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Maintainability analysis considering time-dependent and time-independent covariates

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ABSTRACT

Traditional parametric methods for assessing maintainability most often only consider time to repair (TTR) as a single explanatory variable. However, to predict availability more precisely for high availability systems, a better model is needed to quantify the effect of operational environment on maintainability. The proportional repair model (PRM), which is developed based on proportional hazard model (PHM), may be used to analyze maintainability in the present of covariates. In the PRM, the effect of covariates is considered to be time independent. However this assumption may not be valid for some situations. The aim of this paper is to develop the Cox regression model and its extension in the presence of time-dependent covariates for determining maintainability. A simple case study is used to demonstrate how the model can be applied in a real case.

1. Introduction

Maintainability performance is defined as "*the ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources*" [1]. The "given conditions" refer to the condition under which the item is used and maintained. These conditions can be for example the climate conditions, support conditions, human factors, geographical location, etc.

There are a number of methods and models available for prediction of maintainability performance, and a variety of software such as the *Relex Maintainability Prediction* has been developed as well [2–4]. Hao et al. [5] developed and introduced the concept of maintainability analysis visualization under the AutoCAD environment to analyze product design from the viewpoint of easy maintenance. However, most of these models and methods do not consider the influence of the "given conditions" on the maintainability performance. Hence, the performance prediction may be imprecise and inaccurate, resulting in poor availability performance predictions. It is well known that the local operating environment may have a substantial influence on the maintainability. For example, the local operating conditions such as cold weather, rain or snow, long distance to the suppliers may affect the length of time it takes to perform maintenance work if it is not planned for. From a statistical point of view, the factors which may influence the maintainability characteristics are called covariates. Therefore, the method that is used for maintainability analysis and prediction must be able to quantify the effect of environment condition on maintainability.

When analyzing historical data such as time between failures (TBF) and time to repair (TTR) data sets, a frequently occurring problem is that the data have not been collected under the same condition. Hence, in the reliability field several methods (e.g. proportional hazards model (PHM), proportional covariate model (PCM) and the acceleration model) have been developed to address this problem [6–11]. To quantify the effect of covariates on maintainability performance, Gao et al. [12] propose a proportional repair model (PRM) which is based on the PHM. In the PRM the main assumption is that the covariates are time-independent variables. However, this assumption may not be valid for some cases. For example, in Arctic conditions the process of maintenance is considerably affected by the operating environment. If, for example, a production facility pump needs to be repaired outdoors during adverse weather conditions in the winter, it may take more time to repair than during the summer. Therefore, a similar failure in a production facility may have a different TTR for different seasons. This means that the effect of environment on maintainability performance in such an area is time dependent.

There is literature available on the analysis of reliability performance of a system considering the effect of time-dependent covariates [13,14]. However, there is little literature about the

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prediction of maintainability performance considering the effect of covariates—especially considering time-dependent covariates. Birolini [15] states that "*the exact shape of the repair time distribution has in general less influence on the reliability and availability value at system level*". This is a common belief and may have led to less attention being paid to quantifying the effect of covariates on maintainability. However, if the costs of the production losses due to long downtime are substantial and therefore affect business performance, it may be essential to develop better models for better prediction of repair times and the shape of the repair time distributions.

Hence, to predict the shape of the repair time distribution, it is important to consider the covariates' influence on the repair time and to develop a suitable statistical approach to quantify the effect of such covariates on the maintainability performance. The aim of this paper is thus to study the effect of time-dependent covariates on the analysis of maintainability performance. The first part of the paper reviews the common parametric methods used in maintainability analysis. The PRM for analyzing time-independent covariates is briefly discussed as the first attempt in using the Cox regression model in the maintainability field. An applicable method for maintainability analysis in the presence of time-dependent covariates or non-proportional repair model is thereafter developed and introduced. In the second part, the application of this method is demonstrated using a real case study.

2. Maintainability performance analysis

Maintainability is a design factor and addresses the ease, accuracy, timeliness and economy of maintenance actions. The maintainability goal in the design phase is that the system should be maintained without large investment of time, at the lowest cost, with a minimum impact on the environment, and with a minimum expenditure of resources [16]. Since maintainability improvements often require important changes in the system layout or construction, it is an important task to predict maintainability as precisely and accurately as possible in design and development phases [17].

In maintainability analysis we attempt to model the probability that a successful repair (or preventive maintenance) of the item will be performed within a stated time interval by given procedures and resources. The random variable is the time to repair and the elements of TTR in general can be: time to failure recognition, time for failure localization and diagnosis (isolation), time for failure correction (removal) and time to function checkout [16,18]. The maintainability analysis methods can be categorized in two main groups, namely: parametric and non-parametric methods such as PRM.

2.1. Parametric methods in maintainability analysis

Parametric methods have been used for analysis of historical TTR data sets in many case studies [19–21]. In parametric methods, the main assumption is that the data come from a type of probability distribution and that inferences are made about the distribution parameters. If these assumptions are incorrect, parametric methods may be misleading. Distribution parameters can be estimated using least-squares fit or maximum likelihood per candidate distribution. If there are several candidate distributions (e.g. Exponential, Rayleigh, Weibull, Gamma, Normal, Lognormal) for a TTR dataset, the goodness of fit analysis (e.g. Kolmogorov–Smirnov test [22], Anderson–Darling test [23] and Chi-squared tests [24]) can be performed to find the best fit distribution.

In parametric methods, if T is a random variable which represents time to repair of a failed unit, and if one has a probability density function $m(t)$, then the cumulative distribution function can be defined as follows [25]:

$$M(t) = \Pr\{T \le t\} = \int_0^t m(t')dt' \tag{1}$$

This equation is the probability that a repair will be accomplished within time t. The mean time to repair (MTTR) and repair rate can be calculated as follows [25]:

$$MTTR = \int_0^\infty tm(t)dt = \int_0^\infty (1-M(t))dt \tag{2}$$

$$\mu(t) = \lim_{\delta t \to 0} \frac{1}{\delta t} \Pr\{t \subset T \subseteq t+\delta t | t \subset T\} = -\frac{m(t)}{1-M(t)} \tag{3}$$

In parametric maintainability analysis, it is assumed that some certain identical repair actions are tested under identical conditions. This is due to the statistical rather than practical considerations which may not be true for actual field data. For example, the repair conditions (e.g. available light) or the repair crew may vary during the observation period. This means that the repair rate can have a dynamic nature that may differ according to the environment condition. Therefore, the inclusion of covariates increases the power of the statistical test and removes the bias of confounding variables.

Due to the nature of data in maintainability versus reliability, it seems that the non-parametric methods such as Cox regression model have the ability to be used for analysis of covariates' effect on maintainability performance. However, one should note that the human has a main role in maintainability and may make the analysis more complex. Therefore, the starting point of this paper is the PRM model introduced by Gao et al. [12].

2.2. Proportional repair model (PRM)

Gao et al. [12] proposed PRM in order to predict repair rate considering the operating environment condition. In PRM the repair rate of a component is the product of a baseline repair rate $\mu_0(t)$, and a functional term $\psi(z\beta)$ describes how the repair rate changes as a function of influential covariates. The PRM is described as follows:

$$\mu(t,z) = \mu_0(t)\psi(z\beta) \tag{4}$$

where z is a row vector consisting of the covariates and β is a column vector consisting of the regression parameters. The covariate z is associated with the system, and β is the unknown parameter of the model, defining the effects of the covariates. The baseline repair rate is the repair rate under the standard conditions, $z=0$, and requires $\psi(z\beta)=1$, when there is no influence of covariates on the repair time. The shape of the baseline repair rate and the regression coefficients for the covariates may be estimated from historical data or by using input from experts. Different parameterization forms of $\psi(z\beta)$ can be used in Eq. (4) such as the log linear form, $\psi(z, \beta) = e^{\beta^t z}$; the linear form, $\psi(z,\beta)=1+\beta^t z$ and the logistic, $\psi(z, \beta) = \log(1+\beta^t z)$. If the exponential form is considered, the repair rate can be written as

$$\mu(t,z) = \mu_0(t)\exp(z\beta) = \mu_0(t)\exp\left(\sum_{j=1}^{n} \beta_j z_j\right) \tag{5}$$

The maintainability function is given by

$$M(t, z) = 1-\exp\left[-\int_0^t \mu(t, z)dt\right] = 1-(1-M_0(t))^{\exp\left(\sum_{j=1}^{n} \alpha_j z_j\right)} \tag{6}$$