Are All Designs of Experiments Approaches Suitable for Your Company?

Martín Tanco, Elisabeth Viles, Lourdes Pozueta

Abstract—**Most engineers have surely heard of Design of Experiments (DoE) but are incapable of differentiating among the main approaches followed to implement it (Classical, Shainin and Taguchi). Therefore, this article gives a brief presentation of each approach used for Design of Experiments, in order to initiate debate about them. This will be valuable in ascertaining the usefulness of each approach.**

Index Terms—**Design of Experiments, Taguchi, Shainin.**

I. INTRODUCTION

Lye [1] defined the Design of Experiments (DoE) as a methodology for systematically applying statistics to experimentation. More precisely, it can be defined as a series of tests in which purposeful changes are made to the input variables of a process or system so that one may observe and identify the reasons for these changes in the output response(s) [2].

Since experimentation is a frequent activity at industries, most engineers (and scientists) end up using statistics to analyse their experiments, regardless of their background [3]. DoE is an efficient technique for experimentation which provides a quick and cost-effective method for solving complex problems with many variables.

The statistical approach to Design of Experiments and the Analysis of Variance (ANOVA) technique was developed by R.A. Fisher in 1920. Since then, many have contributed to the development and expansion of this technique. Most techniques, defined throughout this article as "Classical", have adapted Fisher's ideas to various industries, including agriculture. However, engineers Shainin and Taguchi are especially influential due to their contribution of two new approaches to DoE. Both new approaches offer more than just Design of Experiments, as they can be considered quality improvement strategies [4].

Most engineers have surely at least heard of Design of Experiments (DoE), Taguchi Methods or the Shainin System^{TM}. Yet how many of them can really say that they understand the differences among them? Or that they are capable of correctly deciding when to use which technique?

The answer to these questions is heavily influenced by the knowledge and experience one has of each approach to Design of Experiments. Since the majority of practitioners only have experience with a single approach, this article aims to open their minds and compare available approaches.

OFAT (one-factor-at-a-time) is an old-fashioned strategy, usually taught at universities and still widely practiced by companies. It consists of varying one variable at a time, with all other variables held constant. All three approaches to DoE (Classical, Shainin and Taguchi) are far superior to OFAT. The aforementioned approaches have their proponents and opponents, and the debate between them is known to become heated at times. Dr. Deming once said, "Any technique is useful as long as the user understands its limitations." Therefore, the aim of this paper is to present each approach along with its limitations.

Each approach to Design of Experiments will be briefly described in the following section. In section 3, the main criticisms published in literature about each approach are highlighted. Finally, the conclusion and recommendations for engineers and managers working in the manufacturing industry are presented in section 4.

II. APPROACHES TO DESIGN OF EXPERIMENTS

Each approach to DoE is briefly presented in the following section from an industrial engineering perspective. They are presented in chronological order.

A. *The Classical Approach*

Although books on Design of Experiments did not begin to appear until the twentieth century, experimentation is certainly about as old as mankind itself [5]. The one-factor-at-a-time strategy (OFAT) was, and continues to be, used for many years. However, these experimentation strategies became outdated in the early 1920s when Ronald Fisher discovered much more efficient methods of experimentation based on factorial designs [1]. Those designs study every possible combination of factor settings, and are especially useful when experimentation is cheap or when the number of factors under study is small (less than five). Fisher first applied factorial designs to solve an agricultural problem, where the effect of multiple variables

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Martín Tanco is from the Department of Industrial Management Engineering at TECNUN (University of Navarra), Spain. (phone: 34-943219877; e-mail: mtanco@ tecnun.es)

Elisabeth Viles is from the Department of Industrial Management Engineering at TECNUN (University of Navarra), Spain (email: eviles,@tecnun.es)

Lourdes Pozueta is Director of the consultancy firm AVANCEX+i. Email: lourdes.pozueta@avancex.com

was simultaneously (rain, water, fertilizer, etc.) studied to produce the best crop of potatoes. His experiences were published in 1935 in his book "Design of Experiments" [6].

Fractional Factorial designs were proposed in the 1930's and 1940's in response to the overwhelming number of experiments that are involved with full factorial designs. This design consists of a carefully selected fraction of the full factorial experimental design. They provide a cost-effective way of studying many factors in one experiment, at the expense of ignoring some high-order interactions. This is considered to be low risk, as high order interactions are usually insignificant and difficult to interpret anyway.

According to Montgomery [2], the second stage in the era of the classical approach to DoE began in the 1950's when Box & Wilson [7] developed what was later called Response Surface Methodology (RSM). Their methodology allowed DoE to be applied in the chemical industry and afterwards in other industries as well. They touted the advantages of industrial experiments compared to agricultural experiments in the two following areas: *a) Immediacy:* response can be obtained quicker than with agricultural experiments, when results can sometimes take up to a year to be obtained; *b) Sequentially:* The experimenter is able to carry out few experiments, analyse them and again plan new experiments based on findings obtained from the previous experiments. In this era Central Composite designs (CCD) and Box-Behnken designs (BBD) were created.

The third era of the classical approach started with the appearance of the Taguchi and Shainin approach in the US in the 1980's as a simple and efficient method of experimentation. However, the Taguchi movement would soon be met with criticism attacking its statistical validity. Eventually, statisticians and academics began to acknowledge the value of certain engineering ideas of Taguchi and Shainin. This led to positive changes, adopting many ideas of the new approaches (for example, the reduction of variance became an important research area within classical design), and giving importance to constructing methodologies and guidelines to ease application. This leads to the final era of the classical approach.

In this last era, the democratization of statistics, thanks in part to software packages and the spread of Six Sigma thinking throughout industries [8], helped spread Design of Experiments to all types of industries. Moreover, an increasing interest in literature was advocated to Design of Experiments [9]. Furthermore, software packages have made the construction of graphs and calculus easier, further facilitating the application of DoE. Recent books by Funkenbusch (2005) [10] and Robinson (2000) [11] show how this approach can be easily understood by engineers.

Many scientists and statisticians have contributed to DoE development and to its application in different fields, making the classical approach a valid and robust methodology for Design of Experiments. The most commonly cited sources on this approach are Box et al. [12] and Montgomery [2].

B. The Taguchi approach

As a researcher at the Electronic Control Laboratory in Japan, an engineer known as Genechi Taguchi carried out significant research on DoE techniques in the late 1940's. Although he published his first book in Japanese in the 50's, the standardized version of DoE, popularly known as the Taguchi Method or Taguchi approach, wasn't introduced in the US until the early 1980's. His most influential books were "Introduction to Quality Engineering" (1986) [13] and "System of Experimental Design" (1987) [14]. The following decade was rife with heated debate mounted by two distinct camps of professionals, one unfailingly extolling the new-found virtues and power of Taguchi methods, while the other persistently exposed the flaws and limitations inherent to them [15].

Taguchi used and promoted statistical techniques for quality from an engineering perspective rather than from an statistical perspective [16]. Although Taguchi has played an important role in popularising DoE, it would be wrong to consider Taguchi Methods as just another way to perform DoE.

He developed a complete problem solving strategy [4], which he dubbed "Quality Engineering". However, there is general confusion in industry literature when dealing with systems aiming to reduce variation, as the terms robust design, Taguchi Methods, quality engineering and parameter design are used as synonyms [17].

The basic elements of Taguchi's quality philosophy can be summarized as follows [13, 16, 18]:

- A quality product is a product that causes a minimal loss to society during its entire life. The relation between this loss and the technical characteristics is expressed by the loss function, which is proportional to the square of the deviations of the performance characteristics from its target value
- Taguchi breaks down his quality engineering strategies into three phases, which he calls off-line quality control: System design, Parameter design and Tolerance design. System design deals with innovative research, looking for what factors and levels should be. Parameter design is what is commonly known as Taguchi Methods and is covered in this paper. This technique is intended to improve the performance of processes/products by adjusting levels of factors. Finally, Tolerance Design aims to determine the control characteristics for each factor level identified in earlier studies.
- Change experimentation objectives from "achieving conformance to specifications" to "reaching the target and minimising variability".

Since the core of Taguchi's parameter design is based on experimental methods [17], he went to great lengths to make DoE more user-friendly (easy to apply). Basically, Taguchi simplified the use of DoE by incorporating the following: a standard set of experimental design matrices (Orthogonal arrays), a graphical aid to assign the factors to the experimental matrix (linear graphs), clear guidelines for the interpretation of results (cookbook), special data transformation to achieve reduced variation (S/N Ratios) and a formal study of uncontrollable factors using the robust design technique, among others [18]. Finally, he simplified Tolerance Analysis through the use of DoE [19].

Taguchi's main contribution to experimental design was a strong emphasis on variation reduction. Quality is something that cannot be characterised solely by means of a defined quality characteristic such as yield. The variability of those characteristics must also be considered [20]. Therefore, he proposed a novel design, where factors (included in experimentation) are classified into two main groups: Control factors and Noise Factors. The first one includes parameters that can be easily controlled or manipulated, whereas noise factors are difficult or expensive to control. Therefore, the basic idea in parameter design is to identify, through exploiting interactions between control parameters and noise variables, the appropriate setting of control parameters at which the system's performance is capable of withstanding uncontrollable variation among noise factors [21]. Since the goal is to make the system resistant to variation of noise variables, the approach has also been called "Robust design".

A recent bibliography on Taguchi's approach to DoE may be found in Roy (2001) [18] and Taguchi et al.'s (2004) Quality Engineering Handbook [22].

C. The Shainin approach

The Shainin System™ is the name given to a problem solving system developed by Dorian Shainin, who died in 2000. Shainin, in 1975, established his own consulting practice: Shainin LLC. His sons Peter and Richard later joined the family business. Shainin described his colourful method as the American approach to problem solving, with the same goals of the Taguchi approach [23].

Shainin viewed his ideas as private intellectual property, which he was known to sell to clients to help them gain a competitive advantage [24]. As Shainin Systems™ are legally protected trademarks and some of its methods are rarely discussed in literature, it is difficult to obtain a complete overview of the approach [25].

Keki R. Bhote was authorised to publish information in the first and only book about these methods. His company, Motorola, won the Malcolm Baldrige National Quality Award, which stipulates that its methods be shared with other US Companies [26]. Interest in Dorian Shainin's problem solving techniques rose with the 1991 publication of this book (a second edition was published in 2000 [26]).

Dorian Shainin included several techniques- both known and newly invented – in a coherent step-by-step strategy for process improvement in manufacturing environments [25]. Among those powerful tools, he considered Design of Experiments as the centrepiece. Moreover, he didn't believe that DoE was limited to the exclusive province of professionals, but could rather be extended so that the whole factory could be turned loose on problem-solving [26].

The foundation of Shainin's DoE strategy rests on:

- The Pareto Principle: Among many, even hundreds of candidate factors, a single one will be the root cause of variation of the response y. That root cause is called the Red X® and may be a single variable or the interaction of two more separate variables [23]. There may be then a second or a third significant cause, called the Pink X® and Pale Pink X®, respectively.
- Shainin strongly objected to the use of the Fractional Factorial technique. He proposed instead to identify and diagnostically reduce most of the sources of variation down to a manageable number (three or four), at which time he allowed the use of full factorials [27].
- "Talk to the parts, they are smarter than engineers". First, talk to the parts. Then, talk to the workers on the firing line. Last, the least productive methods are to talk to the engineers [26].

The Shainin System presents many tools in a sequence of progressive problem solving. It can be divided into three main groups: Clue Generation tools, Formal DoE and Transition to SPC. The Shainin DoE technique considers as many variables as can be identified [28]. The first groups try to generate clues (like Sherlock Homes) with a number of tools (Multi Vary, Components Search™, Paired Comparison™, Process Search™ and Concentration Chart™) to reduce the number of variables involved in the problem through on-line experimentation. In the second stage, the Variable Search™ technique is used to reduce the number of variables by sequentially (not randomly) experimenting off-line, based on engineering judgement with binary search. Once a few factors are obtained, full factorials are used to analyse their effects and interactions. Afterwards, other techniques (B vs. C™, Response Surface, and ScaterPlots) are used to confirm the results and optimise them when necessary. Finally, in the last step, Positrol™, Process Certification and Pre-Control are recommended to guarantee that results will be obtained in the future.

III. LIMITATIONS OF THE DIFFERENT APPROACHES

A. The Classical approach

Up to the time when "Taguchi Methods" were propagated in the U.S., Design of Experiments (classical) and associated techniques were treated as mathematical tools, more like an adjunct to an engineer's technical resources for the study of product and process characteristics[15].

Taguchi and Shainin were the biggest critics of the Classical Approach. They believed that managers, engineers and workers found the use of DoE to be a complicated, ineffective and frustrating experience [26]. Consequently, those methods tended to be preferred by only those with a statistical or mathematical inclination [16].

However, it is worth mentioning that after a decade of strong opposition to their new ideas, the "classical" proponents began to acknowledge the importance of some of the new ideas proposed by Taguchi and Shainin. For example, there have been many attempts to integrate Taguchi's parameter design principle with well-established statistical techniques [16]. As a consequence, the exploitation of response surface methodology for variance reduction has become a major area of research [29, 30]. Moreover, the simplicity demanded by critics was reached (or at least greatly improved) by the aid of software capable of designing and analysing experimental design. Furthermore, great emphasis was placed on presenting guidelines and including graphical tools to clarify every step in the planning stage. For example, the Pareto Charts of effects or the use of Multi-Vary charts to correctly define the problem were included

B. Taguchi

There was great debate about these methods during the first decade after their appearance in the U.S. [19-21, 31]. Taguchi's approach was criticised for being inefficient and often ineffective [21, 32]. Moreover, Shainin was highly critical of Taguchi, challenging the myth of the "secret super Japanese weapon" [23].

Nair [21] identified three general criticisms of Taguchi's work: (a) The use of the SNR as a measure of the basis of analysis, (b) his analysis methods and (c) his choice of experimental designs.

Many have criticized the use of SNR as a performance measurement. Better approaches to the parameter design problem have been addressed in recent years, such as Box's performance measurement [33] or the Response Surface approach [29].

There has also been much criticism of the new analysis techniques proposed by Taguchi. Most of them are more difficult and less effective than previous ones. An example is the use of accumulation analysis [19, 34].

Finally, and most importantly, is the criticism of experimental designs. Firstly, orthogonal arrays were criticised for underestimating interactions. In response to this criticism, Taguchi stated [27], "A man who does not believe in the existence of non-linear effects is a man removed from reality". He believes, however, in the ability of engineers to decide on the levels of factors (called sliding levels), in order to make some interactions for that particular experiment insignificant. Unfortunately, there is evidence that interaction should be avoided. This is accepted as a matter of faith among Taguchi's followers [15].

On the other hand, the designs proposed by Taguchi to simultaneously study both the mean and the variance (crossed arrays) were also criticized, since they require multiple runs and generally don't allow to study control factor interactions. Therefore, Welch [35], among others, proposed using a combined array to reduce the number of runs. There has been much debate in recent years on this topic and it is not yet clear what the best approach is. Pozueta et al [36] and Kunert et al. [37] have demonstrated, for example, how classical designs are sometimes worse than Taguchi's designs.

It is worth mentioning that whereas some classical statisticians and academics have acknowledged the value of certain engineering ideas of Taguchi, the Taguchi camp has shown few signs of compromise, steadfastly vouching for the unchallengeable effectiveness of the Taguchi package of procedures in its original form [15].

For more details on the technical debate of Taguchi's approach, refer to Nair [21], Pignatello [19], Box [31] and Robinson [20], among others.

C. Shainin

As the Shainin System™ is legally protected, one of the only ways to learn about his method is to go to his classes. The only other alternative is to read Bhote's book [26]. The second edition has integrated new methods such as Quality Function Deployment (QFD), Total Productive Maintenance (TPM) and Poka-Yoke, among others; and has extended its methods to service application. Unfortunately, this book is full of hyperbolic, over optimistic, extremely biased and sometimes even intellectually dishonest claims in its urge to prove that Shainin's techniques are superior to all other methods. For example, Bhote claims, [26] "We are so convinced of the power of the Shainin DoE that we throw out a challenge. Any problem that can be solved by classical or Taguchi Methods, we can solve better, faster, and less expensively with the Shainin methods". Moreover, he presents DoE as the panacea to all kinds of problems and criticises other alternatives such as Six Sigma and TQM without academic basis behind his claims.

Although there is little written in industry literature about Shainin, the existing material is enough to fuel criticism of his methods. The most criticised techniques are the Variable Search™ [27, 28, 38, 39] and Pre-Control [24, 39]. Variable Search™ has much in common with the costly and unreliable "one-factor-at-a-time" method [27]. Shainin's technique relies heavily on using engineering judgement. Its weakness lies in the skill and knowledge required to carry out two tasks: firstly, to correctly identify the variables and secondly, to allocate those variables to the experiment [28].

On the other hand, although Pre-Control is presented as an alternative to statistical process control (SPC), it is not an adequate substitution. In particular, it is not well-suited for poorly performing processes where its use will likely lead to unnecessary tampering [24].

A recent review and discussion by Steiner et al. (2008) [39, 40] provides an in-depth look at the Shainin System™ and its criticisms.

V. Conclusions and Recommendations

Three different approaches to DoE have been presented throughout the last two sections. Although, there is a plethora of written material dedicated to each of these techniques (except for Shainin), there are few articles which give a down-to-earth discussion that could be useful to engineers.

These three approaches, compared with OFAT strategies, are more successful. However, this does not prove that they are the only techniques useful in improving quality and certainly doesn't show that they are necessarily the best.

Therefore, we will give some recommendations and conclusions on each approach based on our experience and research. Firstly, we must commended Shainin for stressing the importance of statistically designed experiments [27]. His methods are easy to learn and can be applied to ongoing processing during full production. Despite their obvious simplicity (which stems from the fact that they are, most of the time, simple versions of one-factor-at-a-time methods), they do not seem to offer a serious alternative to other well-established statistical methodologies. Classical and Taguchi approaches are still much more powerful, more statistically valid and more robust [27]. Shainin methods could perhaps have some applicability in medium-to-high volume processes for which a high level of quality has already been achieved [27]. They can also be used when dealing with binary response (for example, a machine works or not) and the reason behind the response may be due to a huge amount of variables.

On the other hand, the most important contribution of the Taguchi approach is in the area of quality philosophy and engineering methodology, which includes the loss function and robust design [16]. Taguchi Methods have the potential to bring about first-cut improvements in industrial applications. However, owing to their theoretical imperfections, success cannot be assured in every instance [15]. As a general rule, we don't recommend using Taguchi Methods unless you have to deal with two types of problems: Tolerance analysis and robustness to noise factors in products and processes. However, in those cases, the classical approach may also be suitable.

The two new approaches were a reaction to the existing complexity of the techniques used in industry. Both approaches are presented as an easy and effective technique for experimentation. However, since the appearance of both initiatives, the Classical approach has further developed the technique, including the engineering ideas of the new approaches. The introduction of software and graphical aids has made this approach much more user friendly than in the 80's. Therefore, this approach is the most established and has the most statistically valid methods.

However, although the classical approach has outgrown its "competitors", there is still a need to shape an easy experimental design methodology to develop the information necessary for good planning, design and analysis [16, 41]. Therefore, unless classical DoE is developed into easily understood strategies for solving specific problems and made widely available through teaching materials and software packages, we cannot expect it to become widely used on the factory floor.

Another strategy is to combine, with statistical rigor, the best DoE approaches in an easy, simple and integrated methodology from an engineering point of view. Instead of following one approach or another, we should use the most powerful tools available to gain the necessary knowledge of a process [32]. For example, the stress that Shainin placed on carrying out several on-line experiments in a diagnostic stage to analyse and characterise the problem before experimentation must be considered. Moreover, the awareness of the importance of variation in industrial experimentation carried out by Taguchi must force Quality Loss function and Crossed arrays to be integrated in this methodology. Finally, the importance of confirmatory runs, proposed by both of them, should also be stressed.

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