*. IEC 60300-3-3: 2004 [14] argue that costs incurred in the grater number of life cycle phases is necessary to consider LCC, namely the cost of concept and definition phase, the cost of design and development phase, the cost of manufacturing phase, the cost of installation phase, the cost of operation and maintenance phase and also the cost of disposal phase.

Life Cycle Costing can be applied to the entire life cycle of a technical object or to parts or combinations of different life cycle phases. Typical areas (phases) of costs which are included in calculating the object's LCC are shown in *Figure 1.*

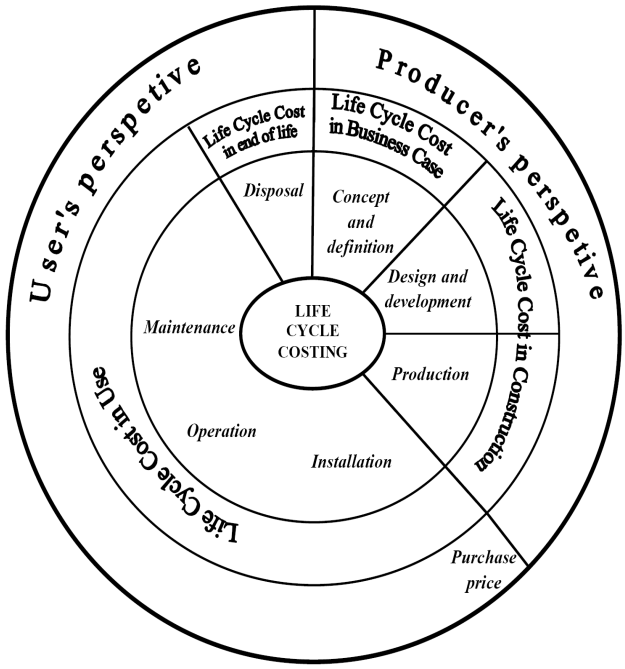


Figure 1. The phases of object's life cycle and associated costs.

To sum up, Life Cycle Cost analysis is an economical-technical method of analyzing the costs of an object over its entire lifespan and assign equations to each investigated element. These equations represent the calculation of the cost of that particular element [10].

From the customer (buyer, user) point of view, the "living way" of an object starts from the purchase moment. Accordingly, from the customer's perspective, LCC is the sum of purchase price, costs being incurred in an usage period and the costs of wear-out process.

Acquisition cost (i.e. purchase price), installation cost and disposal cost are incurred only once, while the operation and maintenance costs are the recurring expenses over the entire useful life of a system.

4. The aspect of reliability in LCCA

The costs that are carried in the operation and maintenance phase of an object very often are the largest component of LCC. One important component of LCC is the cost of system failures [15]. The total cost of unreliability (failures) are presented in *Figure 2*.

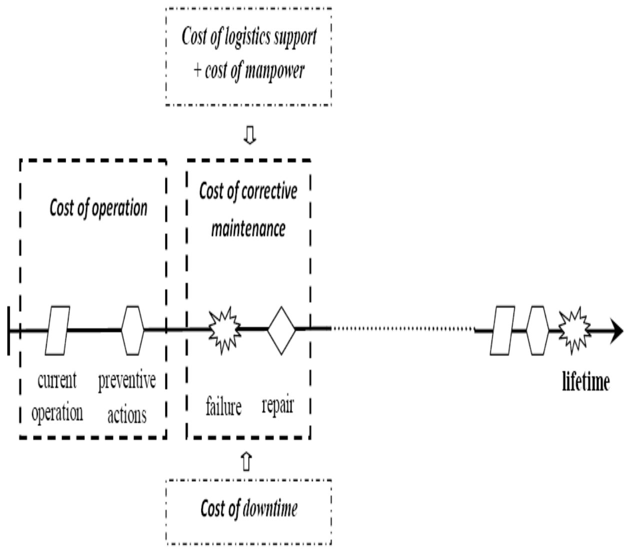


Figure 2. Failure-related costs.

The object characteristics associated with its potential failures are often summarized by the term dependability, which represents an integral view of object availability. One of the three factors (apart from maintainability and maintenance support) influencing the availability of object is reliability [13]. *The reliability of objects is called its capacity for failure-free operation for a defined period of time under given operating conditions, and for minimum time lost for repair and preventive maintenance* [1]. In the mathematical sense, reliability is measured by the probability that an object will work without failure during a specified time interval under given operating conditions [13]. Reliability can be expressed in other ways, for example as the mean time between failures (MTBF) for a repairable system, or mean time to failure (MTTF) for a non-repairable object, or the inverse of these, the failure rate or hazard rate. These reliability parameters can be the basis of life cycle cost analysis within the object durability period.

5. Unreliability costs in LCC evaluation

Objects are not perfect and not free from failures. Everything fails either because of events or from aging deteriorations. The failure frequency, called the rate of occurrence of failures or failure rate, can be interpreted as *a measurement for the risk that a part will fail, with the prerequisite that the component has already survived up to this point in time t* [2]. In practice, the Mean Time Between Failures (MTBF) is often used instead of the failure rate. The MTBF is defined as *the average number of failures per unit time* [16].

The failure frequency is an important reliability measure of elements, since it may be used to compute the expected number of failures in a lifetime *t*. In reliability analysis, several probability distributions are commonly used to model this parameter. Among them are the exponential and Weibull distributions. Accordingly, to assess the object non-reliability costs, caused by failures, in its useful life period, applied the following models:

- constant failure rate, which is the characteristic life parameter of the exponential distribution,
- Weibull distributed failure rate,
- determined failure frequency.

5.1. Non-reliability costs calculating based on exponential distribution failure rate approach

To quantify the cost of non-reliability, considering constant failure rate require fulfilling five steps. These steps are the following:

1) Determine the type of failures (*f*), where $f = 1,\dots,F$ for *F* types of failures.
2) Define the expected frequency of failures (λ_f) per year. As mentioned earlier, in the exponential distribution failure rate is constant, i.e. time-independent. Hence in this approach, the frequency of failures is also invariable value per year for the expected cycle of useful life. The λ is calculated by the following expression:

$$\lambda_f = \frac{1}{m}, \tag{1}$$

where:
λ_f – constant frequency of the failure type *f*, expressed in failures per unit of measurement per year,
m – mean time between failures, or to a failure.

3) Calculate the costs per failure C_f (zl/failure). These costs may include: the costs of replacement parts and the costs of manpower.
4) Calculate the total costs per failure per year (*TC*). The *TC* is obtained by formula:

$$TC = \sum_{f=1}^{F} C_f \cdot \lambda_f, \tag{2}$$

where:
f – the type of specified failures,
F – the total number of failure types,

C_f – cost associated with the failure *f*, expressed in zl/failure.

5) Calculate the total costs per failure in present value (*PVTC*). Given an yearly value *TC*, the current quantity of money (today), that one needs to start saving (today) to be able to pay this annuity for the expected number of years of useful life (*T*), for a discount rate (*r*). Determining the appropriate discount rate is the key to properly valuing future costs. The expression used to estimate the *PVTC* is shown next:

$$PVTC = TC \cdot \frac{(1+r)^T - 1}{r \cdot (1+r)^T}, \tag{3}$$

where:
r - discount rate.

Afterwards, expressed in present value costs for all specified types of failures are added, and in this way, the information about unreliability-related costs that will be incurred over the specified useful time of the object is achieved.

5.2. Non-reliability costs calculating based on Weibull distribution failure rate approach

This approach proposes to evaluate the impact of failures for LCC in the following way [19]:

1) Identify the types of failures (*f*), where $f = 1,\ldots,F$ for *F* types of failures.
2) Determine for each failure type the times between expected failures (t_f).
3) Calculate the costs per failure C_f (zl/failure). These costs may include: the costs of replacement parts and the costs of manpower.
4) Determine in a probabilistic way the frequency of expected failures (λ_f) with the Weibull distribution.

   The two-parameter Weibull probability density function - $f(t_f)$ - is given by:

$$f(t_f) = \frac{\beta}{\eta}\left(\frac{t_f}{\eta}\right)^{\beta-1} e^{-(\frac{t_f}{\eta})^{\beta}}, \tag{4}$$

for $t_f \geq 0$, $\eta > 0$, $\beta > 0$
where:
t_f - time between failures (random variable),
η - scale parameter,
β - shape parameter.

The MTBF is the expected value if the random variable t_f and is given by:

$$MTBF = \eta\Gamma\left(\frac{1}{\beta}+1\right), \tag{5}$$

where:
$\Gamma\left(\frac{1}{\beta}+1\right)$ is the gamma function evaluated at the value of $\left(\frac{1}{\beta}+1\right)$.

The Weibull failure rate function, $\lambda(t_f)$, is given by:

$$\lambda(t_f) = \frac{\beta}{\eta}\left(\frac{t_f}{\eta}\right)^{\beta-1}, \tag{6}$$

The Weibull failure frequency (λ_f) is expressed as:

$$\lambda_f = \frac{1}{\eta}, \tag{7}$$

If assuming that the MTBF is the inverse of the failure frequency, it the Weibull failure frequency (λ_f) may be expressed as:

$$\lambda_f = \frac{1}{MTBF_f}, \tag{8}$$

5) Calculate the total costs per failure per year (*TC*). The *TC* is given by formula (2).
6) Calculate the total costs per failure in present value (*PVTC*). Given a yearly value *TC*, the current quantity of money (today) that one needs to start saving (today) to be able to pay this annuity for the expected number of years of useful life (*T*), for a discount rate (*r*). Determining the appropriate discount rate is the key for proper valuing future costs. The expression to use to estimate the *PVTC* is shown by formula (3).

Later on, expressed in present value costs for all specified types of failures are added, and in this way, the information about non-reliability-related costs what will be carried over the specified useful time of the object is obtained.

5.3. Non-reliability costs calculating based on determined failure frequency approach

To evaluate of unreliability-related costs by using determined frequency of failures should carry out the following steps [19]:

1) Determine the types of failures (*f*), where $f = 1,\ldots,F$ for *F* types of failures.

2) Define in a determined way for each failure type, the expected frequency of failures ($\lambda_f^{\,t}$) for time t. The frequency of failures per year is defined on a determined value, since it is defined starting from failures records, databases and/or experience of maintenance and operations personnel. For example: the observed object failures frequency in the past for given time t may be used to represent the number of failures which represent the future failure frequency of object for time t within the its expected useful period.
3) Calculate the costs per failure C_f (zl/failure). These costs may include: the costs of replacement parts and the costs of manpower.
4) Calculate the costs per failure type per year (CP_f^t).

$$CP_f^{\,t} = \lambda_f^{\,t} \cdot C_f, \tag{9}$$

where:
λ_f^t - frequency of the failure type f, defined in a determined way, for time t.
5) Convert to present value the costs for failure type per year ($PCP_f^{\,t}$). Given a future value $CP_f^{\,t}$ the present value is calculated for every year t to a discount rate (r) and for specific period of time.

$$PCP_f^{\,t} = CP_f^{\,t} \cdot \frac{1}{(1+r)^t}, \tag{10}$$

6) Calculate the total costs per failure in present value ($PVCP_f$). All cost for failures types in present value are summed for the expected number of years of useful life (T).

$$PVCP_f = \sum_{t=1}^{T} (P)CP_f^{\,t}, \tag{11}$$

7) Calculate the annual equivalent total cost ($AETC_f$). Given a present value $PVCP_f$, calculate its annual equivalent total cost for the expected number of years of useful life (T) and the defined discount rate (r).

$$AETC_f = PVCP_f \cdot \frac{r \cdot (1+r)^T}{(1+r)^T - 1}, \tag{12}$$

Afterwards, the annual equivalent total cost for all specified types of failures are added, and in this way, obtaining unreliability-related costs what will be incurred in the period of analysis.

6. Application of the above mentioned methods – an example

The purpose of this case study is to better understand how one may estimate the unreliability costs of an object, that will be incurred in the future, using the different approaches of calculating the failures frequency.

Time between failures has been taken into account as the non-reliability parameter. Data about the time between failures of the electrical system (f) have been used in the investigations. These information have been obtained from the railway company, which performs the passenger transport process with the use of railbuses.

In this electrical system have occurred 12 events of failures during 44 months (T) of useful time observation. The time between expected failures t_f are presented in days (44 months is the equal of 1342 days).

The railbus producer has not provided the information about the repair costs.

The costs of non-reliability resulting from failures frequency were calculated based on the following assumptions:

- time between failures is a random variable,
- the period of analysis is the next 44 months,
- failure parts are replaced by new ones,
- cost of electrical system failure is estimated as 3000 zl/failure,
- the nominal, annual interest rate of a consumer credit is used as discount rate and is 15,65% [11]. Because the duration of analysis is given in months, monthly discount rate was applied. The discounting must be used to convert the future value of costs into their present value. The monthly discount rate is the twelfth root of annual one and is 1,26% approximately,
- the Weibull++ software was used to estimate the essential parameters of reliability and to match theoretical distributions to the real ones obtained from the sample.

Case study results

The aim of this study is to determine the future value of costs, which will be carried on the elimination of electrical system failures in railbus, during the specific period of time (44 months). The predictable, future costs associated with the electrical system unreliability during 44 months are presented in *Figure 3*. More the results of numerical test performed with the use of the methods described above (i.e. in section 5) is shown in *Table 1*.

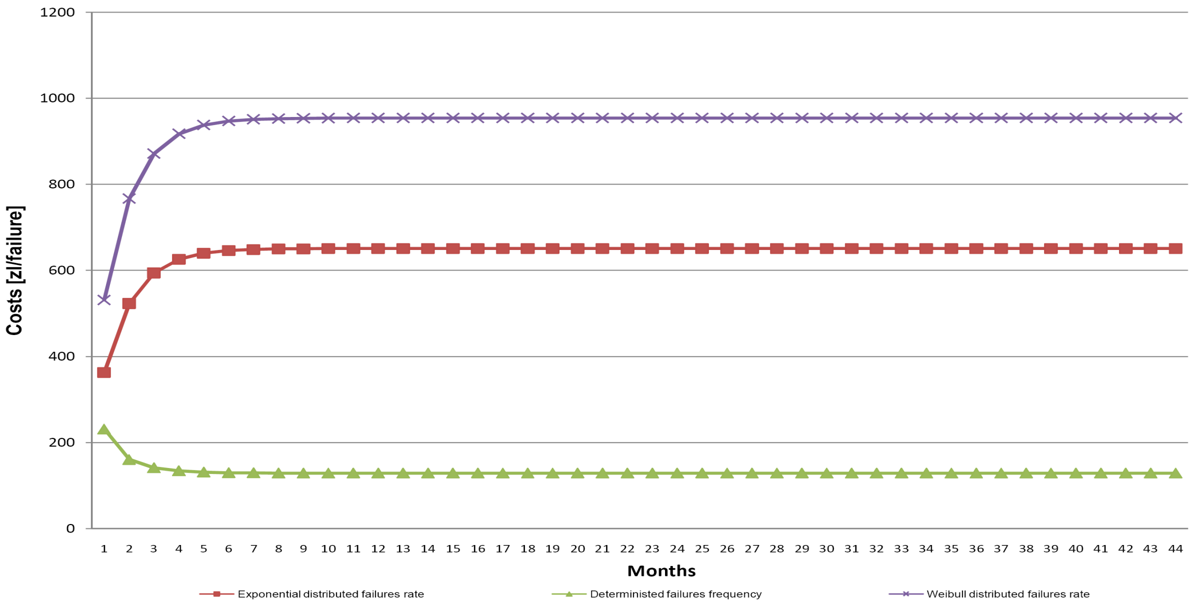
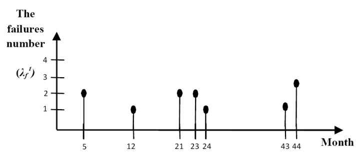


Figure 3. The future, monthly failures cost of the object depending on the accepted failure frequency.

Table 1. Summary of case study results.

The calculation methods of unreliability costs based on:	**The type of failures** (*f*)	**The frequency of failures** (λ_f or $\lambda_f{}^t$)	**Costs per failure** (C_f)	**Total costs per failure** (*TC*)	**Present value total costs per failure** (*PVTC*)	**Cost per failure per given month** (CP_f^t)	**Present value cost for failure per given month** (PCP_f^t)	**Annual equivalent total cost** ($AETC_f$)
Exponential distribution failures rate	The failures of electrical system in railbus	0,273 (*failures per month*)	3000 (*zl/failure*)	818,2 (*zl/failure*)	650,6 (*zl/failure*)	-	-	-
Weibull distribution failure rate		0,399 (*failures per month*)		1199,9 (*zl/failure*)	954,1 (*zl/failure*)	-	-	-
Determined failure frequency				-	-	• 5 month – 6000 *zl/failure* • 12 month – 3000 *zl/failure* • 21 month – 6000 *zl/failure* • 23 month - 6000 *zl/failure* • 24 month – 3000 *zl/failure* • 43 month – 3000 *zl/failure* • 44 month – 9000 *zl/failure*	102,5 (*zl/failure*)	128,9 (*zl/failure*)

The study findings show that forecast, future, monthly non-reliability costs calculated on the basis of determined failures frequency approach are much lower than the costs estimated with the use of the other two methods. However, the present value of future unreliability-related costs estimation by using determined failure frequency of electrical system in railbus are less realistic than for example the value, which has been obtained from the approach of exponential distribution failure rate or Weibull distribution failure rate. It is unlikely, that the number of future failures will be the same as the previous ones. Therefore, there is much better to use the approaches based on i.e. "lifetime distributions", which take into account a random variable such as time between failures.

It is known, that the exponential distributions describe the constant failure rate of objects. Constant frequency of failures occurrence during 44 months is not very probable. On the other hand, it is observed that the time between electrical system failures in railbus is not described by exponential distribution. For those reasons, calculation of the present value of future unreliability costs with the use of the method based on exponentially distributed failure rate is also not entirely correct.

Finally, the Weibull distribution has been fitted to a real life data and the fit has been found to be good. The *Figure 4* shows a Weibull probability plot. This plot shows the expected failures frequency for object over time (in days), with time shown on the x-axis and failure percentages (labelled Unreliability) shown on the y-axis.

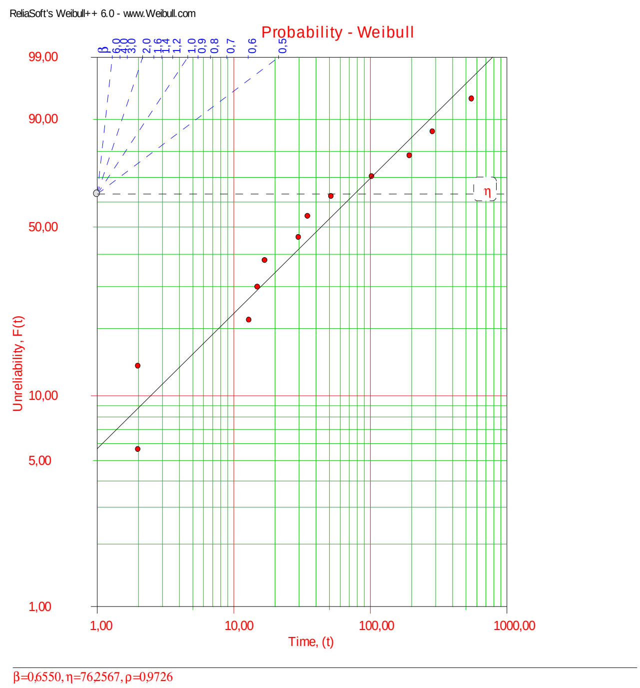


Figure 4. Weibull probability plot.

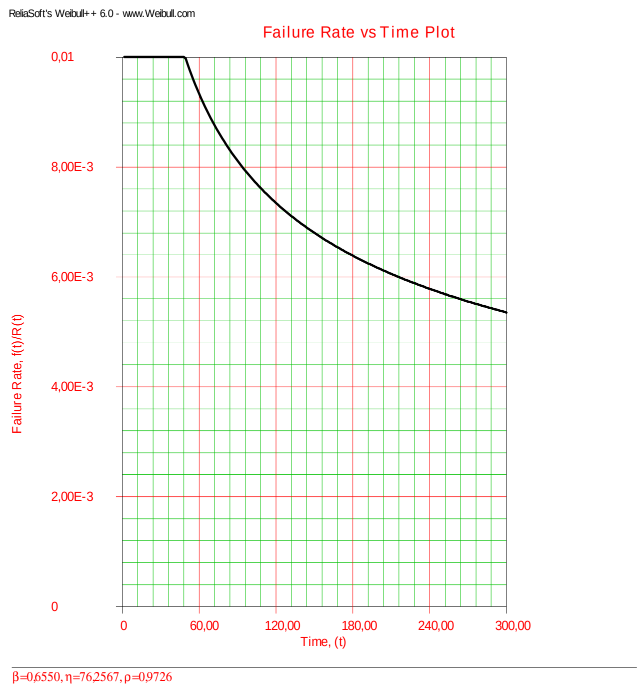


Figure 5. Weibull failure rate plot for electrical system in railbus.

Hence, non-reliability costs estimation based on Weibull distribution failure rate approach are the closest to ones, which probably will appear in 44 month time. The outcomes of this research shows, that in 44 month, the owner of railbus, will pay 954,1 zl on the elimination of electrical system failures in railbus. The main disadvantage of this method (i.e. Weibull distribution failure rate approach) results from the taken assumption, that for every month of expected useful life, the frequency of failures is defined in a constant way (MTBF is the basis for determining the failure rate of system).
Additionally, the study shows that the technical object (i.e. the railbus) is in "infant morality" phase, because failure rate decreases drastically in time. The Weibull failure rate function is showed in *Figure 5.* Information about the time between failures of the electrical system (*f*), which have been used in the investigations, came from the initial exploitation period of the railbus. The railbus was then in guarantee period, so this assumption is true.

7. Conclusion

The analysis of costs in operation and maintenance phase of a system depends on among other things values calculated from reliability analyses like failure rate. In this paper, there are described methods which allow to estimate the reliability impact in Life Cycle Cost Analysis.

Although used to calculations the value cost per failure (C_f) is not real, that study demonstrate the usefulness of presented approach for quantifying the cost associated with reliability of the object. Moreover, as it turned out, the chosen way of calculation the rate of failures occurrence and the discount rate have a significant impact on the future value of costs associated with a system reliability.
The methods for quantifying the present value of future unreliability costs, described in this paper, indicate direct relationship between the reliability and cost, which will be carried in the useful life of an object.

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