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ROBUST DESIGN AND STATISTICAL PROCESS CONTROL IN A COLLABORATIVE ENVIRONMENT

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ABSTRACT

Nowadays, enterprises in global markets have to achieve high levels of performance and competitiveness to stay “alive”. In order to be competitive enterprises must develop capabilities that will enable them to respond quickly to market needs. According to several authors and as frequently mentioned by reports from practical case studies, one of the most relevant sources of competitive advantage is the involvement of enterprises in collaborative networks.

However, in spite of this assumption, it is also frequently mentioned that the lack of operational tools tailored to collaborative networks is not available yet and might be an obstacle for a wider acceptance of this paradigm. In this context, the collaborative networks need new statistical tools, new approaches and concepts of quality improvement.

Starting with a brief discussion about the nature and the role of some tools in order to support the development of robust design, this paper introduces some discussion about the application advantages of product design in a collaborative environment as a contribution to a future identification of methodologies, approaches that are suitable for collaborative contexts.

Keywords: Robust Design, Collaborative Networks, Statistical Process Control (SPC), Design of Experiments (DOE).

INTRODUCTION

The business environment has changed radically during last years, and new changes will certainly continue. Nowadays, trends are a feature of the business world. Some are imagined others are based on fashion, but many are real.

According to various authors on Collaborative Networks (CNs), as well as reports from a growing number of practical case studies, the involvement in a collaborative network is commonly assumed to bring valuable (potential) benefits to the involved entities (Beckett, 2005, Afsarmanesh, 2004, Tenera, 2008). These benefits include an increase of the “survival capability” in a context of market turbulence, but also the possibility to better achieve common or compatible goals. On the basis of these expectations are, among others, the following factors: joining of complementary skills and capacities, access to new / wider markets and new knowledge, etc (Camarinha-Matos, 2004).

Considered unusual and indeed suspicious until a few years ago, cooperation between enterprises is now a usual trend of the work for many enterprises. However, there are three environmental factors that have had the most decisive influence to encourage the cooperation.

The first is economic globalization. The world economy at the start of the twenty-first century is experiencing one of its moments of greatest dynamism and change. This dynamism is reflected in the growing interdependence of markets for goods, services and factors of production.

The second factor is the increase in business uncertainty. The speed in which changes are occurring in the economic world is introducing great uncertainty, especially in business areas where constant transformations, resulting from reductions in technological and product cycles, from improvement in productive processes and so on, often difficult to predict, are demanding greater follow-up capacity from enterprises in order to adapt to the new surrounding conditions.

Finally, the third feature is the high level of competitive rivalry. The increased customer requirements and market saturation are obliging the enterprises constantly to dig deeper in their search for competitive advantages to improve their position in the market. As a result of this, there is a tendency for enterprises to concentrate on know-how, or on those aspects of added value chain they really dominate.

Hence, the proliferations of a large variety of cooperation forms exist, such as: Outsourcing, Spin-off, Franchises, Joint venture, Consortium, and emergence of new forms of cooperation supported by the continuous advances in the information and communication technologies. Examples of these latter developments are advanced and highly integrated supply chains, virtual enterprises/virtual organizations, virtual (professional) communities and value constellations. All these cooperation models provide striking evidence of changes that have occurred in the business world in last years.

In a traditional design environment, the factors that affect a particular quality characteristic can be analyzed and can be fixed to their optimal levels. However, many of the quality characteristics are affected by factors that are barely able to be controlled in the stages of definition, conception and detailed design of the products, because they meet later stages, such as the manufacture or use.

THE ROLE OF ROBUST DESIGN AND SPC ON COLLABORATIVE NETWORKS

Today, it is considered that the variability is the main cause of the poor quality of products and processes and that the best time to solve this problem is in the stages of definition and conception. In other words, the products and processes will not only respond correctly to the laboratory conditions, but also to normal manufacturing conditions, and operating environment in which they are subjected to various types of disturbances (or noise from various sources).

In Japan, in the early '60s, under the leadership of Dr. Genichi Taguchi, a statistical approach to the systematic improvement of products and processes was developed. It introduced the concept of robust product: when a product is designed to be robust it should provide customer satisfaction, even when subjected to extreme conditions in manufacturing or service, that is, one that maintains the characteristics of acceptable quality levels regardless disturbances, whether these are due to manufacturing (process variation), to external causes (environmental factors, usage) or to internal causes (deterioration or degradation).

The method highlights the shifting quality issue for the design phase, focusing on defect prevention by improving the process. The method aims to improve the characteristics of products or processes by identifying and setting its controllable factors, and it succeeded to

minimize the variation of the response of the final product from that intended. By adjusting the factors at their optimal level, the products are to be constructed so that they become more robust, i.e. less sensitive to any changes that may occur, even if it is uncontrollable (environmental conditions, dimensional change, times packaging, etc.).

One of the robust design concerns is the definition of the most relevant quality characteristics and consequently the respective technical specifications, as well as the best levels of the process factors (controllable variables), not least to ensure, at later stages of the productive cycle, doable processes, i.e., revealing the ability to comply with these technical specifications. Before the production phase, several questions are raised related with the achievement of designed settings.

First, it must be ensured that the processes relating to the diverse quality characteristics are stable, i.e., have random evolutions over time (only the existence of common causes of variation). Monitoring of processes is the recommended way to verify this stability. This aspiration is achieved through the application of SPC (Statistical Process Control), using specific statistical techniques, the control charts (Pereira and Requeijo, 2012).

A second question, perhaps of greatest relevance, is to check whether the production output conforms to the technical specifications defined in the design phase, being the application of specific indicators, called process capability indices, the most effective way to respond to this question (Pereira and Requeijo, 2012).

A third concern is to produce with minimal variability. The answer to this question is to define properly the best levels (values) of the factors (controllable variables of the processes). The use of statistical techniques such as the DOE (Design of Experiments) and Taguchi methods are the suggested approaches to achieve that goal (Montgomery, 2012, Pereira and Requeijo, 2012).

STATISTICAL PROCESS CONTROL (SPC)

In robust design, the definition of the relevant product characteristics and its technical specifications is essential to deliver high quality products. At this stage of the life cycle of the product, the definition of the production process is also extremely important because it is intended that the production is consistent, i.e., the values of the quality characteristics are predictable and belong to the range defined by the technical specification.

The desideratum laid down in the preceding paragraph is achieved with the correct application of Statistical Process Control (SPC), which allows you to monitor the process behavior over time. The most widely used statistical techniques of SPC are control charts. The control charts were introduced in the 1920s by Shewhart in Telephone Laboratories (Shewhart, 1931). In the initial phase of implementation of control charts (Phase 1) main objectives are to check the stability of processes and the estimation of the parameters (mean and variance) of the processes.

Known the estimated values of the process parameters, it is crucial to verify the capability to produce in accordance with predefined specifications. Traditionally, the most common way to analyze the process capability consists in use of the capability indices C_p (Juran, 1974) and C_{pk} (Kane 1986). The simultaneous analysis of these two indices allows to evaluate the performance of the process, by comparison between the technical specification and the natural tolerances ($\mu \pm 3\sigma$ in the case of the distribution associated to the quality characteristic can be considered as normal distribution, when is considered a significance level of 0,27%).

Usually two stages are considered in the implementation of the SPC: the Phase 1, known as preliminary or retrospective, and the Phase 2 known as monitoring. In the Phase 1 the process parameters are unknown. In the Phase 1 the data collected will allow to check if the process is stable and to estimate its parameters. In Phase 2 the process parameters have already been estimated previously and thus it is possible to track the process in real time, ie, to monitor the process.

The appropriate implementation of the Shewhart's charts is based on the following principles:

- the samples must be homogeneous, i.e., all units must be produced under the same conditions;
- the sampling frequency, defined according to the characteristics of the process, must maximize the opportunity of variance between samples;
- the collected data should be independent, so the observation i of the sample k is defined by $x_{ik} = \mu + \varepsilon_{ik}$ ($i = 1, \dots, n$; $k = 1, \dots, m$), where $\varepsilon \sim N(0, \sigma^2)$ is a random variable designated by white noise;
- the collected data must follow a Normal distribution ($X \sim N(\mu, \sigma^2)$);
- the control limits of the different charts are located ± 3 standard deviations from the mentioned sample statistics, compared with the average of the distribution of sample statistics to be controlled (center line), corresponding to a level of significance equal to 0,27%.

Usually, the control charts \bar{X} and R , \bar{X} and S or X and MR are used for continuous variables. The processes should reveal which are under statistical control, i.e., submitted only to common causes of variation. The interpretation of Shewhart' control charts is based on the existence of any non-random patterns; the patterns can be detected by the rules of ISO 8258:1991.

Phase 1

In Phase 1 of the SPC, it proceeds to the construction of the more appropriate Shewhart' charts. The upper limit (UCL) and the lower limit (LCL) control of these charts, as well as the central line (CL), are determined using the equations presented in Table 1 (Requeijo and Pereira, 2012).

Table 1 Control limits of Shewhart' charts, in Phase 1 of the SPC

Chart	LCL	CL	UCL
\bar{X} (average)	$\bar{\bar{X}} - A_2 \bar{R}$ ou $\bar{\bar{X}} - A_3 \bar{S}$	$\bar{\bar{X}}$	$\bar{\bar{X}} + A_2 \bar{R}$ ou $\bar{\bar{X}} + A_3 \bar{S}$
X (individual observations)	$\bar{X} - 3(\bar{MR}/d_2)$	\bar{X}	$\bar{X} + 3(\bar{MR}/d_2)$
R (amplitude)	$D_3 \bar{R}$	\bar{R}	$D_4 \bar{R}$
S (standard deviation)	$B_3 \bar{S}$	\bar{S}	$B_4 \bar{S}$
MR (mobile amplitude)	$D_3 \bar{MR}$	\bar{MR}	$D_4 \bar{MR}$

If the process is stable (in-control), it proceeds to the estimation of its parameters using the equations:

$$\hat{\mu} = \bar{\bar{X}} \quad \text{or} \quad \hat{\mu} = \bar{X} \quad (1)$$

$$\hat{\sigma} = \frac{\bar{R}}{d_2} \quad \text{or} \quad \hat{\sigma} = \frac{\bar{S}}{c_4} \quad \text{or} \quad \hat{\sigma} = \frac{\overline{MR}}{d_2} \quad (2)$$

The study of the capacity of each process is carried out through the classical capability indices:

$$C_p = \frac{LSE - LIE}{6\sigma} \quad (3)$$

$$C_{pk} = \min(C_{pkI}, C_{pkS}) \quad (4)$$

$$C_{pkS} = \frac{LSE - \mu}{3\sigma} \quad \text{and} \quad C_{pkI} = \frac{\mu - LIE}{3\sigma} \quad (5)$$

A process is considered as capable if $C_{pk} \geq 1,33$ (bilateral specifications) or $C_{pk} \geq 1,25$ (unilateral specifications).

The equations (3), (4) and (5) can be used only if the evaluated characteristic follows a normal distribution. It is suggested to use the Kolmogorov-Smirnov test to check if the data follow a normal distribution.

If a process is not under statistical control, should be investigated the causes that led to this situation and to make appropriate corrections. If the process is stabilized, but not present enough capacity, there it should be corrected.

Phase 2

After the stability checked and the process capability analyzed in Phase 1 of SPC, the statistical control is continued through the process monitoring, designated as Phase 2 of the SPC. As previously mentioned, it should distinguish two situations where you control one or more products / features.

The techniques to be implemented are the Shewhart' charts, in which the control limits are determined based on estimates of process parameters, calculated in Phase 1. This Phase 2, called monitoring, aims to monitor the process, identifying possible special causes of variation and operate in the production process with appropriate corrective actions.

The formulas used to calculate the control limits of Shewhart' charts for the Phase 2 of the SPC (Pereira and Requeijo, 2012) are presented in Table 2.

DESIGN OF EXPERIMENTS

One of the most important aims of the organizations of the XXI century is to produce consistent and robust to noise products, i.e., the processes with good capacity, centered over the technical specifications, and with reduced variability.

Table 2 Control limits of Shewhart' charts in Phase 2 of the SPC

Chart	<i>LCL</i>	<i>CL</i>	<i>UCL</i>
\bar{X} (average)	$\mu - A\sigma$	μ	$\mu + A\sigma$
<i>X</i> (individual observations)	$\mu - 3\sigma$	μ	$\mu + 3\sigma$
<i>R</i> (amplitude)	$D_1\sigma$	$d_2\sigma$	$D_2\sigma$
<i>S</i> (standard deviation)	$B_5\sigma$	$c_4\sigma$	$B_6\sigma$
<i>MR</i> (mobile amplitude)	$D_1\sigma$	$d_2\sigma$	$D_2\sigma$

The issues arising in the study of the process capability were discussed in the previous chapter, remaining in this context the approach to reducing variability, i.e. reducing the common causes of variation due to different sources of variation, always present in production processes. This desideratum is achieved primarily through two interventions. A more significant reducing can be achieved through the involvement of top management on the amendment of some of the resources allocated to processes, such as new equipment, more skilled suppliers, more effective training of employees of the organization.

If is not available to bring new financial resources, it is possible some reduction in variability by optimizing the levels of factors (controllable variables) present in manufacturing processes.

The Design of Experiments (DOE) is a methodology that allows to select the best combination of the factor levels, in order to optimize the value (s) of the quality characteristic (s), both with regard to its average value as the reduction of variability, i.e., allows to determine which controllable factors are affecting certain quality characteristics and the best levels of those factors in order to increase the product's resistance to noise factors, satisfying the requirements of the various stakeholders in an organization's performance.

Any Design of Experiments requires, before implementation, a systematic approach to its application leads to positive results. Generally, such approach should include the following points:

- Establishment of the research team.
- Clear definition of the objectives of the experiments.
- Background analysis.
- Selection of output, i.e., choice of quality characteristics as well as their measurement methods.
- Selection of controllable factors and their experience levels and, if feasible, the choice of factors and levels of noise.
- Previous analysis of the possible interactions between factors, understanding that there is an interaction between two factors when the effect of one factor in the response depends on the level of another factor.
- Identification of factors that will remain constant during the experimentation.
- Identification of constraints to experimentation.

- Definition of the number of experiments to run, and in the light of this decision and of the number of factors and levels, planning for experiment using the most appropriate matrix, i.e. define what the layout of the experimentation.
- Setting the number of replications (the number of times that specific experience is repeated).
- Execution of the experiments (trials) at random way.

The choice of the layout of the experimentation is performed according to the number of factors and the levels of these factors. Usually, the fractionated schedules are used, i.e. designs which study only a part of the total possible combinations. This paper presents a fractional factorial design with two-level factors, referred as 2^{k-p} , where k represents the total number of factors and p the number of generators. For better understanding of this issue, it is suggested to consult Pereira and Requeijo (2012) and/or Montgomery (2012).

For better understanding, it is presented the fractional factorial 2^{3-1} . It means that the total number of factors is 3 (A, B and C), there is a generator and that the total number of experiments is equal to four ($2^{3-1} = 4$). The planning matrix consists of four experiments, by which two factors are considered “main” and one factor is considered as “generated factor”. Thus, the factor C is chosen as “generated factor”, i.e. the level of this factor on trial will depend on the level of other factors (the generator).

Whereas the generator is given by interaction AB , $C \equiv AB$, (the effect of AB is confused with the effect of C), the planning matrix is given by:

Table 3 Matrix Planning Design 2^{3-1}

Default Order	A	B	C	Result
(1)	–	–	+	$y_{11} \cdots y_{1n}$
a	+	–	–	$y_{21} \cdots y_{2n}$
b	–	+	–	$y_{31} \cdots y_{3n}$
ab	+	+	+	$y_{41} \cdots y_{4n}$

The statistical technique ANOVA (Analysis of Variance) is used to identify factors and interactions having significant influence on the results. So, it is necessary to determine the variations due to each factor/interaction. The variations (SS) are calculated from:

$$SS_x = \text{Variation of Factor X} = \frac{(\text{Contrast X})^2}{2^{k-p}n} = \frac{[(\sum y)_{x^+} - (\sum y)_{x^-}]^2}{2^{k-p}n} \quad (6)$$

The effect of the factor (the average effect of a factor is the change in response caused by a change in the level of this factor) is given by:

$$\text{Effect of Factor X} = \frac{\text{Contrast X}}{2^{k-p-1}n} = \frac{(\sum y)_{x^+} - (\sum y)_{x^-}}{2^{k-p-1}n} \quad (7)$$

The contrast or interaction of a factor is calculated from the values of the responses of multiple replicas of the experiment. For example, the contrast factor A is given by:

$$\text{Contrast of A} = -\sum_{j=1}^n y_{1j} + \sum_{j=1}^n y_{2j} - \sum_{j=1}^n y_{3j} + \sum_{j=1}^n y_{4j} \quad (8)$$

The ANOVA table for the fractional factorial design 2^{3-1} is given according to the main factors and their interactions. In the case chosen ($C \equiv AB$), is given by:

Table 4 ANOVA Table of Design 2^{3-1}

Source of Variation	SS_X	ν_X	MS_X	F_0
A	SS_A	1	SS_A/ν_A	MS_A/MS_{Error}
B	SS_B	1	SS_B/ν_B	MS_B/MS_{Error}
AB	SS_{AB}	1	SS_{AB}/ν_{AB}	MS_{AB}/MS_{Error}
Error	SS_{Error}	$(2^{k-p}n-1)-3$	SS_{Error}/ν_{Error}	
Total	SS_T	$(2^{k-p}n-1)$		

The total variation and the residual variance are given by:

$$SS_T = \text{Total Variation} = \sum_{i=1}^{2^{k-p}} \sum_{j=1}^n y_{ij}^2 - \frac{\left(\sum_{i=1}^{2^{k-p}} \sum_{j=1}^n y_{ij} \right)^2}{2^{k-p}n} \quad (9)$$

$$SS_{Error} = SS_T - \sum SS_X \quad (10)$$

The decision to consider a factor / interaction as significant, is carried out by comparison between the value of the test statistic with its critical value; it is same with any hypothesis test. In the case of ANOVA, where $F_0 > F_{\alpha; \nu_X; \nu_{Error}}$. It is considered that the factor / interaction X is significant, *i.e.*, contributes significantly to a change in value of the response when X passes from one level to another.

In the fractional factorial design it is considered that the effect of higher order interactions (formed by the interaction of three or more factors) is equal to zero, so that it shall consider only the effects of the factors and of the interactions between two factors.

The best factor levels are determined by analyzing the mean values of the response of the significant factors / interactions, for the high level (+) and for the low level (-). Thus, the chosen level must maximize the response, e.g., if the characteristic response of quality is “the bigger is the best”, the best level is the one that maximizes the value of the responses.

After the identification of the effects affecting the response significantly, for the $(k - p)$ main factors and their interactions, you should check with which factors they are confounded, considering now all k planning factors. To identify the confused effects, it is necessary to find the “Definition Relation” of the fractionated factorial; this relation is characterized by the column in which all the experiments are at high level +).

This column (s) is obtained by multiplying the column referring to the generator (s) about it (s) itself (s). Considering the example of the fractional factorial design 2^{3-1} , the definition relation is given by: $I \equiv AB \times AB \equiv AB \times C \equiv ABC$.

The planning set quality is known immediately, based on the definition relation, constituted by all the Identity elements. This indication is given by the "resolution" of the fractional factorial. Three types of resolution are distinguished, R.III, R.IV and R.V, which are characterized by:

- R.III (Resolution III): the main effects are not confused with other main effects, but are confused with two factors interactions, these two factors interactions are confused with each other.
- R.IV (Resolution IV): the main effects are not confused with each other either with the two factors interaction, but the interactions of two factors are confused with each other.
- R.V (Resolution V): both the main effects as the interactions of two factors are not confused with each other, but the interaction of three factors are confused with interaction of two factors.

The structure of the confused effects for a fractional factorial design 2^{3-1} is given by:

$$A \equiv A \times I \equiv A \times ABC \equiv A^2 BC \equiv BC$$

$$B \equiv AC$$

$$C \equiv AB$$

CONCLUSION

In today's world, companies operate in markets exposed to the effects of globalization, the windows of opportunity for doing business are becoming shorter in time, as well as the business environment is increasingly volatile.

Quality and consistence of quality levels at all stages of the life cycle of products is a crucial issue for collaborative networks.

This paper presents a discussion of the advantages and problems of integration and interaction between Robust Design applied to the product design activities, and Statistical Process Control/Design of Experiments applied to the production activities of the same product, in the collaborative network environment. This study can contribute to a future identification of approaches that are suitable for industrial environments.

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