Proceedings of ICAD2009
The Fifth International Conference on Axiomatic Design
Campus de Caparica – March 25-27, 2009
ICAD-2009-27

OPTIMIZATION OF A THERMOFORMING PROCESS FOR AUTOMOTIVE DASHBOARDS

Gabriele Arcidiacono
g.arcidiacono@msn.unimarconi.it
Facoltà di Scienze e Tecnologie Applicate,
Università Telematica G. Marconi
Via Plinio 44, 00193 Roma
Italy

Paolo Citti
paolo.citti@unifi.it
Dipartimento Meccanica Tecnologie Industriali
Università di Firenze
Via Santa Marta, 3 50139 Firenze
Italy

ABSTRACT

This paper describes a Six Sigma project which wants to reduce the percentage of the defects in the production of dashboards. The example shows the most important aspects of the methodology: it sheds a new light on the process comprehension and its possible application to everything we may define as process. The key issues are extensive application of the methodology to all the processes, great flexibility and customization, the improvement opportunities identification and selection, and results evaluation and validation.

Keywords: Thermoforming, Six Sigma, DOE, dashboard.

1 INTRODUCTION

Each of the 5 phases DMAIC in which Six Sigma is structured (*Define, Measure, Analyze, Improve and Control*) brings more comprehension and problem solving and they set a few milestones that indicate the road to follow. The way these milestones are defined, the ability of the people to understand the context, the proper efforts in order to gain the desired goals are issues that may influence the final results. Correct and appropriate use of the tools, the scientific rigour of the method, the step-by-step approach, and a strict time management of projects are surely the basis for a success. In this paper the goal of Six Sigma project is the reduction of the percentage of the defects in the production of dashboards (Figure 1).

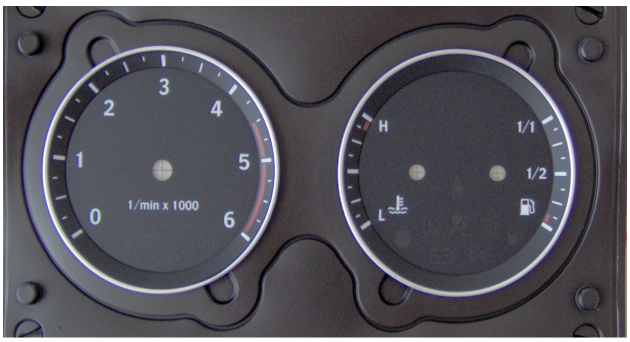


Figure 1. Dashboard

2 SIX SIGMA PROJECT

One of the main goals of Six Sigma is the need to know more in depth the process, especially when it is pretty new, so that it is possible to evaluate its weak and critical phases that could create manufacturing scraps.

2.1 DEFINE

Therefore, at the beginning the process is described with the necessary details in *Define* phase through SIPOC, that stands for Supplier-Input-Process-Ouput-Customer (as in Figure 2). SIPOC defines also the boundaries of the process: in this case the process is described through the sub-processes *Silk-screen printing* of polycarbonate sheets, relative *Drilling*, *Slot shearing* and *Thermoforming* ("scope" of the project).

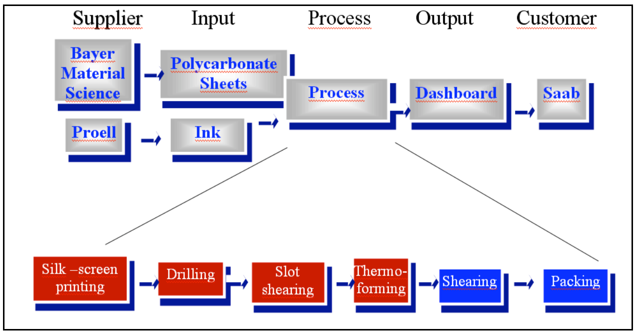


Figure 2. SIPOC

In the industrial market of car dashboards, only two Companies in Italy use the particular machine studied in this paper in order to thermoform the sheets. This process is complex due to different root causes that we want to analyze with this Six Sigma Project. The final client is Saab.

In particular, the practical improvement to achieve is the reduction of defects due to bad centering of the silk-screen printing of the sheets. For this issue it is necessary to find a robust indicator that is representative of the phenomenon considered or, in other words, Critical To Quality (CTQ) for the customer.

In according to Saab we select as CTQ the horizontal distance showed in Figure 3: the USL (Upper Specification Limit) is 4,36mm and LSL (Lower Specification

Limit) is 3,96mm. A dashboard that has this distance out of the range [3,96-4,36] is a defect and not acceptable from the Saab.

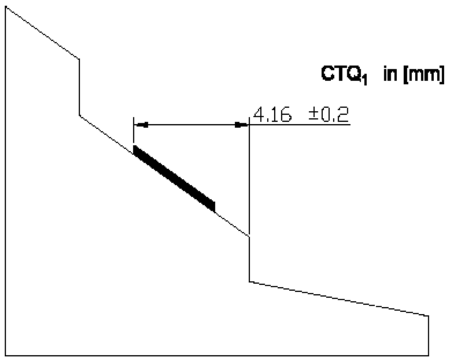


Figure 3. The Critical To Quality (CTQ) indicator

Today the current value of defects is 10% of the total production; the goal of this project is to achieve 0,005%. All these information are in the Project Charter filled out from the Team Leader (the Black Belt) where are defined the Team members, the constraints and the milestones of the Project.

As mentioned above, the first phase of the process is the *Silk-screen printing* by means of which the polycarbonate sheet "acquires" the design previously created by CAD using particular inks.

In the *Drilling* phase the reference system useful for the following phase (*Slot shearing*) is created with some holes. The *Slot shearing* realized by die cutter uses the holes as reference system in order to maintain the sheet in the same position. This is necessary in order to guarantee the right reference of the sheet during *Thermoforming*.

This last phase performs the final product with the desired shape using an "ad hoc" machine.

The machine of the *Thermoforming* (see Figure 4) consists of a paddle with 8 pins where it is possible to fix the sheet with *Slot shearing*.

Figure 4. *Thermoforming* machine (Niebling)

In the examined Project we consider out-of-scope the *Shearing* and the *Packing* because they cannot contribute to the reduction of errors due to bad centering of the *Silk-screen printing* of the sheets.

2.2 MEASURE

After the *Define* phase, the correct view on the problem and on the relative process is ready. Now we can collect the data of the process performance in order to have more information on the examined problem. This phase is *Measure*.

In this phase the goal is to have the right focus on the process steps in order to discover the most critical ones where we have to attack the biggest losses in terms of performances and costs.

Using Cause-Effect or Fishbone Diagram (see Figure 5) it is possible to highlight all potential causes that produce the no-good dashboard.

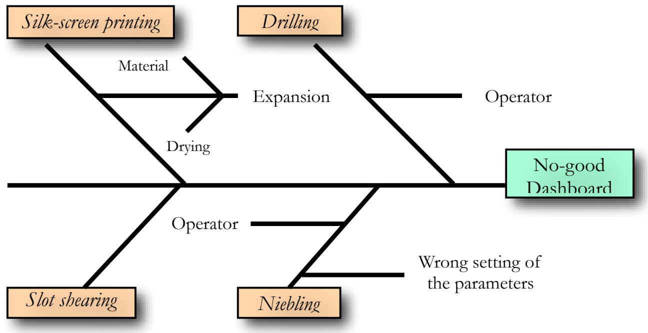


Figure 5. Fishbone Diagram

Regarding to the first bone, *Silk-screen printing*, we want to study in depth the centering problem: it depends on the expansion at high temperature of the polycarbonate sheets due to the material elasticity and to the drying process.

Regarding to the *Drilling* and *Slot shearing* bones, we can consider that their importance and contribution are quite low and not significant to achieve the goal of the Six Sigma Project.

The last bone is the *Thermoforming* executed by a German machine named "Niebling": the non conformities during *Thermoforming* are due to operator and, in particular, to wrong setting of the machine parameters.

However Fishbone Diagram provides only a qualitative idea of the main critical issues without a correct prioritization necessary to establish the sequence of the actions to be taken.

For this reason, by means of FMEA (Failure Modes and Effects Analysis) it is possible quantify the importance of the potential causes in order to focus on the most critical process steps.

This point is of paramount importance: the recommended actions depend on the threshold values of RPN (Risk Priority Number) following the Severity as below:

Table 1. FMEA: Severity vs. RPN

Severity	RPN
9-10	≥40
7-8	≥100
4-5-6	≥120
1-2-3	≥150

The process steps that have RPN ≥ threshold values are considered critical ones and are the first to be "attacked" in order to reduce the relative RPN.

2.3 DESCRIPTION OF *THERMOFORMING* MACHINE

The *Thermoforming* machine is called Niebling: it consists of a paddle with 8 pins (Figure 6) where it is possible to fix the polycarbonate sheet. The paddle brings the material into machine (Figure 7) and goes through the cycle returning the thermoformed-part to the operator: the machine has two plates depending on the shape and the geometry of the mold to thermoform the polycarbonate sheet (Figure 8).

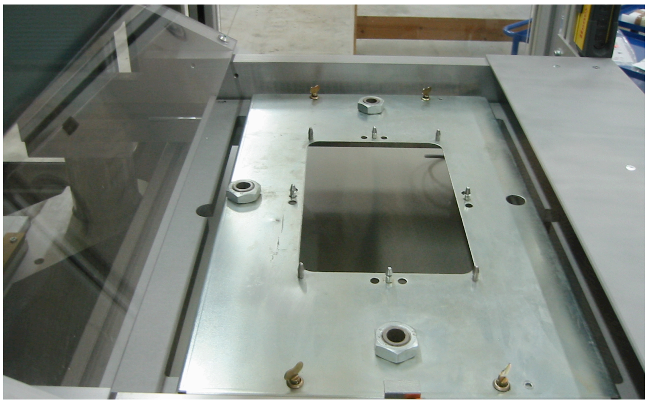


Figure 6. Paddle

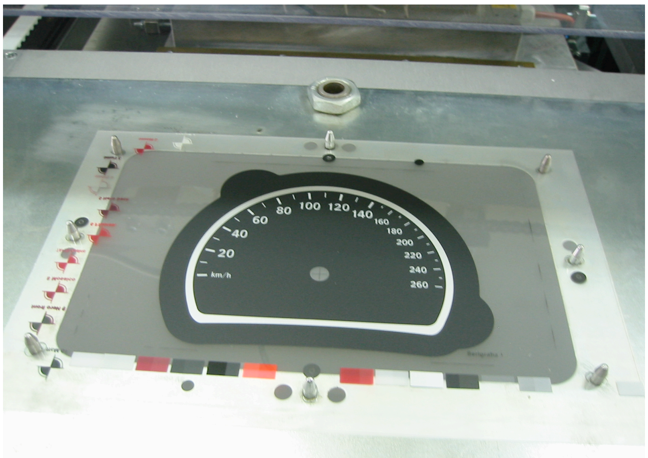


Figure 7. The part before manufacturing

Figure 8. The mold in the *Thermoforming* machine

Each plate has 42 tiles. The operator sets the temperature of the plates and of each tile in order to give an uniform distribution of the heat to the part (see Section 2.5).

The polycarbonate sheet is situated on the paddle that brings it between the two plates. Some parameters such as the Heating Time, Temperature of Upper Plate and Lower Plate, are significant regarding to the process.

Also the Mold Temperature, the Mold Maximum Pressure (Pmax), Pmax Time are important too; in the other hand the expansion depends on the Air Speed.

All these 7 machine-parameters influence the *Thermoforming*.

2.4 ANALYZE

The main cause of the scraps and claims is the variability. Every process is characterized by a value of variability: the relative root-causes are common or special.

The common causes are in the process, on the other hand the special causes are out-of-the process. The first ones can be eliminated only modifying the entire process and depend on the machine, tools, operators, measurement system, etc. On the other hand the second ones can be eliminated only attacking the singular external causes which are the source of the variability. They depend on wrong calibration of the measurement tool, use of bad raw material, etc.

As mentioned in Subsection 2.1, the performance of the process is measurable through CTQ: in particular we analyze 3 points for the left dial (Mark 0, 3 and 6) and in 4 points for the right dial (H, L, 1/1 and 0/1), as shown in Figure 9.

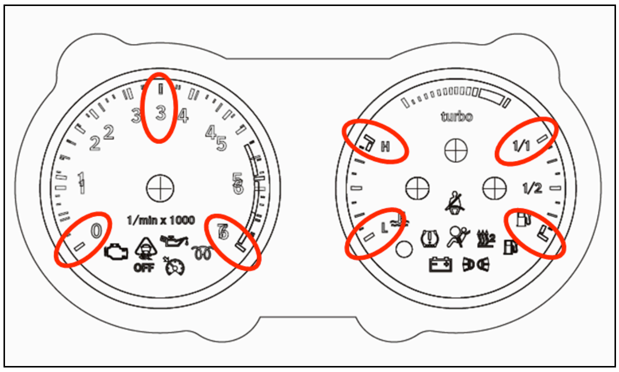


Figure 9. CTQs

In the past, the operator modified one parameter at a time: since this *modus operandi* was very expensive, the companies forsook the experimentation phase and adopted new solutions without a deep knowledge of the relative effects.

Today in order to optimize the *Thermoforming* process we have to study the critical parameters and their interactions: the advantage of a Design of Experiments (DOE) is to find the best setting of the previous critical parameters.

The Design of Experiments requires as first step the choice of the factors and the relative levels. We use the ANOVA in order to evaluate the statistical significance of each factor.

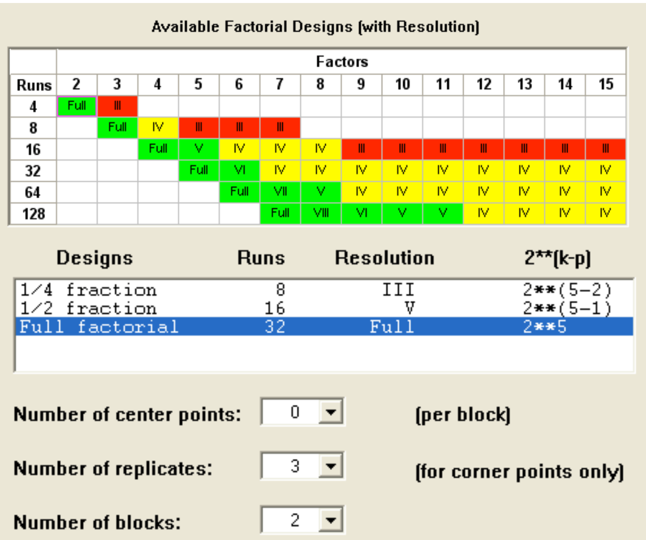
Among the 7 parameters mentioned above, we don't consider the variation of Temperature of Lower Plate, fixed at 380°C, trade-off between the maximum value allowed to the machine (400°C) and a low temperature that could increase the cycle time of *Thermoforming*. Then we select Mold Temperature as "block", since it would be difficult randomize it during the experimental runs.

Summarizing we consider 5 factors and one block defining lower and upper levels for every parameter as below:

Table 2. Levels of Factors

Factors	Lower Level	Upper Level
Temperature of Upper Plate	340°C	360°C
Mold Maximum Pressure	150bar	250bar
Air Speed	1m/s	5m/s
Heating Time	10 s	11,4 s
Pmax Time	4 s	7 s
Mold Temperature (block)	100°C	120°C

If we apply a Full Factorial Design, from Figure 10 we have 32x3 = 96 runs (considering 3 replicates).


Available Factorial Designs (with Resolution)

	Factors													
Runs	2	3	4	5	6	7	8	9	10	11	12	13	14	15
4	Full	III												
8		Full	IV	III	III	III								
16			Full	V	IV	IV	IV	III	III	III	III	III	III	III
32				Full	VI	IV	IV	IV	IV	IV	IV	IV	IV	IV
64					Full	VII	V	IV	IV	IV	IV	IV	IV	IV
128						Full	VIII	VI	V	V	IV	IV	IV	IV

Designs	Runs	Resolution	2**(k-p)
1/4 fraction	8	III	2**(5-2)
1/2 fraction	16	V	2**(5-1)
Full factorial	32	Full	2**5

Number of center points: 0 (per block)

Number of replicates: 3 (for corner points only)

Number of blocks: 2

Figure 10. Factorial Design

As well as the analysis of the seven nicks, we want to measure the gap (in X and Y) between graphical center and mechanical center ("Centro grafico-mecc") for both right and left dials. The mechanical center, always firm, is the center of the mold circumference, while the graphical center is the center of the circumference passing for the end of the nicks (internal and external circumference in Figure 11).

The measure of this gap gains understanding of the influence of some machine parameters on the graphics deformations. From the experimental runs it is possible to analyze the results on statistical point of view: at the beginning we consider the optimization for each singular CTQ, 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 we find the optimization for the right on one hand and left dial on the other hand. In the end we set the levels of the main significant factors on statistical and physical perspective in order to optimize all seven CTQs of the examined dashboard.

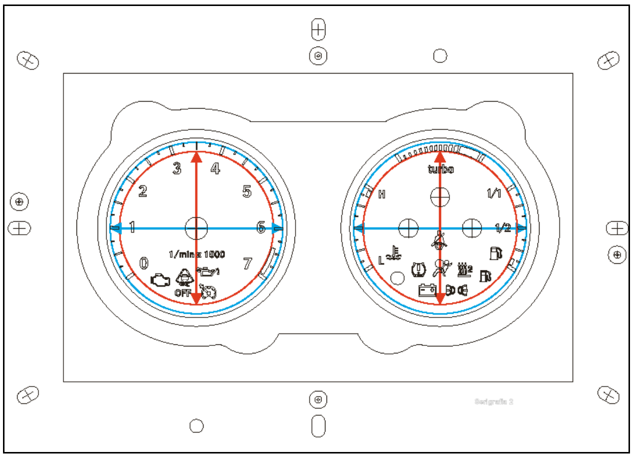


Figure 11. Mold circumference (internal) and circumference passing for the end of the nicks (external)

About the optimization for CTQ-0 we consider the statistical analysis from ANOVA (Table 3) where both Main Effects and 2-Way Interactions are significant (P-value<0,05).

Table 3. ANOVA for CTQ-0 (coded units)

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Main Effects	5	1,85665	1,85665	0,37133	29,59	0,000
2-Way Interact.	10	0,29546	0,29546	0,02955	2,35	0,032
Residual Error	32	0,40157	0,40157	0,01255		
Pure Error	32	0,40157	0,40157	0,01255		
Total	47	2,55368				

In particular the factors and the interactions are Temperature of Upper Plate, Heating Time, Temperature of Upper Plate* Pmax Time (see Table 4).

Table 4. P-Values for CTQ-0

Term	P
Constant	0,000
Temperature of Upper Plate(Risc. Superiore)	**0,000**
Mold Maximum Pressure (Press. Max Stampo)	0,312
Air Speed (Velocità Aria)	0,605
Heating Time (Tempo Riscaldamento)	**0,000**
Pmax Time (Tempo Alta Pressione)	0,099
Risc. Superiore*Press. Max Stampo	0,282
Risc. Superiore*Velocità Aria	0,174
Risc. Superiore*Tempo Riscaldamento	0,088
Risc. Superiore*Tempo Alta Pressione	**0,015**
Press. Max Stampo*Velocità Aria	0,487
Press. Max Stampo*Tempo Riscaldamento	0,122
Press. Max Stampo* Tempo Alta Pressione	0,966
Velocità Aria*Tempo Riscaldamento	0,409
Velocità Aria*Tempo Alta Pressione	0,148

On graphical point of view, we can analyze the statistical results looking at the Figure 12 (Main Effect Plot for CTQ-0) and the Figure 13 (Interaction Plot for CTQ-0).

The graphical plots confirm the statistical importance of the factors and of the interactions.

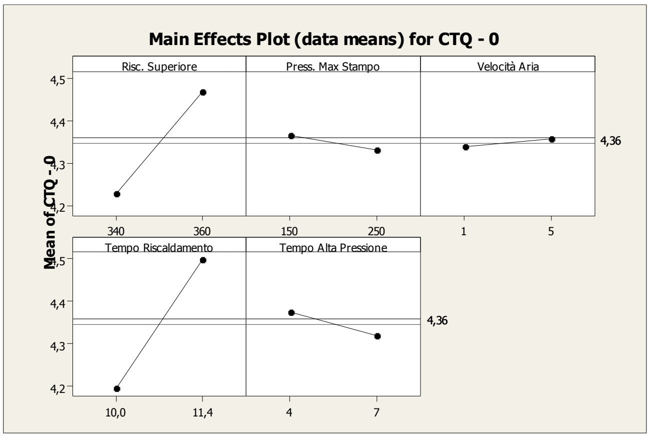


Figure 12. Main Effect Plot for CTQ-0

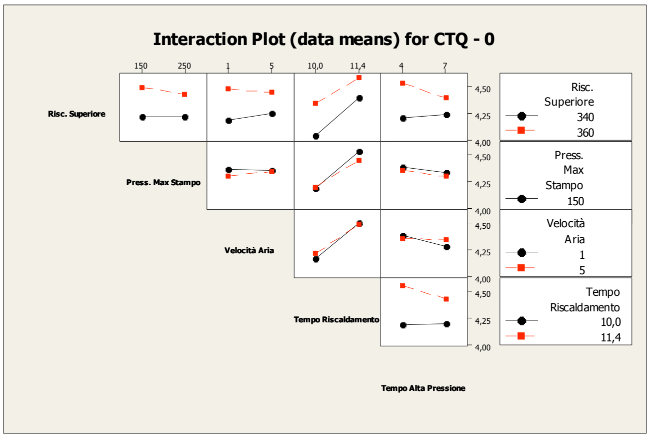


Figure 13. Interaction Plot for CTQ-0

From Matrix Plot (Figure 14) it is possible to observe that the 3 nicks are positive correlated each other. For this reason if one nick has a external displacement, the same behavior happens for the others and vice versa.

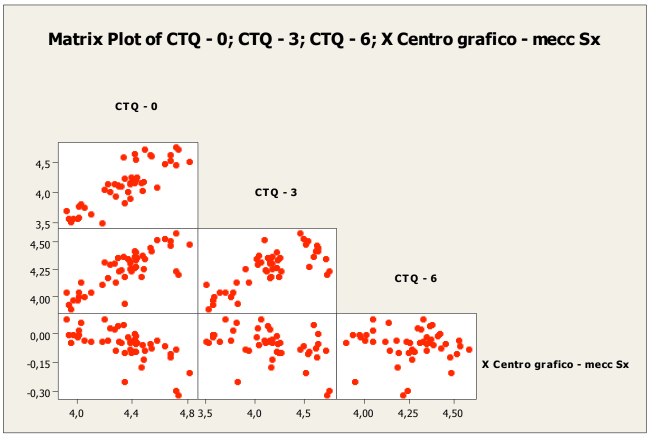


Figure 14. Matrix Plot for CTQ-0

In the Matrix Plot there is a negative correlation between "0" and "X Centro grafico-meccanico" nick: the increase of X, that consists of the displacement of the left dial "centro grafico" right bound, creates a movement of "0" nick inbound.

Another very useful tool is the Response Optimizer (Figure 15) which allowed to give evidence to the levels of the factors that optimize the CTQ:

- we have to set the Target and the specifications limits;
- we can determine the optimal level for each factor ("Current"), that is obviously between "Hi" and "Low" ones;
- the optimal D (Desiderability) is 1

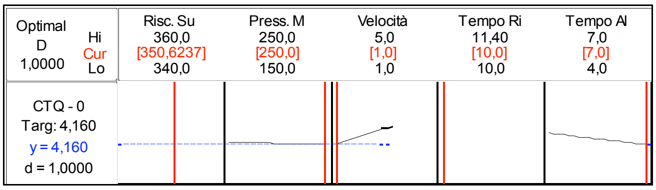


Figure 15. Response Optimizer for CTQ-0

The same procedure is analyzed for CTQ-3, CTQ-6 and "X Centro grafico-mecc Left"; here we omit the singular results and graphics for each CTQ.

After the study of each singular nick the conclusions on left dial are: the most significant factors for the 3 nicks are Temperature of Upper Plate and Heating Time. Therefore the behavior of these 3 nicks is very similar each other, as they have the same positive correlation with the 2 factors mentioned above and each other.

About the displacements (X and Y) of the "centro grafico" vs. "centro mecc" (left dial): the "centro grafico" goes up and left bound increasing Temperature of Upper Plate or/and Heating Time. Other results: on one hand if X, the displacement of the "centro grafico", increases right bound, so a movement of "0" nick is inbound; on the other hand if Y, the displacement of the "centro grafico", increases going up, so a movement of "3" nick is outbound.

Now, after these considerations we have to set the optimal levels of the factors for all nicks of the left dial. Using Response Optimizer, we determine the factors' levels able to optimize the CTQ-0, CTQ-3, CTQ-6 (Figure 16).

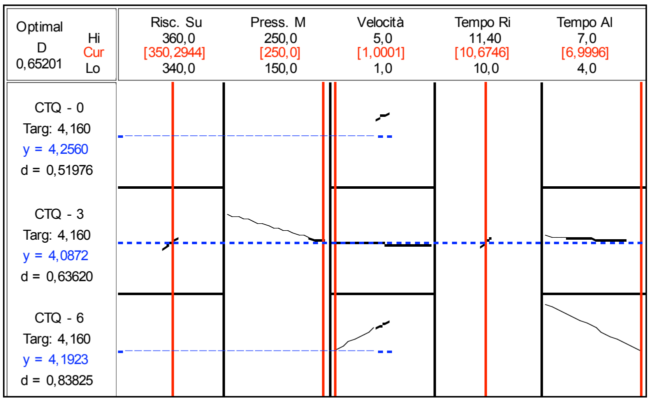


Figure 16. Response Optimizer: CTQ-0, CTQ-3, CTQ-6

As the significant factors on statistical perspective are two, using Contour Plot, we determine for each nick the area where to search the optimal levels of these 2 factors.

Then using Overlaid Contour Plot we optimize all 3 nicks simultaneously.

By means of Contour Plot we determine the areas with different colours (different ranges of CTQ) depending on the combination of the factors' levels. In Figure 17-18-19 we have the Contour Plot of CTQ-0, CTQ-3, CTQ-6.

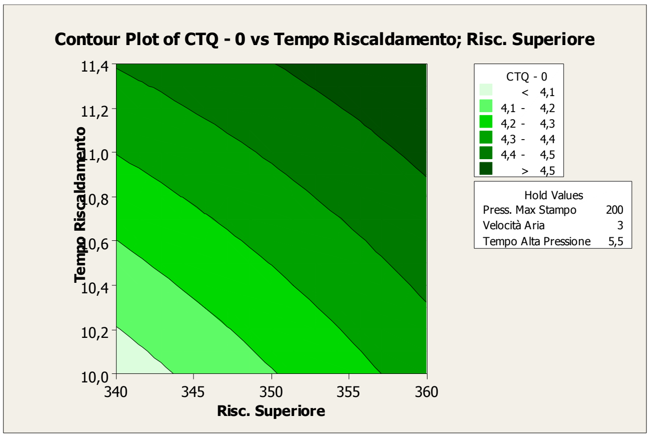


Figure 17. Contour Plot of CTQ-0

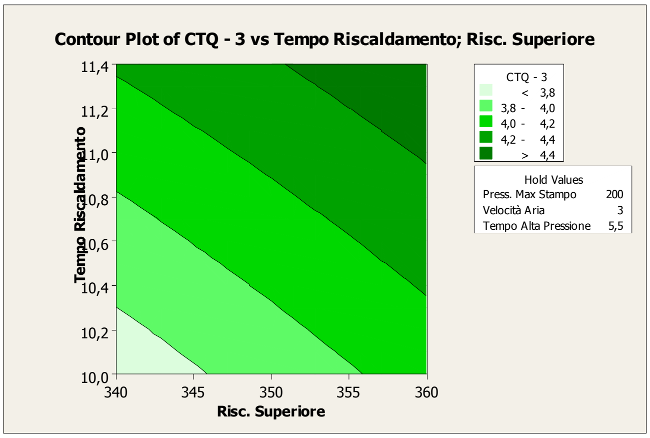


Figure 18. Contour Plot of CTQ-3

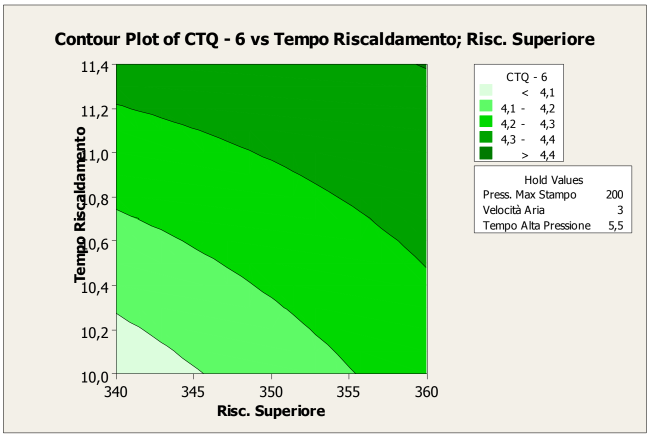


Figure 19. Contour Plot of CTQ-6

First of all for each plot we give evidence of the area able to satisfy the target of CTQ and then we select the best levels for each nick in order to optimize simultaneously all the nicks.

This goal is possible using directly Overlaid Contour Plot. Response Optimizer provides the levels for the non-significant factors (Mold Maximum Pressure=250bar, Air Speed=1 m/s and Pmax Time=7 s); Overlaid Contour Plot (Figure 20) shows the area (white colour) of the best setting of the significant factors' levels.

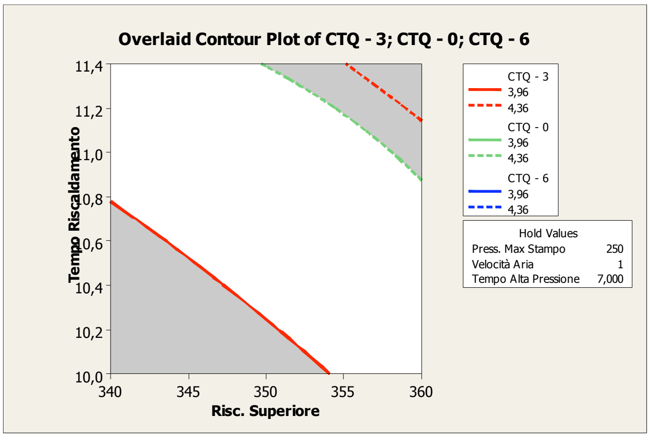


Figure 20. Overlaid Plot: CTQ-0, CTQ-3, CTQ-6

Now we have completed the optimization of the left dial: we have to do the same procedure (study of singular nicks and then their simultaneous optimization) for the right dial.

The most significant factors for the 4 nicks of the right dial are Temperature of Upper Plate and Heating Time. The behavior of these 4 nicks is quite similar to 3 nicks of the left dial, since they have a positive correlation with 2 significant factors and, for this reason, also with each other.

About the displacements (X and Y) of the "centro grafico" vs. "centro mecc" (right dial): the "centro grafico" goes up increasing Temperature of Upper Plate or/and Heating Time. As the displacement Y of the "centro grafico", is up bound, as a movement of the four nicks is outbound.

Using the same procedure executed for the left dial, we determine the optimization also for the right dial.

Response Optimizer provides the levels for the factors which optimize CTQ-H, CTQ-L, CTQ-1/1, CTQ-0/1 (Figure 21).

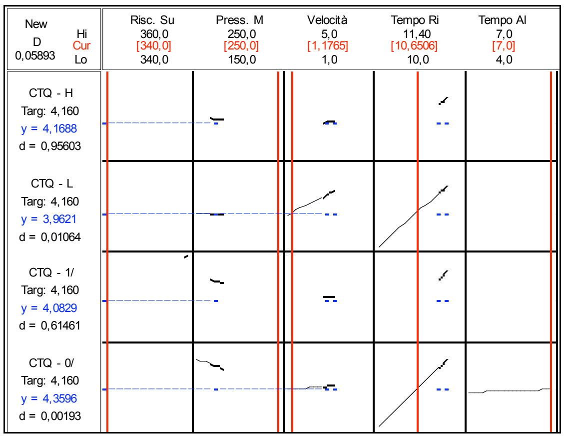


Figure 21. Response Optimizer: CTQ-H, CTQ-L, CTQ-1/1, CTQ-0/1

As the significant factors on statistical perspective are two, using Contour Plot, we determine for each nick the area where to search the optimal levels of these 2 factors.

The levels provided previously by Response Optimizer for the non-significant factors are used to build the Overlaid Contour Plot.

At the end Overlaid Contour Plot (Figure 22) shows the area (white colour) of the best setting of the significant factors' levels for the 4 nicks simultaneously.

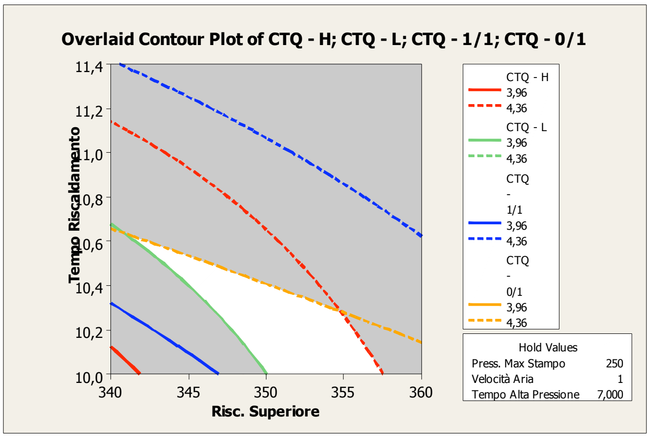


Figure 22. Overlaid Plot: CTQ-H, CTQ-L, CTQ-1/1, CTQ-0/1

We have two optimal solutions: on one hand the left dial, on the other the right one. Now it's necessary to calculate the area (Figure 23) of the significant factors' levels able to optimize simultaneously all seven CTQs (CTQ-0, CTQ-3, CTQ-6, CTQ-H, CTQ-L, CTQ 1/1, CTQ-0/1).

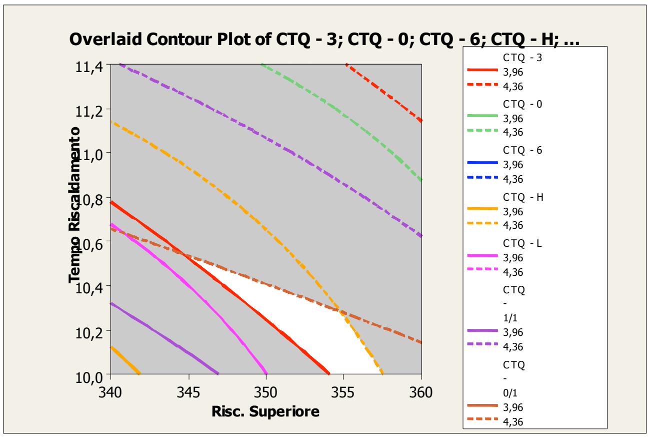


Figure 23 Overlaid Plot: CTQ-0, CTQ-3, CTQ-6, CTQ-H, CTQ-L, CTQ-1/1, CTQ-0/1

At the end of this deep analysis, using again Response Optimizer, it provides the levels for each factor which optimize all seven CTQs, that are CTQ-0, CTQ-3, CTQ-6, CTQ-H, CTQ-L, CTQ 1/1, CTQ-0/1 (as we can see in Figure 24).

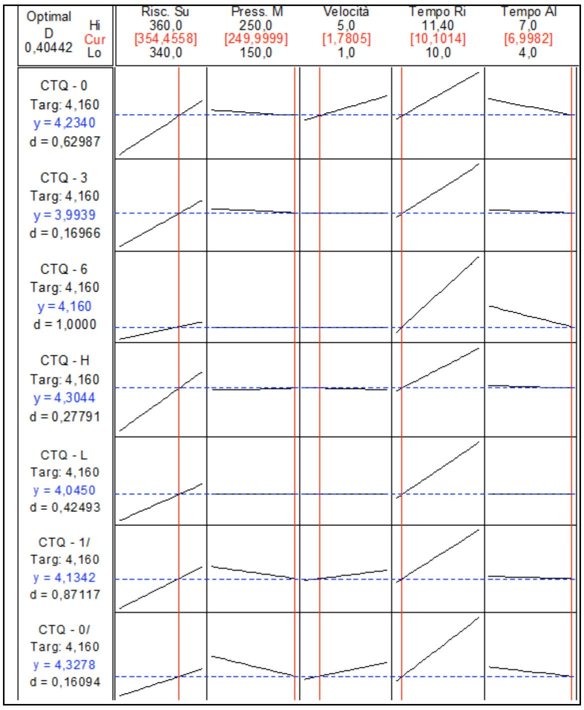


Figure 24. Response Optimizer: CTQ-0, CTQ-3, CTQ-6, CTQ-H, CTQ-L, CTQ-1/1, CTQ-0/1

2.5 IMPROVE & CONTROL

After the first 3 steps of DMAIC the Six Sigma project in *Improve* phase can "walk the talk". In other words it is possible to deploy the analytical and statistical information in recommended actions! From the theory to the reality through good practice! On the other hand it's obviously true that an improvement without the necessary deep analysis could be very often less efficient and complete.

Without any kind of doubt after the Definition of the problem (*Define*), after the data collection of the most representative indicators of the process (*Measure*) and after the correct analysis of the root-causes by means of statistical tools and a scientific approach (*Analyze*) we have a very good knowledge of the problem and it is possible not to "jump" to the solutions, but to "drive and sustain" them.

In particular in Improve phase we have two kind of improvements:

1. "Just Do It";
2. "Classical" *Improve*.

The "Just Do It" actions are called also *blitz Kaizen Events*; usually they don't require deep statistical analysis, because the problem is clear and the process is already known in terms of root-causes. In this situation first of all is important to restore basic conditions, that often are sufficient to gain good savings without expensive actions.

In our project, as the distribution of the heat was not uniform (Figure 25), the first improvement is "Just Do It": the goal is to guarantee the homogeneous temperature for each tile (Figure 26).

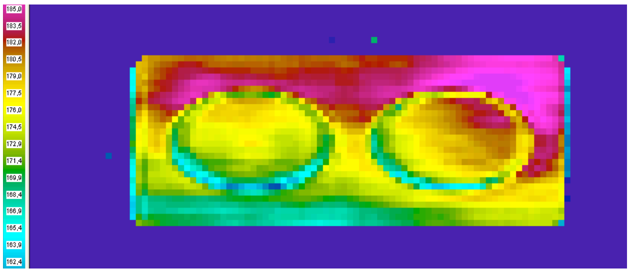


Figure 25. Non-uniform distribution of the heat

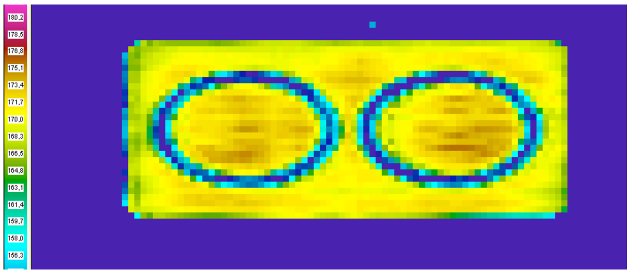


Figure 26. Uniform distribution of the heat

To achieve this goal is possible using an infrared camera in order to observe the distribution of the heat, so that we adjusted consequently the contribution of each tile of Upper Plate and Lower one (42 upper tiles + 42 lower tiles).

The uniform distribution of the heat is also a request necessary to apply correctly the DOE: as matter of fact if we modify some factors (Temperature of Upper Plate and Lower Plate, Heating Time, etc.), the output is linear in every area of the product, otherwise this would be impossible. Therefore, if the distribution is not uniform, we could have products with different outputs even without any change of the factors' levels.

About "Classical" *Improve*, we set the factors' levels as calculated by means of statistical tools used in *Analyze* phase: the best setting of Control Factors is in Table 5

Table 5. Best setting of Control Factors

Temperature of Upper Plate	354,46 °C
Mold Maximum Pressure	249,99 bar
Air Speed	1,78 m/s
Heating Time	10,10 s
Pmax Time	6,99 s

The final goal is minimizing the effect of the Noise Factors and maximizing the robustness of the product, that has a reduced variability in terms of output (CTQs).

After these actions, the results were very positive and according to expectations. The final phase (*Control*) in the project is now to sustain the improvements for the future. The tool that is able to monitor day by day the performance of our process is Control Chart (X bar-R).

3 CONCLUSION

The *Six Sigma* approach provides a scientific procedure and very focused on the results. The use of very significant statistical details can give a deep knowledge of the entire process. Through *Define* phase we decide to attack the most important root-causes in order to optimize as more as possible the CTQs selected from the Customer.

In particular in this paper the goal of the *Six Sigma* project is the reduction of defects due to bad centering of the silk-screen printing of the sheets.

Among different sub processes to be examined the most critical one is *Thermoforming* process.

The described project "drives" the improvements especially of the *Thermoforming* process during the manufacture of the car dashboards. The statistical analysis in *Analyze* phase allowes the best setting of machine-parameters able to optimize the CTQs to have a good centering of the silk-screen printing of the sheets.

In conclusion, the duration of this project took 3 months after, the process performance increased as the target of Project Charter and the relative savings were 70.000 Euro/year.

If we want a potential further improvement of the reduction of the defects, the obtained result is a very good starting point of a next DOE: we could consider obviously only 2, instead of previous 5, Control Factors (Temperature of Upper Plate, Heating Time) and model the robustness of the process against Noise Factors.

4 REFERENCES

[1] Montgomery, D.C., *Design and Analysis of Experiments*, Wiley & Sons, 2001.

[2] Arcidiacono, G., "Keys to success for Six Sigma", *Fourth International Conference on Axiomatic Design, Proceedings of ICAD2006*, Firenze (Italy), 2006.

[3] Arcidiacono, G., Citti, P., Gualtieri, E., Rossi, S., "Applicazione della metodologia Sei Sigma alla ottimizzazione fluidodinamica dei condotti di aspirazione e scarico di un motore ad elevata potenza specifica", *Proceedings of the XXXV AIAS*, Ancona (Italy), 2006.