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An innovative approach for planning and execution of pre-experimental runs for Design of Experiments

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ABSTRACT

This paper addresses the study of the pre-experimental planning phase of the Design of Experiments (DoE) in order to improve the final product quality. The pre-experimental planning phase includes a clear identification of the problem statement, selection of control factors and their respective levels and ranges. To improve production quality based on the DoE a new approach for the pre-experimental planning phase, called Non-Conformity Matrix (NCM), is presented. This article also addresses the key steps of the pre-experimental runs considering a consumer goods manufacturing process. Results of the application for an industrial case show that this methodology can support a clear definition of the problem and also a correct identification of the factor ranges in particular situations. The proposed new approach allows modeling the entire manufacturing system holistically and correctly defining the factor ranges and respective levels for a more effective application of DoE. This new approach can be a useful resource for both research and industrial practitioners who are dedicated to large DoE projects with unknown factor interactions, when the operational levels and ranges are not completely defined.

1. Introduction

Design of Experiments (DoE) is one of the most powerful tools for process improvement and optimization in the scientific and engineering disciplines. It is widely used to develop robust processes, so that they are less affected by external sources of variability. Objectives of DoE are to study the performance of processes and systems and to better understand the behavior of the process factors, as well as their impact on the quality characteristics of the product and process under analysis. In other words, experiments are performed to (Montgomery, Keatsa, Perrya, Thompsonb, & Messinab, 2000):

- Determine which controllable factors have most influence on the response(s);
- Determine where to set the significant controllable factors in order to assure that the response(s) are close to their target value;
- Determine where to set the significant controllable factors in order to assure that the effects of the uncontrollable and noise factors on the response(s) are minimal.

Application of DoE in process improvements can result in improved process yields, reduced process variability and reduced overall costs (Montgomery, 2008). Over the past many years, industries have successfully applied DoE to improve process performance and reduce variability (Javorsky, Franchetti, & Zhang, 2014; Montgomery et al., 2000). However, other applications of DoE are also realized in the areas of product development (Fowlkes & Creveling, 1996) and performance optimization of automation technologies (Subulan & Cakmakci, 2011).

DoE consists of three important phases: pre-experimental planning; execution of the experiments; and statistical analysis of the data collected. Pre-experimental planning is a key phase for the successful implementation of the experiments because final conclusions largely depend on the way in which the experiments are planned. At the end of the pre-experimental planning phase, it is expected that the objectives of the experiment, the selection of response variables, factors and their levels and ranges required are clearly defined.

Definition of the problem and selection of factors and their levels and ranges are thus critical steps in any DoE analysis. Incorrect

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identification of the problem will lead to final recommendations that are not meaningful. Typically, in order to define and characterize the problem, cause-and-effect-diagram and Failure Mode and Effect Analysis techniques are applied as simple and straightforward methods to identify potential design factors. However, these techniques are applied once the region of interest is identified (Taguchi, Chowdhury, & Wu, 2005). In order to better identify this region, a Systems Engineering tool called Non-Conformity Matrix (NCM) is presented in this paper. This tool enables to model the entire system (e.g. industrial process) holistically, also allowing a systematic analysis of the interactions between its elements that, in our particular case, are the non-conformities identified along the production process.

After the region of interest is clearly defined, it is important to select the right factors and ranges that will be the subject of optimization through DoE, thus improving the quality of the final product. Factors are the input variables of a process that affect directly the response variables. In order to select factors and their levels and ranges, it is required that the experimenter has a deep process knowledge, based on a combination of practical experience and theoretical understanding, as well as historical data and/or previous experimental results, though, even considering all these information, there are still particular situations where the correct identification of factor levels and ranges is hard to accomplish. This might be due to a variety of causes, such as a certain immaturity of the process, a random behavior of the factor levels and ranges each time the production is run or even to the presence of unpredictable noise factors. The ideal way to address these problems consists in performing the pre-experimental runs to identify the factor levels and ranges for the above-discussed situations. In fact Czitrom (2003) and Coleman and Montgomery (1993) have also mentioned that if additional information is required on factor levels and ranges it is advisable to consider performing pre-experimental runs.

The objective of this paper is to study the pre-experimental planning phase of the DoE for an industrial case in order to improve the final product quality. The pre-experimental planning phase includes: (1) a clear identification of the problem, that was better achieved with the help of the NCM, as well as (2) the correct selection of control factors and their respective levels and ranges. Furthermore, application to the industrial case comprises studying practical problems typically faced while performing pre-experimental runs and selecting factor levels and ranges, highlighting the most important problems and cautions that should be taken into account at this phase of the experiment.

In the following sections, a brief introduction is presented on Design of Experiments and the techniques used in the pre-experimental planning phase. Also in this section an overview of the basics and principles of the Non-Conformity Matrix (NCM) is presented. Then, a comprehensive study is provided for the experimenters (scientists or engineers) in order to determine when the pre-experimental runs are required and what the key steps for its successful implementation are.

2. Guidelines for Design of Experiments (DoE)

The successful implementation of DoE is comprised of eight steps, as summarized in Table 1. The first four steps are normally termed as the pre-experimental planning phase (Montgomery, 2008).

The pre-experimental planning phase is one of the most important and critical phases of a DoE analysis that compromises the validity of the final results. In this phase, the statisticians or consultants, who design the experiments together with engineers and experimenters, have to bridge a gap in experience, available resources and knowledge. The current paper discusses in detail what is critical in steps I and II from Table 1, applying the defined procedures to an industrial example.

2.1. Pre-experimental planning phase techniques

Cause-and-effect-diagram techniques (Ishikawa diagrams), Quality Functional Deployment (QFD), and Failure Mode and Effects Analysis (FMEA) are typically used in the pre-experimental planning phase (Fahmy et al., 2012; Montgomery, 2008; Taguchi et al., 2005) to identify potential design factors. These techniques are often applied once the region of interest (where DoE is performed) is identified (Taguchi et al., 2005). In cause-and-effect-diagrams, first, all the controllable and uncontrollable factors that could influence the quality of the product are identified. This process is normally held in brainstorming sessions bringing together process engineers, quality engineers and line operators, and then these factors are hierarchically organized. This technique is also referred as fishbone diagram, because the effect of interest is drawn along the spine of the diagram and the causes are written along the ribs. The causes listed in the fishbone diagram are a big help in the correct identification of the potential failure modes.

FMEA can also be used instead of cause-and-effect diagram with additional advantages of identifying the seriousness of effects, how frequently effects occur, and how they can be detected. These metrics are represented by a risk priority number (RPN) for each effect and are calculated on a subjective basis (Fahmy et al., 2012).

Another technique that can be utilized to develop process matrix exhibiting interactions between the system elements is Quality Functional Deployment (QFD) (Browning, 2001). This technique is a four-phase process: understanding customer requirements (product planning), develop design planning matrix, develop process planning matrix, and develop operations planning matrix (Hassan, Siadata, Dantana, & Martina, 2010; Taguchi et al., 2005).

The technique proposed in this paper to identify potential key area consists of a systems engineering tool called Non-Conformity Matrix (NCM). This matrix models the entire system holistically, presenting the cause-and-effect relations between the system elements in a matrix form. The proposed tool, once compared to the more traditional quality tools, has three additional advantages: (i) Identification of the region of interest by analyzing the entire man-

Table 1
Guidelines for design of experiments.

Step	Phase
1. Problem statement and/or definition	Pre-experimental planning phase
2. Select factors and their levels and ranges	Pre-experimental planning phase
3. Select the response variable(s)	Pre-experimental planning phase
4. Choose the experimental design	Pre-experimental planning phase
5. Perform the experiment	Execution phase
6. Statistical analysis of the acquired data	Execution phase
7. Results validation using confirmatory runs	Statistical analysis and recommendation phase
8. Conclusions and recommendations	Statistical analysis and recommendation phase