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A methodology for product reliability enhancement via saturated–unreplicated fractional factorial designs

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ABSTRACT

Reliability enhancement constitutes an important component in product quality improvement. This work presents a methodology that unites the test effectiveness of Taguchi-type orthogonal arrays with the contrasting efficiency of order statistics at small sampling rates to create an optimization technique for improving reliability. The method relies on decoupling shape and scale effects and after a rank transformation, the super-ranking technique is applied to assign statistical significance to examined control factors. A case study based on aluminum milling operations is utilized to illustrate how the method presented here is adopted in screening through a can-stock product in order to achieve optimal levels of reliability.

1. Introduction

Reliability remains a product quality indicator of paramount importance in competitive manufacturing operations. Offering novel ideas in enhancing product reliability levels is a subject of continuous research [1]. Among the most popular approaches that aid in boosting reliability in manufactured products has been channeled through design of experiments (DOE). Standard DOE methodology requires that a score of relative product control factors be investigated in a predetermined range of selected factor settings (or levels) [2,3]. The examined product traits are modulated under structured experimentation and product responses are amenable to statistical comparisons to recover active effects that in turn result to optimal adjustments. A particularly interesting aspect of DOE data collecting schemes are the fractional factorial designs [4]. Fractionated designs have been shown to be useful for economical and timely product testing. Gathered field data are usually processed with a standard multi-factorial analysis tool such as the analysis of variance (ANOVA). However, reliability testing necessitates a series of replicates to be performed before statistical inference is drawn [5]. In such cases a usual approach is to resort to the signal-to-noise ratio (SNR) proposed by Dr. Genichi Taguchi several decades ago [6]. The SNR concept was originally thought of capturing simultaneous location and variation contributions from trial repetitions while incurring a convenient data preprocessing before enacting the multi-contrasting capabilities of the ANOVA method on the collected dataset. Nevertheless, there seems to be some concern about using the SNR data transformation inexplicably in reliability studies without taking in account several underlying criteria especially when assessing product response behavior [3,5]. Therefore, there is a need for approaching reliability improvement in DOE studies through a framework indigenous to the generally accepted concepts of the reliability theory itself. Barring threshold presence, the methodology we outline in the following sections is applicable to the 2-parameter Weibull model. The reliability optimization technique suggested herein incorporates directly the information that trial-run replicates carry by splitting first the respective influences according to shape and scale fluctuations between the conducted experiments. Then, this decoupled information is concurrently fed to a powerful non-parametric processor thus generating robust inferences. This notion is motivated by the fact that reliability engineers ought to figure out those control factors that maximize eventually the mean-time-to-failure (MTTF). For the standard two-parameter Weibull model, MTTF depends linearly on the scale estimator (for a constant shape value) while the shape estimator influences MTTF through a gamma function expression [7]. Moreover, following the bath-tub model, product life is extended for maximum scale parameter settings. Gamma function is also maximized when the shape parameter is maximized for values greater than one. Hence, optimal product reliability settings should be attained when the optimization method detects independently and in synchronous fashion the sources and their settings that account statistically for the best reliability performance. The methodology described herein is attempting to decouple the shape and scale effects from data collected from a Taguchi-type non-linear orthogonal array averting direct adoption of data reduction through the SNR concept. Decoupled reliability parameters are homogenized

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and manipulated via the super-ranking concept [8,9]. Efficient non-parametric techniques [10] are used to offer robust screening inference on the influence of control factors on the investigated reliability parameters. It is shown that the method is practical and effective while uniting well-established aspects in reliability theory and order statistics. A case study dedicated to the can-making sector targets manufacturing product reliability on aluminum can-stock containers intended for the soft-drink and beverage industry. Buckle strength data obtained from "drawing-and-ironing" forming operations have been programmed according to Taguchi's $L_9(3^4)$ saturated orthogonal array (OA). Resulting responses transformed to two-parameter Weibull model are confronted as though they were two sets of unreplicated quality characteristics. The method stresses the embodied convenience and built-in robustness in carrying out reliability improvement studies while eliminating data distribution concerns appearing due to anticipated shape and scale variations.

2. A brief literature review

A contemporary account of the evolution of the robust design methodology has been summarized in the work of Arvidsson and Gremyr [11]. The indispensability of DOE tools in building quality and reliability into a product while providing support to modern generalized improvement action plans such as those coded under the brand name of Six Sigma has been detailed previously [12,13]. Among the most useful applications of reliability enhancement have been implemented in the field of packaging. Taguchi methods have been employed to improve reliability of molded 225 plastic ball grid arrays and chip scale packages [14,15]. The effects of environmental stresses on electronics-packaging manufacturing maintain great interest especially when multiple environmental loading conditions are considered. Board level solder joints in PBGA packages have undergone reliability analysis under environmental stresses and optimized by Taguchi methods [16,17]. Soldering and surface mount technologies have presented many opportunities for strengthening reliability by resorting to classical DOE tools either focusing directly on a final PBGA product, or by influencing process conditions in a lead-free PCB assembly [18,19]. Of significant concern has been deemed the statistical treatment of reliability amelioration in microelectronic devises such as transistors [20,21]. For a state of the art exploration of the issues emerged in the field of reliability up to new challenges emanating in the world technological infrastructures has been the subject of a comprehensive review by Zio [22]. The need for conducting swift reliability tests has been well addressed [23]. DOE is an important component to reduce time for trial-execution completion [1].

Current trends in DOE standard methodology have evolved around concepts of fuzzy-rule classification in association with a Taguchi-type orthogonal multi-factorial sampling [24,25]. Goal programming and more entailed neural networks have also enjoyed extensive deployment in perplexing problem solving in manufacturing [26–29]. These methods are considered sophisticated yet powerful while requiring a substantial level of expertise to be carried out by ordinary quality and reliability engineers. Simpler techniques that utilize mainstream data mining tools may still be welcomed [30–33].

3. A methodology for non-parametric reliability improvement

3.1. Basic concepts on reliability definitions

The basic model for describing reliability parameters in a product has been proposed by Weibull [7]. In its more general form, the Weibull model requires three parameters in order to provide a quantification of the failure tendency possessed by a product trait. This tendency is easily discerned to a three-phase product life-time behavior as captured by the well-known "bath-tub" model. The three parameters involved in the Weibull model are: (1) the shape, β, (2) the scale, n, and (3) the threshold, γ. We will consider ordinary situations where the two-parameter model applies therefore anticipating that the threshold parameter is known or expected to be zero for the investigated product functions. The Weibull distribution, $f(t)$, for the two-parameter model when time t is the time elapsed since the product has been in use is expressed as

$$f(t)=\frac{\beta}{n}\left(\frac{t}{n}\right)^{\beta-1}\exp\left(-\left(\frac{t}{n}\right)^{\beta}\right) \tag{1}$$

It is clear that for optimal reliability behavior to occur the tested product should experience failings at the third phase of its life (wear-out phase) when $\beta>1$. At the same time it is the scale that it also that we seek to maximize. This is better understandable if one directly considers the respective mean-time-to-failure (*MTTF*) expression for the two-parameter Weibull distribution in Eq. (2)

$$MTTF=n\Gamma\left(1+\frac{1}{\beta}\right) \tag{2}$$

where $\Gamma(\cdot)$ denotes the gamma function [38]. It is noted that *MTTF* is maximized when the scale value is maximized. Independently, *MTTF* is also maximized when the Γ-function expression in Eq. (2) is maximized. The maximum value for Γ-function is reached either when β=1 leading to $\Gamma(2)$=1.00 or at the asymptotic limit $\beta\to+\infty$, where then $\Gamma(+\infty)\to 1.00$. Within this range of β-values, the Γ-function is minimized for β=2.222… rendering a value for the Γ-function of 0.8857. This shows that maximum modulation enforced on the *MTTF* value due to shape variability may not be larger than about 12%. Therefore, the corresponding reliability function, $R(t)$ (Eq. (3)) is optimized for the crucial time interval up to a time coinciding with the maximum attainable scale value while maintaining the shape value maximized during this time-interval

$$R(t)=\exp\left[-\left(\frac{t}{n}\right)^{\beta}\right] \tag{3}$$

Summarizing, it may be beneficial when performing DOE studies to maximize concurrently and independently the scale and shape parameters in order to improve reliability.

3.2. Design of experiments and the super-ranking concept in reliability enhancement

To enhance reliability in a product (or process), it is customary to experiment with pertinent control factors that are suspected to influence some group of product (or process) responses. We saw in the previous section that scale and shape parameters may play the role of independent reliability responses. These two responses may be treated by the super-ranking concept for an efficient non-parametrical optimal solution [8,9]. Super-ranking uses the same statistical processor that is shown to be efficient and effective for the single response case because it does not require information about the inherent distribution of the investigated responses [10]. For the two-sample contrasting case the comparison test of choice has been shown in the aforementioned references to be that of Wilcoxon–Mann–Whitney (WMW). However, for the non-linear case studied in this work, the classical Kruskal–Wallis (KW) test is the corresponding contrast routine that it is suitable for engaging more than two factor