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Fuzzy reliability analysis with only censored data

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ABSTRACT

It is expected that samples in reliability analysis contain both censored and complete failure data; thus, the maximum likelihood method is used to estimate the parameters of the related distribution. Nonetheless, samples may contain only censored data; therefore introducing a high degree of uncertainty which does result in non-viability for either the likelihood method or for statistical inference. This paper proposes the use of fuzzy probability theory to account for the uncertainty and the prior knowledge of the process in the parameters' estimation, for censored data. The proposed method was applied to risk based inspection. Results demonstrate that our method represents a reliable option for using the expert knowledge about the component and the physics of the failure mode. Additionally, an inspection time was estimated based on target risk; the results confirm that the methodology could be used to develop maintenance plans.

1. Introduction

A critical factor of productivity in an industry is the timely maintenance of its installations; improving maintenance performance is thus a key objective. Developing an effective maintenance program requires extensive knowledge about reliability and maintainability; this knowledge is implicit for reliability engineering, which provides the theoretical and practical tools through which the probability and capacity of components fulfill their required functions in determined periods of time without failures (Murthi, 2003). In the field of reliability engineering, the Weibull analysis is capable of working with samples as small as two or three failures for engineering analysis; moreover, it is flexible enough to provide a good fit for a wide variety of data sets. In addition to being the most useful density function for reliability calculations, the Weibull analysis provides the information required for troubleshooting, classifying failure types, scheduling preventive maintenance and scheduling inspections (Dodson, 1994). This model has been widely used in the reliability field because of its properties; e.g., the parameters have an interpretation related to the component and its failure mode.

In the process of applying the Weibull analysis (testing a component), the data obtained sometimes cannot be recorded or collected precisely due to unexpected case scenarios. Since the failure times in many cases are not observable and the censoring mechanism may or may not be known, new approaches have been developed. For example, at petroleum installation plants, there is usually not enough information for elaborating an inspection plan, thus, the Weibull parameters are estimated by means of opinions from experts, MTTF or other methods. For such scenarios, the sample contains only censored data; hence, the likelihood method is not applicable, which introduces a high degree of uncertainty in the parameters estimation. Moreover, the lifetime of the components cannot be measured precisely. Because of all these reasons, researches have been drawn to the fuzzy set theory to reliability analysis (Hsien Chung (2004)). The papers edited by Onisawa and Kacprzyk (1995) provided plentiful approaches to fuzzy reliability. Li (2008) showed the modeling of periodic preventive maintenance policies of a system and its parameter estimation of failure distribution and restoration effects on the degradation rate. A fuzzy system was built using the Particle swarm optimization method. The performance of the fuzzy system was used as a fitness function to guide the search in Particle swarm optimization. Marano et al. (2008) proposed a reliability of reinforced concrete structures; an efficient alternative approach was made by considering fuzzy time-dependent reliability analysis. Sharma et al. (2008) proposed the combination of qualitative and quantitative techniques for risk and reliability analysis of a paper mill where fuzzy synthesis of failure and repair data fuzzy arithmetics had been used. A new intelligent system for detecting the occurrence of a fault in machinery in real time was proposed by Wang (2008); this approach uses a monitoring reliability by integrating the predicted machinery conditioned to fault diagnosis. Hsien Chung (2004)) realized a Bayesian estimation on lifetime data

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assuming the parameters as a fuzzy random variables with fuzzy prior distributions. The author used the conventional Bayesian estimation method to create the fuzzy Bayes point estimator, considering gamma and exponential distributions for complete and censored samples. Cai (1996) mentions some applications of the fuzzy methodology in system failure engineering which traces back to contributions by Kaufmann and Gupla (1988). An interesting application related to the present work is fuzzy methodology in mechanical/structural reliability. When a system failure occurs as the system stress (load) exceeds the system strength (resistance), the failure criterion and the system load should be fuzzy; of course, the system behavior can be fuzzy too. Mosleh et al. (2011) developed a hybrid method based on fuzzy neural network for approximating fuzzy coefficients of fuzzy polynomial regression models with fuzzy output and crisp inputs. They proposed an algorithm from the cost function of the fuzzy neural network.

Regarding the application of fuzzy theory in engineering reliability, Bowles and Peláez (1995) showed the applications of the main concepts of the fuzzy logic, fuzzy arithmetic and linguistic variables for the analysis of system structures, fault trees, the reliability of degradable systems and its probability of occurrence. Recently, Pereguda and Timashov (2010) proposed a fuzzy reliability model for automated complex system, which assumes that parameters of reliability model and reliability indices are fuzzy variables. Their approach allows taking into account the uncertainty of reliability model parameters and reliability indices. Dong et al., (2003) realized a model for analyzing fuzzy reliability; they mentioned that the analytical equations for calculating fuzzy reliability indices of machine part could not be obtained in most cases. Chadna and Ram (2013) stated that given the fact that reliability parameters are often subjectively or ill-defined, the conventional measurement approaches cannot effectively handle the vagueness and ambiguity which exist within reliability parameters; hence, fuzzy theory is rather useful. In this research the authors applied the fuzzy reliability evaluation approach to merit the input failure rates of a system; fuzzy reliability indices were evaluated by means of linguistic variables assessed by experts. Conversely, although classical concepts of statistics, such as estimators, confidence intervals and tests of hypotheses, which have their interpretations in terms of frequencies, were widely used in the past for the analysis of reliability data, the continuous improvement of reliability of components and systems have rendered those classical methods insufficient for practical applications (Hryniewicz, 2007). Hryniewicz presents only main ideas and results that have been published in a few papers, related to the reliability analysis of systems with the usage of imprecise probabilities. Bearing in mind the previous work referenced above, the need for a new method for reliability analyzing when ill-defined or subjective information is handled.

In this sense, for modeling data with certain deficiencies, for instance, when there are no failures (only censored data) or few failures, we propose using the Weibayes methodology (Abernethy, 2008). Such methodology constructs a Weibull distribution by fixing the shape parameter. Although, Abernethy proposes a method to estimate the parameters of the probabilistic model, the uncertainty caused by the lack of information about the components of the process is not considered. Furthermore, the author is not proposing any means for modeling subjective information. Therefore, knowing that in engineering reliability the parameters have a specific interpretation, we propose to model shape parameter considering the engineering knowledge of physics of the failure by means of fuzzy numbers (with triangular functions); as a result, fuzzy failure probability and fuzzy MTTF were obtained. Accordingly, this work presents a methodological framework in which a drawback in maximum likelihood parametric estimation (MLE) due to only censored data can be improved, specifically for the Weibull MLE process for reliability engineering application.

In the application, results show that our proposed method is easier to implement and that estimations are equally or more reliable than the classical method in the case of heavily censored data. Moreover, the proposed method represents a reliable option for including expert knowledge about the component as well as the physics of the failure mode; hence, it is a novel methodology. In addition, inspection time was estimated based on target risk; those results could be used to develop maintenance plans and to establish inspection frequencies.

2. Reliability engineering

As stated before, a critical factor of productivity in an industry is the timely maintenance of its installations, and thus maintenance's performance is a key objective. Developing an effective maintenance program requires extensive knowledge about reliability and maintainability; parametric analysis (which uses probability distribution functions) is an essential tool for such purpose.

Let the probability distribution function $F(x)$ represent the results obtained in a random experiment. Then for a given number x, the probability $P(X \le x)$ is given by the function $F(x) = P(X \le x)$. This function is denominated the cumulative distribution function of the variable X and represents the probability that the variable takes a value from $-\infty$ to x. Thus, if T is a random variable that represents the component life and assuming that T has a cumulative distribution function $F(t)$ expressed by $F(t) = P(T \le t)$, then the density probability function $f(t)$ is expressed as follows (Nahmias, 2009):

$$f(t) = \frac{dF(t)}{dt} \tag{1}$$

In addition to $f(t)$ and $F(t)$, other useful functions exist. One of them is the reliability function $R(t)$ (also called survival function); this function is defined as the probability that a new component survives no longer than time t and is expressed as follows (Mann et al., 1974):

$$R(t) = P\{T \le t\} = 1 - F(t) = \int_{-x}^{\infty} f(t)dt \tag{2}$$

In the reliability theory there is a fundamental relationship between $f(t)$ and $R(t)$, called the *hazard rate* function. Suppose that the lifetime is a positive random variable with density function $f(t)$ and cumulative function $F(t)$; then the function

$$\lambda(t) = \frac{f(t)}{1 - F(t)} = \frac{f(t)}{R(t)} \tag{3}$$

defines the failure hazard rate. This function represents the instantaneous change over the conditional probability at an instant t. It can be regarded as a probability measurement of a component that has survived until time t, failing at the following instant (Modarres et al., 1999). Knowing the failure rate $\lambda(t)$, it is now possible to construct its lifetime cumulative function given the useful relationship between reliability $R(t) = 1 - F(t) = P(T > t)$ and the failure rate $\lambda(t)$

$$P(T > t) = R(t) = \exp\left(\int_0^t \lambda(u)du\right) \tag{4}$$

by representing the integral in the above equation as $-\int_0^t d[\log(1 - F(t))]$. On the other hand, a random variable T is of increasing/decreasing failure rate type if the corresponding failure rate $\lambda(t)$ is an increasing/decreasing function of t, i.e. $T \in$ IFR (DFR) if $\lambda(t)$ is increasing (decreasing). Note that the exponential random variable is by definition, of both IFR and DFR; for reliability theory, a phenomenon closely related to this