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Interuniversity Research Center "STEERING" - STatistics for EnginERING: Design, Quality and Reliability

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Abstract

In this paper we present the Interuniversity Research Center STEERING, formed in June 2017. The Research Center has been founded by three Italian Universities through five Departments. It represents the connection between Statistics and Engineering. The five Departments promoting it are the following: Department of Innovation and Information Engineering (Guglielmo Marconi University, Rome); Department of Statistics Computer Science Applications, Department of Information Engineering, Department of Industrial Engineering (University of Florence); Department of Mechanical and Civil Engineering (University of Cassino and Lazio Meridionale). The potentiality of the Research Center and some of its aims are explained through three empirical case studies.

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1. Introduction

The technological developments and the productivity of a country are strictly related to the scientific research in the engineering field. With this spirit, the necessity has become increasingly clear of improving the interdisciplinary feature for the scientific research, substantially by joining the statistical resources and knowledge, based on mathematical and quantitative sciences, with engineering. In the statistical field, the recent methodological developments occurred for the last two decades have confirmed the need of improvement for quality and reliability starting from the product design step, in order to reduce actions during production. Therefore, process optimization is one of the fundamental steps to achieve high technological levels in almost of all the engineering fields: starting from materials, also for environmental sustainability, up to experimental studies relating the design of mechanical characteristics, by also

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considering costs and better performances. In this context, the Interuniversity Research Center STEERING (Statistics for Engineering: Design, Quality and Reliability) has been formed to promote scientific research and studies regarding the application and the methodological developments of statistics for improving engineering issues, such as the application of experimental designs and modeling for quality and reliability. To this end the Research Center focuses on scientific collaborations among academics and industrialists through research projects and conferences, at national and international level.

1.1. The Research Center: potentialities and aims

The industrial use of quantitative techniques such as Lean Six Sigma (Arcidiacono et al. (2012)) has the advantage to combine the application of statistical tools and methods for analyzing data (Six Sigma) with the Lean properties, by reducing costs and time. The Lean Six Sigma novelty was the inclusion of well-known statistical methods in a systematic procedure where data play the basic and main role for process knowledge. Undoubtedly, the collection of data-sets, especially when performed according to statistical criteria, is now the starting point for improving and developing quality within companies. Furthermore, currently, the statistical methods based on design of experiment methodology allow for achieving optimal responses through the robust process optimization techniques, in which the experimental design and statistical modeling are jointly applied, and by involving control (process) variables studied in conjunction with (and conditional to) noise random effects.

Therefore, the aims of this Research Center are mainly addressed to the development of experimental methods and strategies for technological applications by strictly following a scientific approach, and they may be summarized as follows:

- To promote the collaboration between statistics and engineering for improving scientific research at national level; more precisely, to develop studies and applications of statistical methods for design, reliability and quality;
- To promote collaboration between statistics and engineering within the firms, by highlighting the advantages of statistics when applied in conjunction with engineering for evaluating the quality control and the reliability of a product, giving valid and constructive solutions;
- To implement integrated management systems for the sustainability & safety of production processes;
- To develop the technological research, particularly for statistical theory and methods useful to solve new quality and reliability issues and challenges that engineering may suggest.

2. Case studies

This section introduces three examples of case studies related to specific applicative and research projects in which their authors, who are also the Research Center promoters, were involved. For each example, specific references have been detailed.

2.1. Case study no.1: a robust process optimization of the soldering process with electrically conductive adhesives in electronic equipment

In these researches Catelani et al. (2011) and Berni et al. (2013) carried out experimental and comparative studies on soldering made up of epoxy adhesives. In particular, Electrically Conductive Adhesives (ECA) constituted by metallic particles (silver), normally in the form of flakes, in a polymer matrix are considered. The novelty of the kind of adhesive considered is the Ag filler loadings of 50-65% by volume. At these loadings, the materials achieve the percolation threshold and are electrically conductive in all directions after the materials are cured. Two different types of conductive adhesives, characterized by different chemical structures and compositions, have been experimented and tested. Then, since the lead-free soldering process is characterized by several critical factors, a statistical approach is used to optimize this process. The goal is to understand and to optimize the electrical performance of ECAs film with bulk electrical resistance measure. Following the literature of the past few decades related to the generalization of the Taguchi's two-step procedure (Nair (1992)) and the concept of robust design performed through a dual-response approach by applying Generalized Linear Models (GLMs), as introduced by Nelder and Lee (1991) and Lee and

Nelder (2003), in our study we use GLMs (McCullagh and Nelder (1989)) jointly with a Combined Array (Myers et al. (1992)) structured for the experimental design. Therefore, a dual-response approach defined by two distinct models, one for the mean and one for the dispersion, able to optimize the soldering production process, is carried out separately for each ECA. The planned experimental design is a mixed-level fractional factorial design with Resolution V, with two added center points ($n_0 = 2$) for each block, where a block corresponds to an ECA. The building of the mixed level design is performed by using a fractional factorial with five main column vectors. Furthermore, this design allows us to study each ECA through 16 runs by blocking in an unreplicated design; the $n_0 = 2$ center points are added in order to improve the finding of quadratic effects and the optimization step for each block. The considered variables were the following: the electrical resistance [Ω] as response variable; a block factor which considers two types of adhesive: mono and bi-component; during the spin-coating procedure: the spin-coating time [*s*] and the radial velocity in [round-per-minutes]; during the curing procedure: the temperature of curing [°C] and the curing time [*min*]. The final experimental design involved the block factor and three variables: radial velocity, spin-coating time and curing temperature; 36 trials were carried out, 18 runs for each ECA. During the modeling step, the GLMs application allows for evaluating two models for each ECAs: location and dispersion models without performing replicates. The final step is the dual-response optimization carried out for each ECA, in which two weights were calculated, one for the mean and one for the dispersion model. The complete analysis (modeling, and optimization) was carried out on the coded experimental region. Furthermore, the target value posed at 0.04 Ω has been achieved for both ECAs conditioning to a curing temperature below 150 °C. In the following table (Table 1), the optimization results are illustrated for each ECA; the optimal factor levels allows for achieving the target value.

Table 1. Optimal factor values achieved for each ECA.

ECA	Radial vel. [rpm]	Spin-coat. Time [s]	Curing Temp. [°C]
Mono-component	6055.61	23.64	146.79
Bi-component	4820.00	10.62	144.60

2.2. Case study no.2: Six Sigma project to reduce the defects in dashboard

In this case study each of the 5 DMAIC (*Define*, *Measure*, *Analyze*, *Improve* and *Control*) phases structuring the Six Sigma project sets a few milestones to indicate a way to follow in order to achieve higher process comprehension and more efficient problem solving strategies. Issues that may influence the final results in Six Sigma applications, as explained by Arcidiacono et al. (2016), are: the way these milestones are defined, the ability people have to understand the context, and the proper efforts to gain the desired goals. At the basis of the success of Six Sigma applications are: the correct and appropriate use of tools, the scientific rigor of the method, as developed by Arcidiacono et al. (2017) within other works , the step-by-step approach, and a strict time management of projects. The goal of this project is the reduction of the percentage of defects or non-conformities in the production of car dashboards (Fig. 1a). The authors have already developed the reduction of non-conformities in Giorgetti et al. (2017).

This case study presents how Six Sigma methodology can develop improvement in manufacturing process by following the 5 DMAIC phases. The subject of the study was taken in consideration due to the rarity of usage of a specific machine in Italy. The Six Sigma method was adopted since one its main goals as presented by Ismyrlis and Moschidis (2013), is to know the process more in depth, especially when it is relatively new, so that it would be possible to evaluate its weaknesses and critical phases that could create manufacturing scraps.

The process was initially described with the necessary details in the *Define* phase defining the boundaries of the process: in this case the process is described through the sub-processes of *Silk-screen printing* of polycarbonate sheets, relative *Drilling*, *Slot shearing* and *Thermoforming*. In the car dashboards industry, only two Companies in Italy use the particular machine to thermoform the sheets which was the object of study. Due to different root-causes this process is complex and therefore the purpose of this work is to analyze it through the Six Sigma method. In particular, the practical improvement to be achieved is the reduction of defects due to bad centering of the *Silk-screen printing* of the sheets. Because of this issue it is necessary to find a robust indicator representing the considered phenomenon,

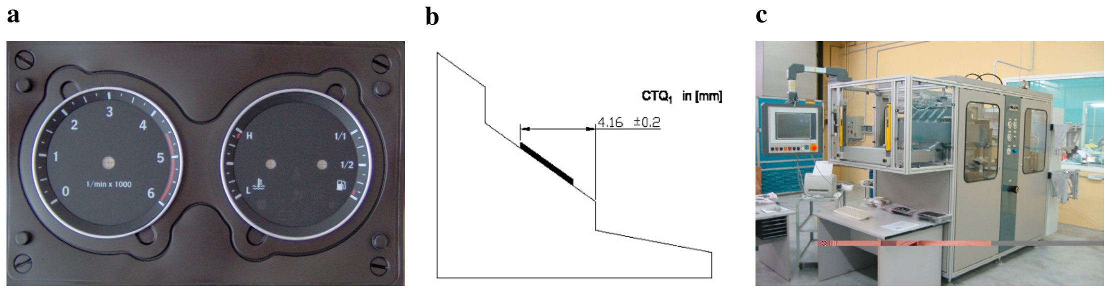

Figure 1. (a) Car dashboards; (b) CTQ; (c) Niebling machine.

or, in other words, what is Critical To Quality (CTQ) for the customer (Fig. 1b). As agreed with the end client, the horizontal distance was selected as CTQ. The USL (Upper Specification Limit) was set at 4.36mm and LSL (Lower Specification Limit) at 3.96mm. A dashboard with a distance out of the range [3.96-4.36] is considered defective, and therefore not acceptable for the client. The process under scrutiny was made up of different phases, namely the Silk-screen printing phase, the Drilling phase, the Slot shearing, and the Thermoforming phase performed with a Niebling machine (Fig. 1c). After the completion of the *Define* phase, process performance data were collected in order to have additional information on the examined problem in the *Measure* phase. The various phases of the process were analyzed to identify the most critical ones and prioritize intervention. From the "as is" picture of the process, *Thermoforming* optimization clearly emerged to be a priority on which to intervene. The problem was at this point defined, and its entity refined through a sum of measures which allowed for further analysis. The *Analyze* phase helped to focus on the process steps to discover the most critical ones, and attack the higher losses in terms of performances and costs: the Cause-Effect or Fishbone Diagram was used hereby to highlight all of the potential causes that produce the defected dashboards. The process performance was measured through CTQs; in particular the 3 points for the left dial (Mark 0, 3 and 6) and the 4 points for the right dial (H, L, 1/1 and 0/1) were analyzed. For the *Improve* phase, the critical parameters and their interactions were studied within the *Thermoforming* process in order to optimize it by using Design of Experiments (DOE). To begin with, the optimization of each singular CTQ was considered, that is each singular nick for left (CTQ-0, CTQ-3, CTQ-6) and right (CTQ-H, CTQ-L, CTQ-1/1, CTQ-0/1) dial; then the optimization for the right on one hand and left dial on the other hand. The levels of the main significant factors were set on statistical and physical perspective in order to optimize all seven CTQs of the examined dashboard. For the optimization for CTQ-0 a statistical analysis by ANOVA was performed where both Main Effects and 2-Way Interactions were proved to be significant (P-value < 0.05). Using the Overlaid Contour Plot, each plot showed the area which was able to satisfy the target of the CTQ in order to select the best levels for each nick to optimize them all simultaneously. At the end of the necessary analysis, the Response Optimizer provided the levels for each factor able to optimize all the seven CTQs that had be isolated. The final goal was then achieved to minimize the effects of the Noise Factors and maximize the robustness of the production that has a reduced output variability (CTQs). The last phase (*Control*) of the project was to sustain the achieved improvement for the future, monitoring it day by day through the Control Chart (Xbar-R). In conclusion, the statistical analysis performed allowed to set machine parameters at best to optimize the CTQs, through a good centering of the *Silk-screen printing* of the sheets. The project out featured by this case study lasted 3 months, after which the process performance increased, according to the target of the Project Charter. The defect percentage was 10% of the total production, at the start of the case study; the goal achieved a defect percentage equal to 0.005%. Eventually, the financial benefits related to the project amount to 70,000 Euro/year.

2.3. Case study no.3: Split-Plot and robust optimization for a Numerical Control machine in a multiple response case

This last example is related to the robust process optimization of a numerical control (N/C) machine studied by Berni and Gonnelli (2006) and Berni (2010) through the application of a split-plot design and modelling in a 2^{nd} order Response Surface Methodology (RSM) setting. Since 1992, split-plot design has received great attention as a valid plan in the technological field and for a robust design approach as suggested by Box and Jones (1992). In this study, our main aim is to analyze this experimental design from two points of view: the theoretical basis of a split-plot is

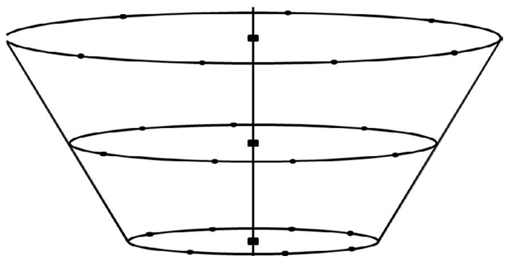

Figure 2. The frustum of cone.

first evaluated as a specific and valid experimentation for the robust-design concept, in order to estimate with accuracy the interaction terms related to noise and design (control) factors; the second point relates to the split-plot and the optimization in a multiresponse case, within the RSM setting (Vining et al. (2005)), by involving just one objective function and the possibility of weighting the response variables according to their role in achieving the optimal value. In order to solve the problem of optimization in the multiple response case of RSM and in the dual approach (two surfaces which consider location and dispersion effects), we suggest a single measure (a weighted function of several variables of interest) which allows us to fit just one surface in terms of all the dependent variables. The aim of experiment is the improvement of the accuracy in measurements of a N/C machine and the reduction of the measuring time. The machine works by a feeler pin and it has a movable bridge framework to facilitate the positioning of the piece which must be checked. For practical purposes, reference will be made to a dental implant as the piece to be measured, but the specific nature of the piece is irrelevant. Note also that, the reduction of measurement time is implicitly the only possibility in order to reduce the costs, which are a secondary problem in this case, where the risk for a patient is the most relevant problem due to the measurement accuracy. The machine needs specific environment conditions to be functioning properly: it has an integrated thermal compensation system which ensures proper measuring conditions and the setting of the external temperature has been solved previously by Berni and Gonnelli (2006). The steps of the experimental planning can be outlined as in the following:

- The response variables are five quantitative variables related to the different positioning of the feeler pin on the dental implant during the process measurement steps.
- The full measurement process includes six phases. In order to reduce the measuring time, the only step where we may intervene is the location of the frustum of cone by 3 circles; i.e. the frustum of cone is located by 3 circles at 3 different distances (see Fig. 2).
- In order to locate each circle, the N/C machine software identifies a circumference by selecting several points by the feeler pin. A measuring time improvement may be achieved by reducing the number of points.
- Two other sources of variability are included in our planning: the measurement speed (mm/sec) for each point; and the speed of the feeler pin (mm/sec) when it is drawn onto the piece or it turns around the piece. Both factors are considered as fixed levels; their setting is chosen before beginning the measurements process.

Therefore, a split-plot design with 3 factors is planned; the two whole-plot factors, both at two levels, are the drift speed and the measurement speed, while the single sub-plot factor (of greater interest) is defined as the number of points selected to measure each circle in order to identify the frustum of cone (named “circle point”). In Fig. 2, we show the frustum of cone formed by the three circumferences, each one identified by seven points (to be reduced). The application, (computed with the SAS-software), starts by considering the results obtained for the estimated surface for each response variable (5 surfaces). These estimates, are used to optimize the objective function, all surfaces simultaneously.

Note that the simultaneous optimization was reached by conditioning on the specific setting of points corresponding to the levels of the ”circle-point”, for details (Berni (2010)). The optimal experimental solution in terms of robust design is also identified according to the nearness to the target values jointly with the reduction of measuring time and the level of drift speed. Weighting is a specific problem and it is included in the optimization procedure through the minimization of the objective function with respect to the weights as well as the factors.

References

Arcidiacono, G., Berni, R., Cantone, L., Placidoli, P., 2017. Kriging models for payload distribution optimisation of freight trains. International Journal of Production Research 55, 4878–4890.

Arcidiacono, G., Calabrese, C., Yang, K., 2012. Leading Processes to Lead Companies: Lean Six Sigma: Kaizen Leader & Green Belt Handbook. Springer Science & Business Media.

Arcidiacono, G., Costantino, N., Yang, K., 2016. The amse lean six sigma governance model. International Journal of Lean Six Sigma 7, 233–266.

Berni, R., 2010. Split-plot and robust designs: Weighting and optimization in the multiple response case. mODa 9–Advances in Model-Oriented Design and Analysis , 25–32.

Berni, R., Gonnelli, C., 2006. Planning and optimization of a numerical control machine in a multiple response case. Quality and Reliability Engineering International 22, 517–526.

Berni, R., Scarano, V.L., Bertocci, F., Catelani, M., 2013. Mixed response surface models and bayesian analysis of variance components for electrically conductive adhesives. Applied Stochastic Models in Business and Industry 29, 387–398.

Box, G., Jones, S., 1992. Split-plot designs for robust product experimentation. Journal of Applied Statistics 19, 3–26.

Catelani, M., Scarano, V.L., Bertocci, F., Berni, R., 2011. Optimization of the soldering process with ecas in electronic equipment: characterization measurement and experimental design. IEEE Transactions on Components, Packaging and Manufacturing Technology 1, 1616–1626.

Giorgetti, A., Cavallini, C., Ciappi, A., Arcidiacono, G., Citti, P., 2017. A holistic model for the proactive reduction of non-conformities within new industrial technologies, in: International Conference on Mechanical Engineering and Electrical Systems-MATEC Web of Conferences.

Ismyrlis, V., Moschidis, O., 2013. Six sigma's critical success factors and toolbox. International Journal of Lean Six Sigma 4, 108–117.

Lee, Y., Nelder, J.A., 2003. Robust design via generalized linear models. Journal of Quality Technology 35, 2.

McCullagh, P., Nelder, J., 1989. Generalized Linear Models. 2 ed., Chapman & Hall.

Myers, R.H., Khuri, A.I., Vining, G., 1992. Response surface alternatives to the taguchi robust parameter design approach. The American Statistician 46, 131–139.

Nair, V., 1992. Taguchis parameter design: a panel discussion. Technometrics 30, 127.

Nelder, J.A., Lee, Y., 1991. Generalized linear models for the analysis of taguchi-type experiments. Applied Stochastic Models in Business and Industry 7, 107–120.

Vining, G.G., Kowalski, S.M., Montgomery, D.C., 2005. Response surface designs within a split-plot structure. Journal of Quality Technology 37, 115.