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A PRODUCT DEVELOPMENT USING THE ROBUST DESIGN CONCEPT AND THE TAGUCHI METHOD

Maria NEAGU[1]

[1]"Dunărea de Jos" University of Galaţi, Manufacturing Engineering Department, Galaţi, România

ABSTRACT

The robust design of a new product is exemplified in this paper as an exercise that every engineering student could do for a better understanding of the DFSS (″Design For Six Sigma″) process. The design of a new paper binder is presented through several steps that make the process easy to follow and to understand by the student. Both classical mathematical pursuit and modern technology are presented as viable ways of solving the problem.

Keywords: robust design, product development, Taguchi method, Minitab

1. INTRODUCTION

The robust design of a piece is a way of developing a product that presents little variation during functioning no matter the values of the external factors. The most known and applied method of robust design — DFSS (″Design for Six Sigma″) — is used as an example in this paper as well as in other research articles of the scientific literature [1-27]. Two of the DFSS phases are emphasized here. The first phase where ″the voice of the consumer″ analysis is realized and the optimization phase where the Taguchi method is used occupy the major part of the analysis presented here. Both mathematical and modern technology methods are presented as ways of analysing the data. The ″paper binder″ is the product that is used as an example of robust design analysis.

2. THE ROBUST DESIGN PROCESS

For a better understanding of the DFSS process, seven steps are defined here as a guide for the student that learns the basics of robust design.

Step 1. CHOOSE THE PRODUCT

As an exercise that the student develops, the choosing of the product of his exercise is the first step in the product development project.

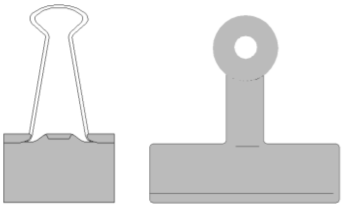


Fig. 1. *Paper binder*

The computer/hand drawing is the materialization of this step. Figure 1 presents the drawing of the product taken as an example in this paper — a ″paper binder″.

Step 2. DEFINE THE CONTROL FACTORS

The control factors of a product are, in this project, the design factors, those aspects/ characteristics/ features that you can improve. For the product taken as an example, Table 1 defines four control factors: ″Mechanism″, ″Color″, ″Application″ and ″Pattern″. ″Step 3″ defines their levels of variation.

Step 3. DEFINE THE LEVELS OF VARIATION OF EACH CONTROL FACTOR

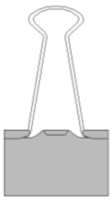
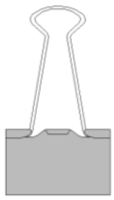
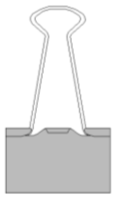
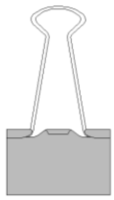
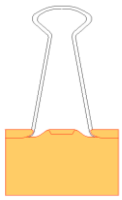
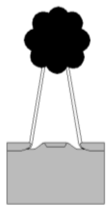
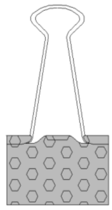
The levels of variation of the control factors are the dimensions/ forms/ characteristics/ variation domains each control factor takes. For the analyzed example, each control factor has two values (Table 1):

- the ″Mechanism″ factor can be: ″M_1″ ─ elasticity or ″M_2″ ─ string;
- the ″Color″ factor can be: ″C_1″ ─ metallic or ″M_2″ ─ colored;
- the ″Application″ factor can be: ″Ap_1″ ─ no application or ″Ap_2″ ─ with application;
- the ″Pattern″ factor can be: P_1″ ─ no pattern or ″P_2″ ─ with pattern.

Step 4. DEFINE THE ORTHOGONAL MATRIX

From the scientific literature [1-3], we choose the matrix $L_8(2^4)$ — a matrix that is presented in Figure 2 and Table 2 — a matrix that defines the eight versions of the product that will be taken into consideration.

Table 1. *Control factors and their variation levels*

Factors /Levels	Mechanism		Colour		Application		Pattern	
1	M_1 elasticity		C_1 metallic		Ap_1 no application		P_1 no pattern	
2	M_2 string		C_2 coloured		Ap_2 with application		P_2 with pattern	

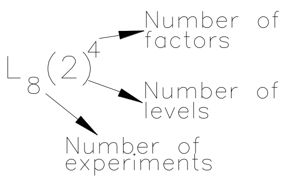


Fig. 2. *Orthogonal matrix definition*

At the same time, Table 2 defines the characteristics of each version of the product that will be analyzed further. For example, the first version of the product, $M_1C_1Ap_1P_1$ has the following characteristics: the "Mechanism" factor has the value M_1—elasticity, the "Colour" factor has the value C_1 — metallic, the "Application" factor has the value Ad_1 — no application, the "Pattern" factor has the value P_1 — no pattern.

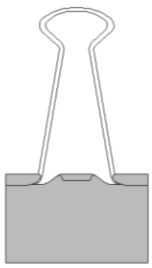
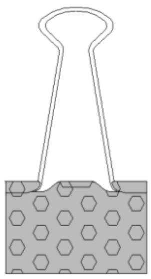
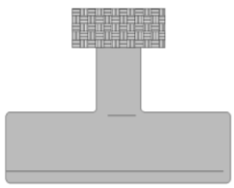
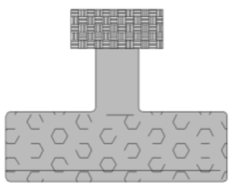
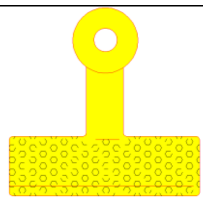
STEP 5. DRAW THE DESIGN VERSIONS OF THE PRODUCT

As a function of the control factors, at this stage of the project, the team that develops the product draws its constructive versions. These versions have been described above and they are presented in Table 3.

Table 2. *The orthogonal matrix $L_8(2^4)$*

Nr. experiment	Factors			
	1	2	3	4
1	1	1	1	1
2	1	1	1	2
3	1	2	2	1
4	1	2	2	2
5	2	1	2	1
6	2	1	2	2
7	2	2	1	1
8	2	2	1	2

Table 3. *Versions of the next product*

Design version	**1**	**2**	**3**	**4**
Drawing				
Notation	$M_1C_1Ap_1P_1$	$M_1C_1Ap_1P_2$	$M_1C_2Ap_2P_1$	$M_1C_2Ap_2P_2$
Design version	**5**	**6**	**7**	**8**
Drawing				
Notation	$M_2C_1Ap_2P_1$	$M_2C_1Ap_2P_2$	$M_2C_2Ap_1P_1$	$M_2C_2Ap_1P_2$

Step 6. ESTABLISH THE QUESTIONNAIRE

Table 4 presents an example of a questionnaire. Each respondent gives a mark from 1 (very little) to 9 (very much) for each version of the product.

Table 4. *Questionnaire version*

Design version	How do you appreciate this product version ?								
1	1 Very little	2	3	4	5	6	7	8	9 Very much
2	1 Very little	2	3	4	5	6	7	8	9 Very much
3	1 Very little	2	3	4	5	6	7	8	9 Very much
4	1 Very little	2	3	4	5	6	7	8	9 Very much
5	1 Very little	2	3	4	5	6	7	8	9 Very much
6	1 Very little	2	3	4	5	6	7	8	9 Very much
7	1 Very little	2	3	4	5	6	7	8	9 Very much
8	1 Very little	2	3	4	5	6	7	8	9 Very much

STEP 7. THE ANALYSIS OF THE RESULTS

The analysis of the results can be realized numerically (Section A) or using modern technology (the ″Minitab″ software) (Section B).

A. NUMERICAL ANALYSIS OF THE RESULTS

The evaluations given by each respondent to the product versions is noted in Table 5. In this way, we have a general view of the ″voice of the consumer″, the opinion that the consumer has on the preferred version of the future product.

Table 5 presents not only the medium scores obtained by each product version but also the S/N (″signal/noise″) values corresponding to each version. We notice that the 4th version obtains the biggest values for both the medium and the S/N ratio value.

Observation: if "y" is the dependent variable and "n" is the number of the measurements, then the Taguchi method requires optimization by maximizing the ″signal/noise″ (S/N) ratio [1]:

$$S / N = -10 \log\left(1 / n \sum_{i=1}^{n} 1 / y_i^2\right), \quad (1)$$

Further, the interpretation of the results requires the analysis of the medium and the ″signal/noise″ (S/N) ratio for each factor and level as Table 6 suggests. The effect of each factor is given by the performance difference of the corresponding levels. Consequently, we can notice that the biggest effect belongs to the "Mechanism" (M) factor, followed by the ″Application″ (Ap), "Color" (C) and "Pattern" (P) factor.

Table 5. *Experimental data collection*

Design versions	Respondents responses										Analysis	
	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	Medium	S/N
1	2	4	7	6	2	6	2	6	6	3	4,4	9,766
2	3	7	6	7	6	7	7	7	7	8	6,5	15,160
3	9	8	8	8	8	9	8	8	8	7	8,1	18,111
4	8	9	9	9	9	8	9	9	9	9	8,8	18,860
5	6	6	5	2	5	3	6	5	3	6	4,7	11,528
6	7	3	3	3	7	4	5	2	2	4	4	9,833
7	4	5	4	4	4	5	3	4	4	2	3,9	10,882
8	5	2	2	5	3	2	4	3	5	5	3,6	9,227

Table 6. *Numerical interpretation of the results*

	Analysis				Medium				S/N			
Level	M	C	Ap	P	M	C	Ap	P	M	C	Ap	P
1	1,2,3,4	1,2,5,6	1,2,7,8	1,3,5,7	6,95	4,9	4,6	5,275	15,474	11,572	11,259	12,572
2	5,6,7,8	3,4,7,8	3,4,5,6	2,4,6,8	4,05	6,1	6,4	5,725	10,367	14,270	14,583	13,270
Effect					2,9	1,2	1,8	0,45	5,1069	2,698	3,323	0,698
Rank					1	3	2	4	1	3	2	4

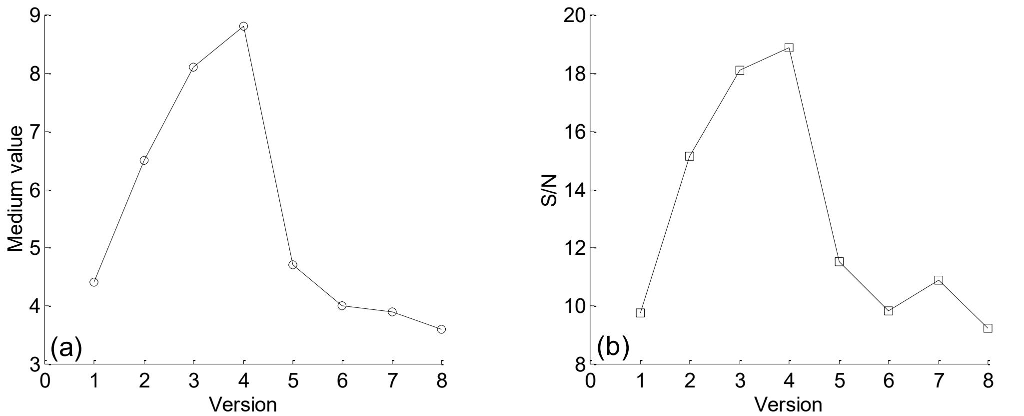


Fig. 3. *Medium (a) and S/N (b) values of each product version*

Analyzing the evolution of the medium values and the S/N ratio (Figure 4 and Figure 5) as a function of each factor level: "Mechanism" (a), "Colour" (b), "Application" (c) and ″Pattern″ (d), we notice that the medium values as well as the S/N ratio decreases as the "Mechanism" factor level increases and it increases as the ″Color″, "Application" and "Pattern" factors level increases.

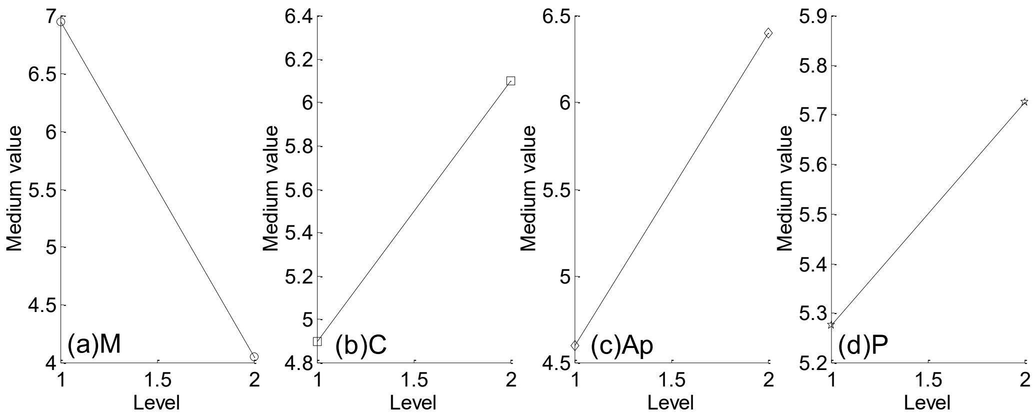


Fig. 4. *The evolution of the medium value as a function of the control factors "Mechanism" (Figure 4a), "Colour" (Figure 4b), "Application" (Figure 4c) and ″Pattern″ (Figure 4d)*

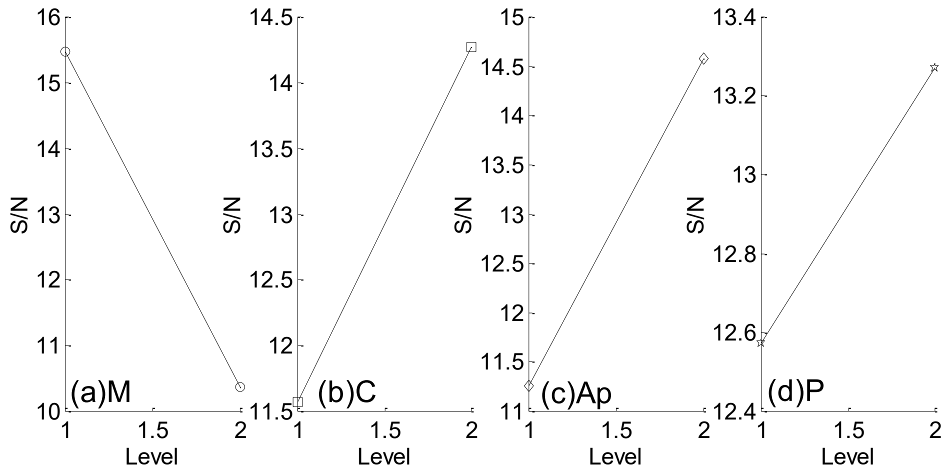


Fig. 5. *The evolution of the S/N ratio as a function of the control factors "Mechanism" (Figure 5a), "Colour" (Figure 5b), "Application" (Figure 5c) and ″Pattern″ (Figure 5d)*

Because a maximum value of the S/N ratio is desired, the development team has to choose the product version: $F_1Ad_2C_2$ (Figure 6), a version that corresponds to the fourth product from both Table 2 and Table 3. We arrive to the conclusion presented in Table 5.

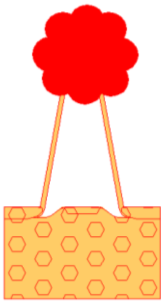


Fig. 6. *The next product version*

Figure 6 presents the design version preferred by the study respondents. It is the version that will be analyzed by the multidisciplinary team and taken into consideration as the next product version.

B. RESULTS ANALYSIS USING THE MODERN TECHNOLOGY

The "Minitab" software will be used here. This software opens the "Session" window and the "Worksheet" window as Figure 7 indicates :

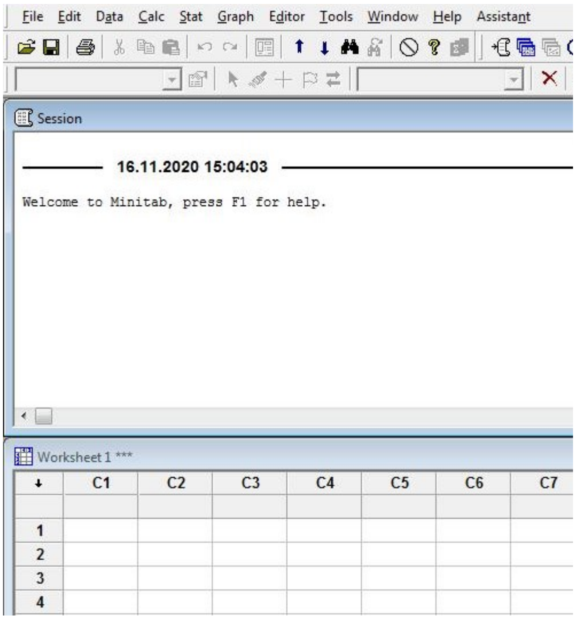


Fig. 7. *"Session" and "Worksheet" window*

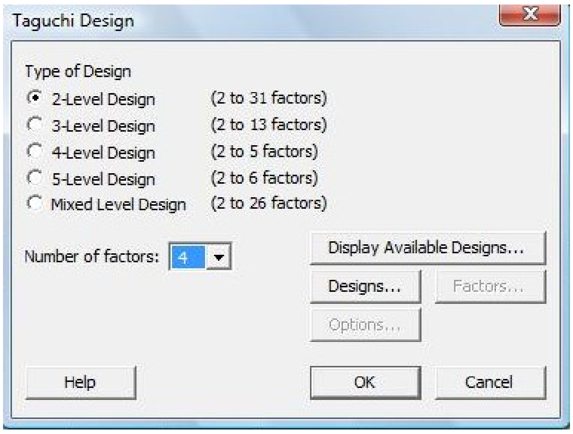
- ***the "Session" window*** contains the results obtained by running the Minitab software;
- ***the "Worksheet" window*** contains the input data: factors, experimental results and results obtained through their mathematical interpretation. In the worksheet window, we notice the columns noted C_1, C_2, etc. Under these names, there is a blank line that contains the columns name given by the student. Figure 11 shows the columns name for this particular example: "Mechanism", "Colour", "Application" and "Pattern". This step can be realised directly (by writing the name in the cell situated above the corresponding column) or by following further the steps established here for the robust design using the Taguchi method.

Define the experimental matrix

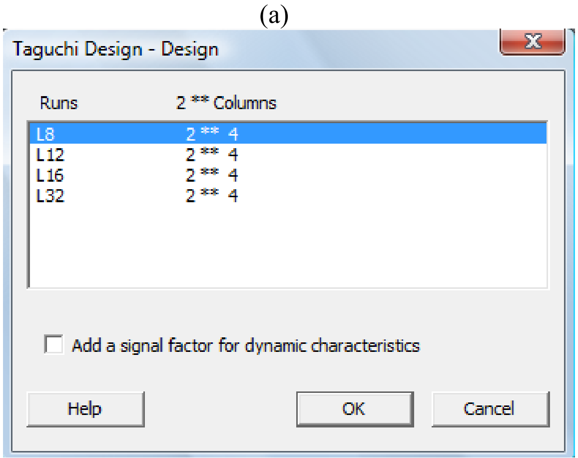
Each of the four factors: "Mechanism", "Colour", "Application" and "Pattern", has two levels of variation: "elastic/spring", "metallic"/"colored", "without"/"with application" and "without"/"with pattern" . Follow the instructions succession:

- **Stat → DOE → Taguchi → Create Taguchi Design**

to choose the Taguchi matrix, L_8, for the 4 factors and 2 levels of variation version (Figure 8).



(a)



(b)

Fig. 8. *The orthogonal Taguchi matrix definition*

Further, the design modification, the factors and the level definition require the following instructions succession:

- **Stat → DOE → Modify Design → "Modify factors in inner array" → "Specify"**

which leads to the window presented in Figure 9.

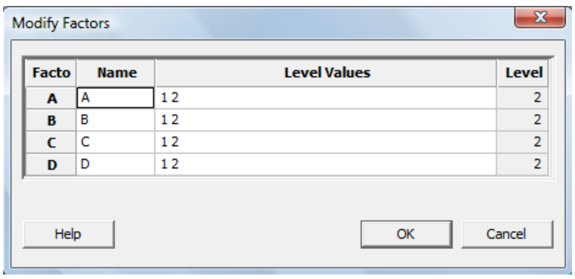
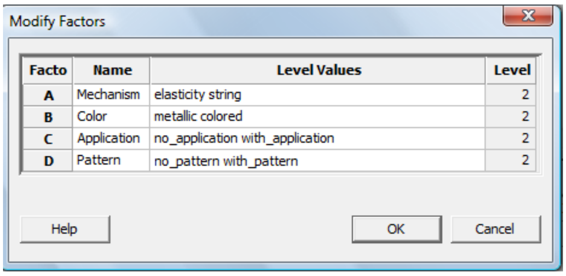
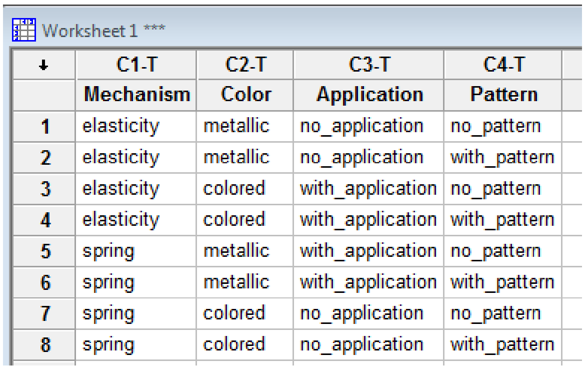


Fig. 9. *The modification of the Taguchi design*



Facto	Name	Level Values	Level
A	Mechanism	elasticity string	2
B	Color	metallic colored	2
C	Application	no_application with_application	2
D	Pattern	no_pattern with_pattern	2

Fig. 10. *The design factors and their levels*



↓	C1-T Mechanism	C2-T Color	C3-T Application	C4-T Pattern
1	elasticity	metallic	no_application	no_pattern
2	elasticity	metallic	no_application	with_pattern
3	elasticity	colored	with_application	no_pattern
4	elasticity	colored	with_application	with_pattern
5	spring	metallic	with_application	no_pattern
6	spring	metallic	with_application	with_pattern
7	spring	colored	no_application	no_pattern
8	spring	colored	no_application	with_pattern

Fig. 11. *The experimental matrix*

Here, we will rename the factors A, B, C and D as Figure 10 indicates. The final form of the experiments matrix takes the form given in Figure 11.

The definition of the experimental matrix

We define and name nine columns: R1÷R10 and, further, we complete these columns with the appreciation of the voice of the customer questionaire (Table 6). Figure 12 shows both these columns and the way we define and calculate the medium values of the questionnaire results: we define the C15 column named "Total" using the "f_w" function of the main menu of the Minitab software.

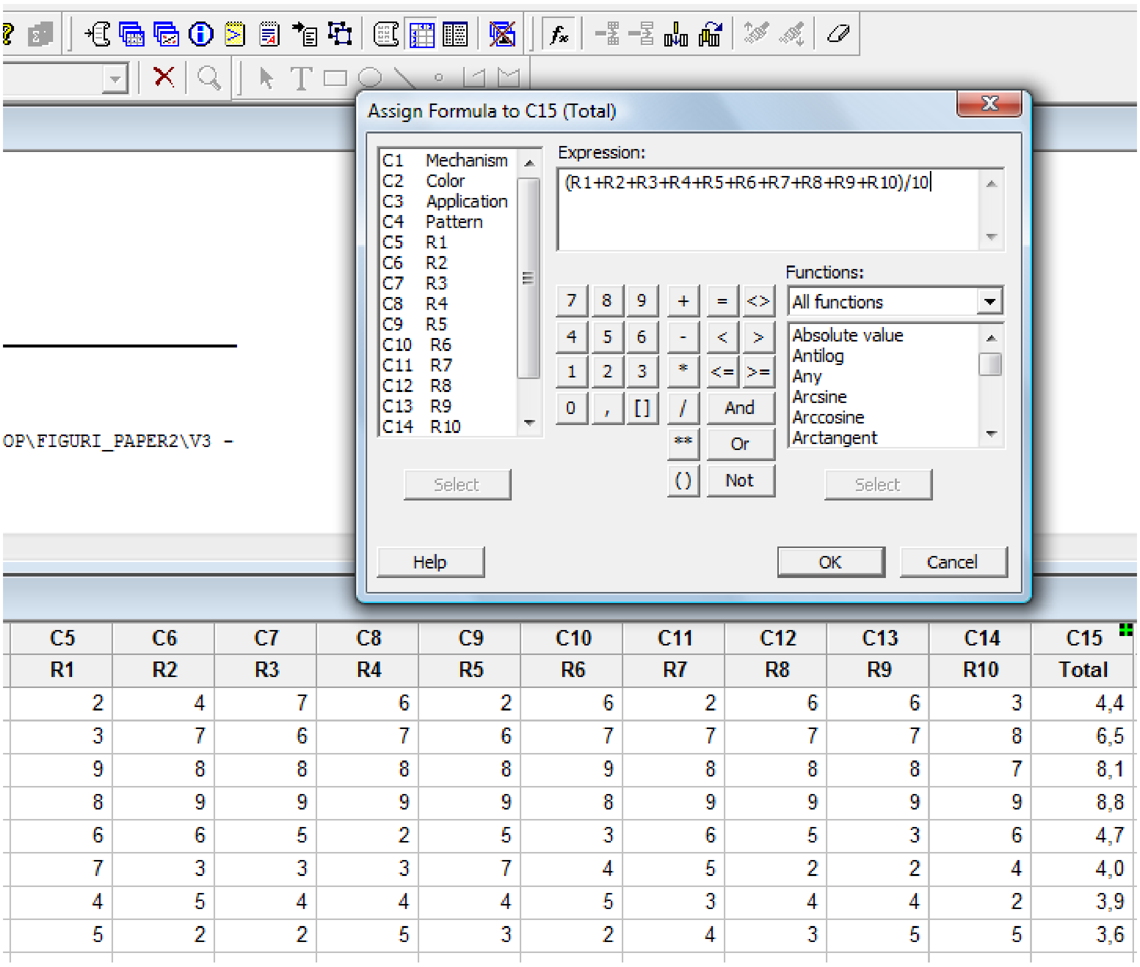
Analyse the product versions

The instructions succession :

■ **Stat → DOE → Taguchi → Define Custom Taguchi Design**

leads to Figure 13 where, we choose "Factors": "Mechanism", "Colour", "Application" and "Pattern". Figure 14 presents the window obtained using the instruction succession :

Stat → DOE → Taguchi → Analyze Taguchi Design



C5 R1	C6 R2	C7 R3	C8 R4	C9 R5	C10 R6	C11 R7	C12 R8	C13 R9	C14 R10	C15 Total
2	4	7	6	2	6	2	6	6	3	4,4
3	7	6	7	6	7	7	7	7	8	6,5
9	8	8	8	8	9	8	8	8	7	8,1
8	9	9	9	9	8	9	9	9	9	8,8
6	6	5	2	5	3	6	5	3	6	4,7
7	3	3	3	7	4	5	2	2	4	4,0
4	5	4	4	4	5	3	4	4	2	3,9
5	2	2	5	3	2	4	3	5	5	3,6

Fig. 12. *The definition of the analysis results in the worksheet*

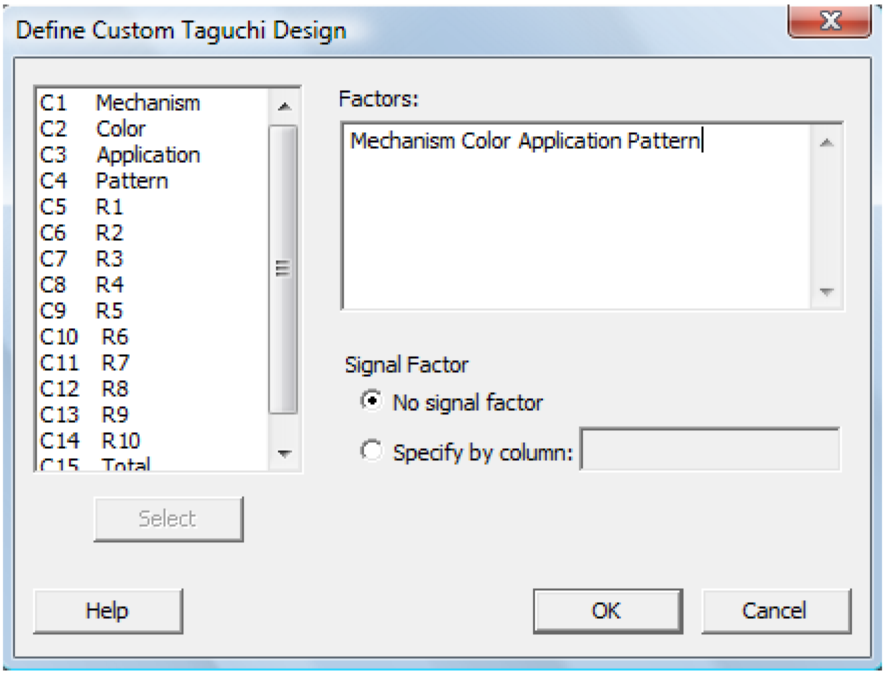
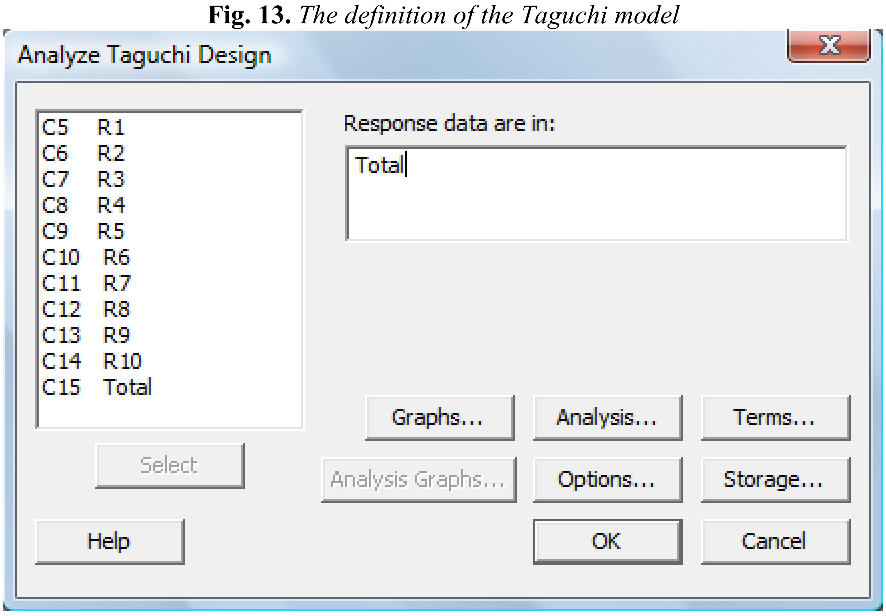


Fig. 13. *The definition of the Taguchi model*



(a)

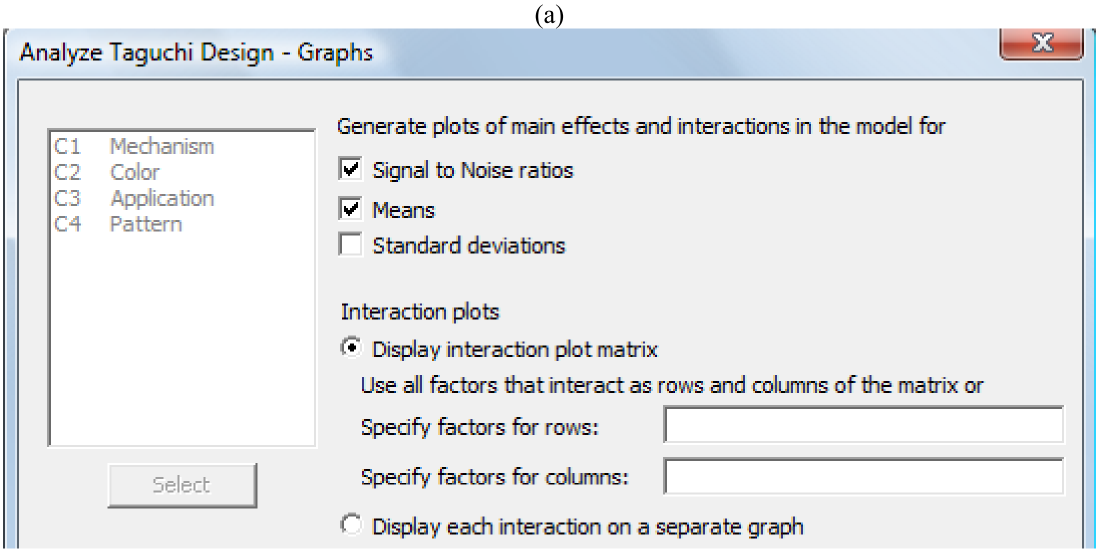


Fig. 14. *Model analysis (a). Activation of "Graphs" command (b)*

The model analysis requires not only "Response data in the "Total" column, but also the commands:

- "**Graphs**" (Figure 14). Here, we are choosing the plots: "Signal to Noise ratios" and "Means";
- "**Analysis**" (Figure 15). Here, we are choosing as results: "Signal to Noise ratios" and "Means";
- "**Options**"(Figure 16), where we choose "Larger is better" because we want to design a product that has a higher value of S/N ratio.
- "**Terms**" (Figure 17), where we determine the analysis factors.
- "**Storage**"(Figure 18); we choose to retain the values: "Signal to Noise ratios" and "Means".

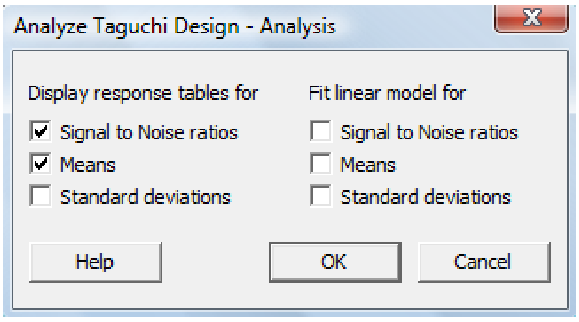


Fig. 15. *"Analysis" command activation*

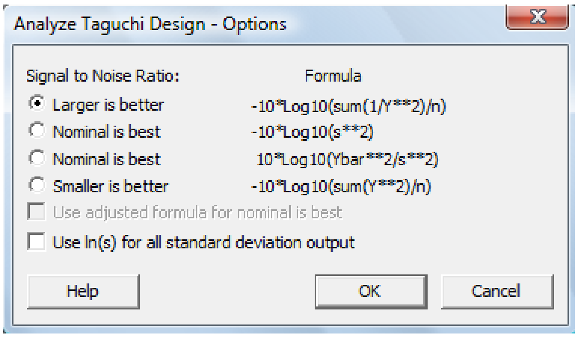


Fig. 16. *"Options" command activation*

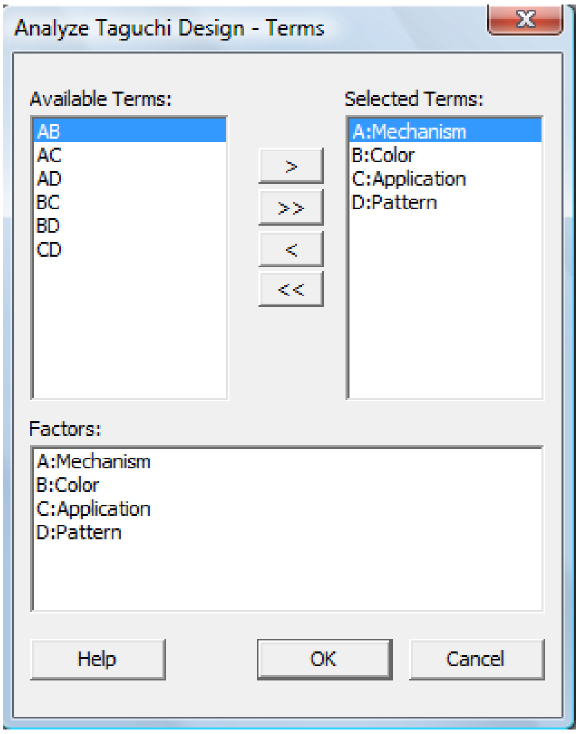


Fig. 17. *"Terms" command activation*

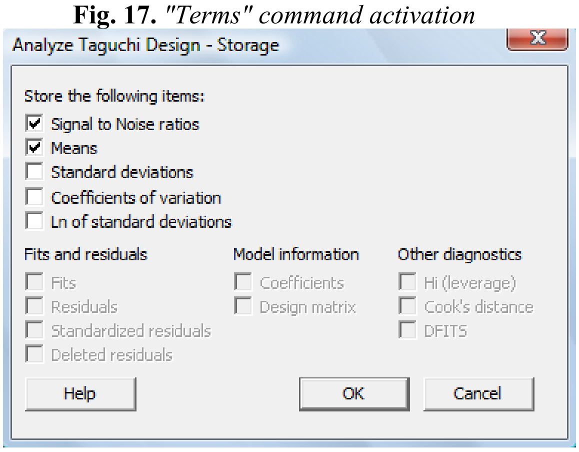


Fig. 18. *"Storage" command activation*

Taguchi Analysis: Total versus Mechanism; Color; Application; Pattern

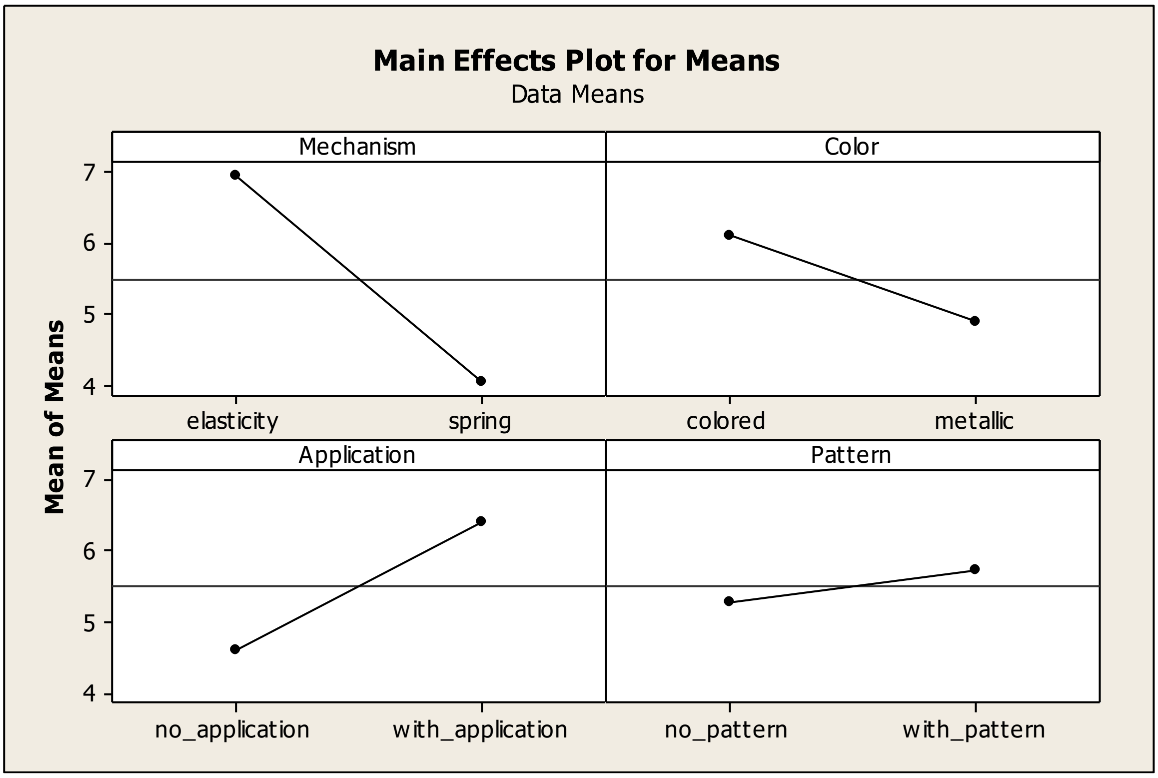
Response Table for Signal-to-Noise Ratios
Larger is better

Level	Mechanism	Color	Application	Pattern
1	16,55	15,00	13,02	14,08
2	12,11	13,65	15,64	14,58
Delta	4,44	1,35	2,62	0,50
Rank	1	3	2	4

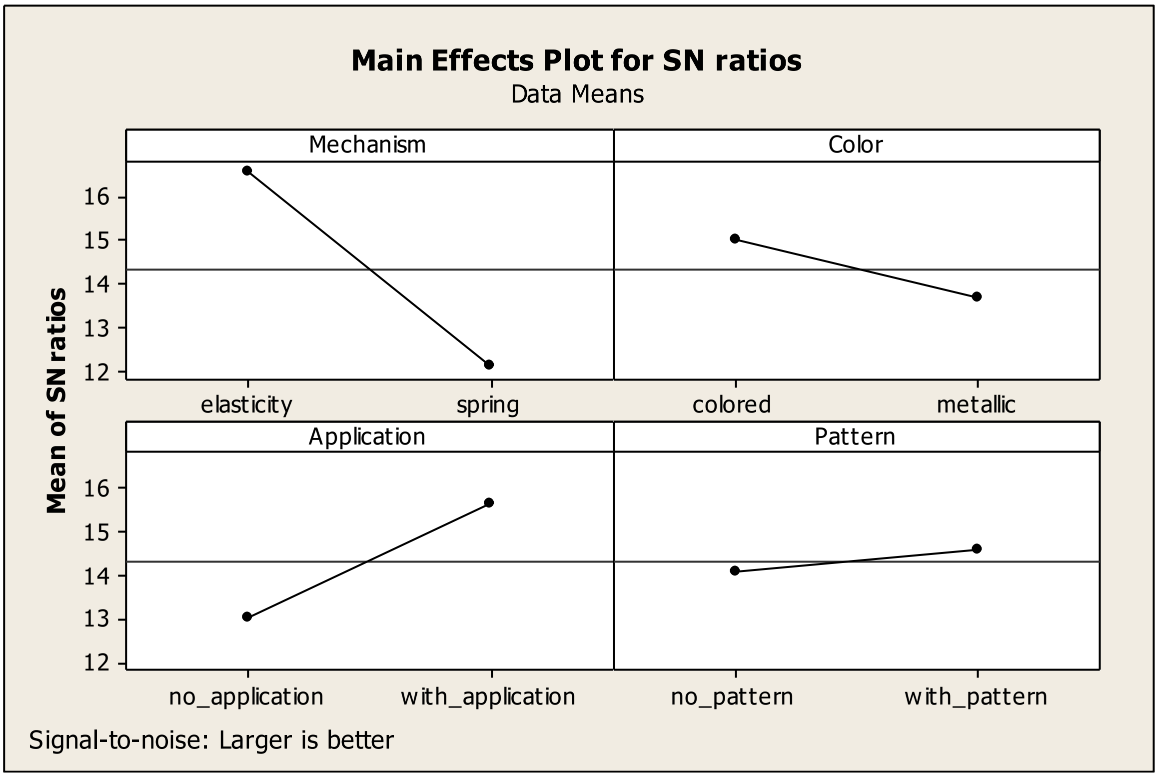
Response Table for Means

Level	Mechanism	Color	Application	Pattern
1	6,950	6,100	4,600	5,275
2	4,050	4,900	6,400	5,725
Delta	2,900	1,200	1,800	0,450
Rank	1	3	2	4

Fig. 19. *The results of the analysis*



(a)



(b)

Fig. 20. *The analysis of the medium (a) and S/N (b) values*

Figure 19, obtained automatically, presents the medium and the S/N ratio for each factor and each level. We regain the results of the numerical analysis for both the medium values and the S/N ratio: the ″Mechanism″ factor has the greatest importance, the second place is occupied by the ″Application″ factor, on the third place we find the "Color" factor followed by the "Pattern" factor.

The plots of Figure 20 present the medium values (Figure 20 a) and the S/N values (Figure 20 b) of each control factor as a function of their variation levels. We notice the agreement between Figure 20, Figure 4 and Figure 5: the greatest appreciation (and S/N values) is obtained by the coloured paper binder that has the elasticity mechanism, application and pattern.

ANOVA analysis of the experimental data

The instruction succession:

Stat → ANOVA → One-Way

allows us the ANOVA analysis set-up (Figure 21).

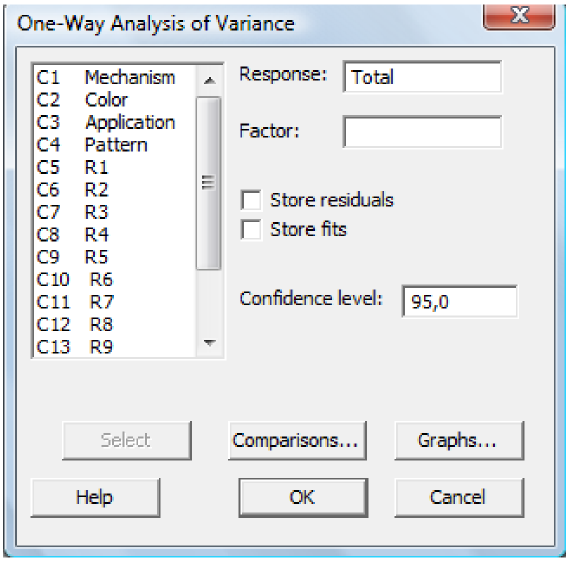


Fig. 21. *The ANOVA analysis*

One-way ANOVA: Total versus Mechanism

Source	DF	SS	MS	F	P
Mechanism	1	16,82	16,82	8,34	0,028
Error	6	12,10	2,02		
Total	7	28,92			

S = 1,420 R-Sq = 58,16% R-Sq(adj) = 51,19%

One-way ANOVA: Total versus Color

Source	DF	SS	MS	F	P
Color	1	2,88	2,88	0,66	0,446
Error	6	26,04	4,34		
Total	7	28,92			

S = 2,083 R-Sq = 9,96% R-Sq(adj) = 0,00%

One-way ANOVA: Total versus Application

Source	DF	SS	MS	F	P
Application	1	6,48	6,48	1,73	0,236
Error	6	22,44	3,74		
Total	7	28,92			

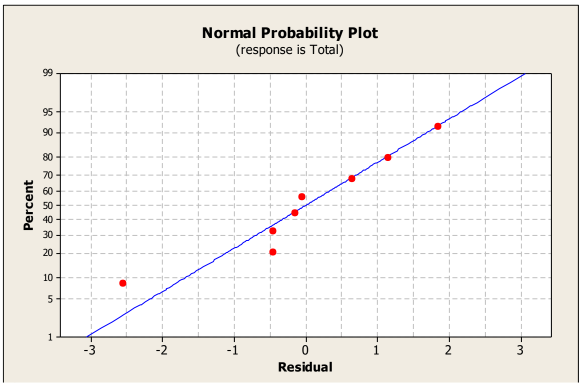
S = 1,934 R-Sq = 22,41%
R-Sq(adj) = 9,47%

One-way ANOVA: Total versus Pattern

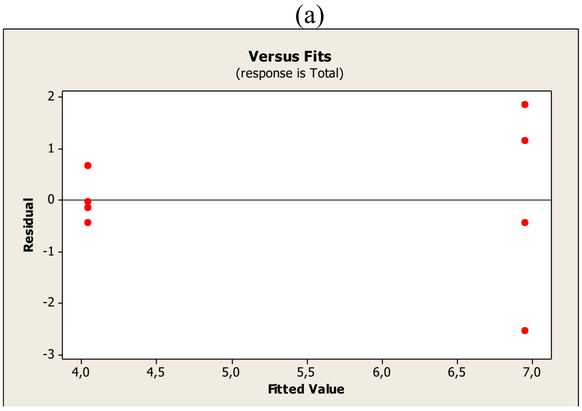
Source	DF	SS	MS	F	P
Pattern	1	0,41	0,41	0,09	0,780
Error	6	28,52	4,75		
Total	7	28,92			

S = 2,180 R-Sq = 1,40% R-Sq(adj) = 0,00%

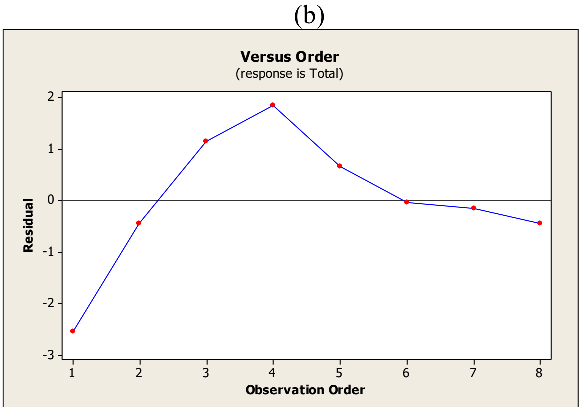
Fig. 22. *ANOVA analysis results*



(a)



(b)



(c)

Fig. 23. *The graphs of the ANOVA analysis for the "Mechanism" factor: (a) "Normal plots of residuals", (b) "Residuals versus fits", (c) "Residuals versus order"*

Setting each control factor, successively, in the window presented by Figure 21, the results presented by Figure 22 are obtained. We notice here the high value of the "F" factor for the "Mechanism" factor (8.34), followed by 1.73 for the "Application" factor and 0.66 for the "Color" factor. These results show the statistical importance of these factors and their correlation with the previous results of this paper.

Figure 23 presents (as an example) the graphs of the ANOVA analysis for the "Mechanism" factor: "Normal plots of residuals", Figure 23(a); "Residuals versus fits", Figure 23(b) and "Residuals versus order", Figure 23(c). It shows the normality, independence and random distribution of the residual values and the validity of the ANOVA analysis.

3. CONCLUSION

This paper brings a clear view of the steps a student should take on the project of designing a new product having as a point of start the voice of the customer. Classical numerical methods as well as modern techniques are emphasized as tools in the journey of a student toward a better understanding and mastering of the subject.

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