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AN AXIOMATIC DESIGN APPROACH FOR THE COST OPTIMISATION OF INDUSTRIAL COUPLED DESIGNS: A CASE STUDY

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ABSTRACT

The aim of this work is to present a methodology for optimising the costs of some industrial products that are coupled designs based on Axiomatic Design (AD). The proposed methodology consists in combining Response Surface Methodology (RSM) and Axiomatic Design as applied to both the engineering characteristics and cost functions of the products through a common set of explanatory design variables. The response surfaces are generated during the development of the product's prototype, and the methodology allows predicting the values for the design parameters of other products of the same family, in order to fulfil the functional requirements at a prescribed cost. The paper includes a case study related to the development of rubbercork raw material.

Keywords: Axiomatic Design, Response Surface Methodology, industrial costs, product development.

1. INTRODUCTION

Product performance can be appraised by using the so-called engineering (or applied) sciences, which development was significantly enhanced since the beginning of the 19th century, as a consequence of the Industrial Revolution.

Concerning to the cost of products, they always have been important but their significance is growing faster and faster after World War II, since the global market driving forces of supply and demand turn out to be prevalent. Therefore, there is a need for dependable procedures for the early cost estimation of products, in order to allow good decision-making from the outset of the product's design process [1].

The main difficulty in attaining reliable, early cost estimates is due to the manner in which data are handled by the adopted costing systems, and often cost estimation is only possible to attain after the product has been designed. By this time, however, it is too late for efficiently implementing a "design for manufacturing" strategy. In fact, it is more difficult and expensive to make changes in a product after its design solutions have been already selected.

Therefore, the adoption of efficient, reliable cost estimation methodologies became crucial to enhance the concurrent engineering teams, concerning to lowering costs and time-to-market while improving the product's performance [2].

Efficient cost estimating methodologies should allow capturing the main features (or relevant variables) of a given product, in order to make them useful in the cost estimation of new products with some degree of similitude in the course of their design and development process. The performance of these methodologies can be enhanced by simulation, as a means to better understand how the design parameters can be optimised during the development of the products [3]. This can be done through design of experiments (DoE) leading to the representation of the results in the form of response surfaces or hyper-surfaces.

A methodology for optimising the costs of industrial coupled designs based on AD and RSM is presented in this paper, with the aim of crossing the ranges of good product performance with the ranges of low industrial cost, which implies that both performance and cost must be expressed in terms of the same variables. This allows constructing cost models with which one can derive meaningful manufacturing cost estimates based on data that was previously collected.

2. THE PROPOSED METHODOLOGY

The proposed methodology consists in combining the Response Surface Methodology [4] and Axiomatic Design [5], as applied to both the engineering characteristics and cost functions of the products through a common set of explanatory design variables.

The methodology allows representing the response of the product to the specified design variables within their interesting ranges of values, as carried out during the prototype development.

The aim of the proposed methodology is to combine different functional requirements and/or constraints in such a way that allows for multi-criteria decisions. This is made combining data acquired in a set of experiments that are represented by a response surface. The surface of the cost is derived from the knowledge about the costs of materials and the costs of the manufacturing processes. This can be achieved during the product's development phase if a concurrent engineering background is used, since it is need data and knowledge from several sectors. A crucial factor to combine data and knowledge is representing technical and costs data in terms of the same variables.

The following case study explains how this was possible in an industrial case that was successfully achieved.

3. A CASE STUDY

3.1 THE RUBBERCORK PRODUCTION

Rubbercork is a composite material that combines some noteworthy rubber features — such as durability and swelling resistance to the action of lubricants and hydraulic fluids — with the outstanding cork characteristics in what regards to compressibility, recovery and low Poisson coefficient. These properties are suitable for sealing gaskets for engines, gear boxes and hydraulic equipment, natural gas meters, voltage transformers, as well as for static sealing of industrial oils, solvents, lubricant greases, refrigerating fluids, water and gases, just to name a few.

The main rubbercork engineering specifications are the tensile strength, the compressibility, the recovery, the flexibility, the hardness and the swelling resistance to lubricants and hydraulic fluids.

Those characteristics depend on a number of design variables expressing the relative quantities of constituents, as well as on the in-mould mass per volume unit, a property that is closely related to the density of the final product.

The typical constituents of rubbercork are: elastomer, cork granulate, plasticizer, inert fillers, activators, vulcanizers, accelerators, and antioxidants. The relative quantities of the first four constituents govern the physical proprieties of the composite, while the last four control the chemical reactions of vulcanization and prevention against oxidation.

Since the relative quantities of activators, vulcanizers, accelerators, and antioxidants are usually set to some unchanging, reference production values, only the relative quantities of elastomer, cork granulate, plasticizer and inert fillers, as well as the in-mould mass per volume unit, are considered design variables.

The rubbercork manufacturing process is performed through a chain of technological operations as shown in Fig. 1. First, the different constituents are mixed in internal mixers and homogenised in roll mills, as usually in the rubber industry [6]. The mixture is subsequently poured into steel moulds. A definite mass of mixture remains inside each mould while it is closed under controlled pressure. Next, the material is vulcanized during several hours at around 165º C. The vulcanizing time depends on the size and shape of the moulds. The composite is demoulded after cooling down, and the cured product is further processed and delivered in blocks, sheet or stamped gaskets.

Due to the small number of manufacturers all over the world, and to the lack of scientific knowledge about rubbercork, the product development is usually based on the expertise acquired over the years by the technical staff of small and medium enterprises. As a rule, costumers require some engineering specifications for a rubbercork product and manufacturers develop the composite material according to those requirements, which is usually achieved through a time consuming series of trial-and-error experiments.

Therefore, our goal was to identify the most relevant design variables and to find out phenomenological models that could be used to predict the product's final characteristics, including performance and cost, in a short time and with a small number of experiments.

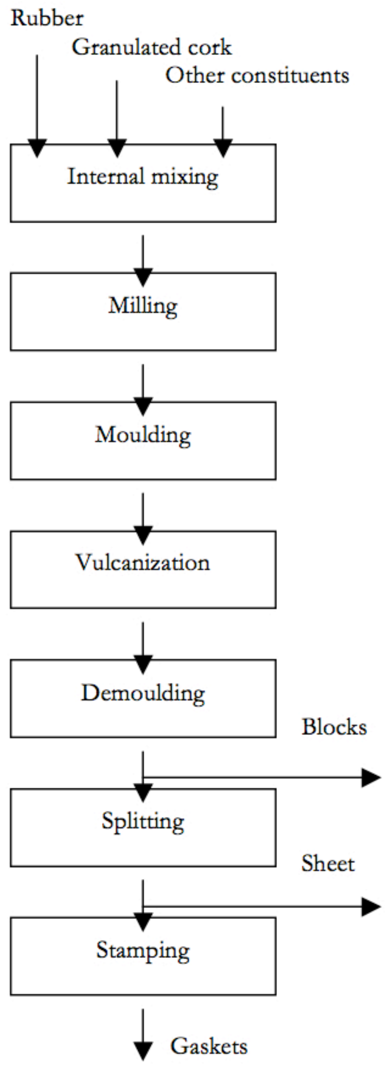

Figure 1. The rubbercork manufacturing process flowchart [7]

Despite the apparent simplicity, rubbercork engineering characteristics depend on several process variables, namely, mixing temperature and time, and vulcanization temperature and time. The process variables are essentially dependent on the available production equipment and are usually set to a general-purpose production condition.

3.2 THE PERFORMANCE ANALYSIS

As a means to satisfy the typical requirements of a large number of customers, the rubbercork responses that were experimentally studied in this performance analysis were the tensile strength, *T*, the compressibility, *C*, and the recovery, *R*. The considered design variables were the in-mould mass per volume unit, X_1, the relative cork quantity, X_2, the relative plasticizer quantity, X_3, the relative inert filler quantity, X_4, and the cork granule size range, X_5.

Our experimental research was divided into two phases, and an ISO 9001 qualified rubbercork producer has made all the required block specimens that were used in the experiments, as well as all the related tests according to the appropriate ASTM standards [8, 9]. One single specimen was employed for each experiment, from which nine samples evenly gathered from the entire specimen volume were tested for each one of the three responses under analysis.

A hypothetic polynomial function was explored in order to correlate the *j*-th experimental response, Y_j, to the design variables, X_i, within the usual manufacturing ranges, in order to find out relationships of the type:

$$Y_j = f_j\left(X_1, X_2, \ldots, X_k\right) + \varepsilon_j \,, \qquad (1)$$

where ε_j is the experimental random error.

Table 1. Values of the design variables (1st phase)

Variables		x_i levels -1	x_i levels +1
In-mould mass per volume unit (kg/m^3)	X_1	710	750
Relative cork quantity (PHR)	X_2	170	210
Relative plasticizer quantity (PHR)	X_3	15	25
Relative inert filler quantity (PHR)	X_4	85	115
Cork granule size (mm)	X_5	1~2	2~4

Table 2. Design of experiments and results (1st phase).

Exp.	Coded Variables: In-mould mass per volume unit X_1	Relative cork quantity X_2	Relative plasticizer quantity X_3	Relative inert filler quantity X_4	Cork granule size X_5	Tensile strength (MPa)	Compressibility (%)	Recovery (%)
1	-1	-1	-1	-1	-1	2,57	35,1	85,1
2	1	-1	-1	-1	-1	3,00	28,8	85,2
3	-1	1	-1	-1	-1	2,79	25,7	85,7
4	1	1	-1	-1	-1	3,17	23,2	86,6
5	-1	-1	1	-1	-1	2,64	32,4	86,0
6	1	-1	1	-1	-1	2,81	30,2	86,3
7	-1	1	1	-1	-1	2,49	34,3	85,3
8	1	1	1	-1	-1	2,98	26,9	86,2
9	-1	-1	-1	1	-1	2,40	34,9	85,4
10	1	-1	-1	1	-1	2,94	28,4	86,3
11	-1	1	-1	1	-1	2,37	28,9	85,3
12	1	1	-1	1	-1	2,91	28,0	85,8
13	-1	-1	1	1	-1	2,56	34,9	85,7
14	1	-1	1	1	-1	2,84	31,1	85,5
15	-1	1	1	1	-1	2,63	32,6	86,2
16	1	1	1	1	-1	2,71	31,3	86,0
17	-1	-1	-1	-1	1	2,61	29,8	84,8
18	1	-1	-1	-1	1	2,86	27,3	84,3
19	-1	1	-1	-1	1	2,56	29,2	84,6
20	1	1	-1	-1	1	2,64	27,3	83,9
21	-1	-1	1	-1	1	2,38	31,5	84,2
22	1	-1	1	-1	1	2,57	29,8	84,4
23	-1	1	1	-1	1	2,48	28,5	84,5
24	1	1	1	-1	1	2,61	28,7	84,4
25	-1	-1	-1	1	1	2,33	33,6	85,2
26	1	-1	-1	1	1	2,60	30,1	86,0
27	-1	1	-1	1	1	2,45	29,9	84,1
28	1	1	-1	1	1	2,67	26,8	83,9
29	-1	-1	1	1	1	2,44	33,3	86,7
30	1	-1	1	1	1	2,71	31,6	85,8
31	-1	1	1	1	1	2,51	30,2	85,0
32	1	1	1	1	1	2,76	27,3	85,0

The first phase of the experiment consisted in a "screening" procedure aimed at identifying the relevant design variables. A full factorial design of experiments with the five variables at two levels, totalling 32 experiments, was performed in this phase.

Table 1 presents the values of the five original design variables as coded to the levels -1 and +1. The amounts of constituents are expressed in terms of relative weight (PHR - parts per hundred of rubber), while Table 2 contains the design of experiments and the results that were attained through tensile, compressibility and recovery tests.

The significance of the design variables for the different responses were assessed through the ANOVA tables presented in the Tables 3, 4 and 5, by comparing the results of the *F*-test with the critical value of the *F* distribution for a significance level of 5%.

Table 3. ANOVA table relative to tensile strength

	Square sum	*DoF*	*Mean square*	*F*
x_1	0,6470	1	0,6470	64,97
x_2	0,0063	1	0,0063	0,64
x_3	0,0195	1	0,0195	1,96
x_4	0,0570	1	0,0570	5,72
x_5	0,2129	1	0,2129	21,38
$x_1 x_2$	0,0017	1	0,0017	0,17
$x_1 x_3$	0,0237	1	0,0237	2,38
$x_1 x_4$	0,0034	1	0,0034	0,34
$x_1 x_5$	0,0488	1	0,0488	4,90
$x_2 x_3$	0,0001	1	0,0001	0,01
$x_2 x_4$	0,0003	1	0,0003	0,03
$x_2 x_5$	0,0004	1	0,0004	0,04
$x_3 x_4$	0,0957	1	0,0957	9,61
$x_3 x_5$	0,0014	1	0,0014	0,14
$x_4 x_5$	0,0205	1	0,0205	2,06
Residual	0,1593	16	0,0100	
Total SS	1,2978	31		

$R^2 = 0.877$; $\alpha = 5\%$; $F(1,16,0.05) = 4.49$

Table 4. ANOVA table relative to compressibility

	Square sum	*DoF*	*Mean square*	*F*
x_1	73,3059	1	73,3059	21,58
x_2	60,5917	1	60,5917	17,84
x_3	23,0634	1	23,0634	6,79
x_4	18,0500	1	18,0500	5,31
x_5	4,4750	1	4,4750	1,32
$x_1 x_2$	2,2934	1	2,2934	0,68
$x_1 x_3$	1,2934	1	1,2934	0,38
$x_1 x_4$	0,0003	1	0,0003	0,00
$x_1 x_5$	5,8653	1	5,8653	1,73
$x_2 x_3$	6,3903	1	6,3903	1,88
$x_2 x_4$	0,0834	1	0,0834	0,02
$x_2 x_5$	1,0634	1	1,0634	0,31
$x_3 x_4$	0,5084	1	0,5084	0,15
$x_3 x_5$	5,8084	1	5,8084	1,71
$x_4 x_5$	0,2167	1	0,2167	0,06
Residual	54,3439	16	3,3965	
Total SS	257,3527	31		

$R^2 = 0.789$; $\alpha = 5\%$; $F(1,16,0.05) = 4.49$

Table 5. ANOVA table relative to recovery

	Sq. sum	*DoF*	*Mean sq.*	*F*
x_1	0,1012	1	0,1012	0,39
x_2	0,6422	1	0,6422	2,47
x_3	0,8022	1	0,8022	3,08
x_4	1,0272	1	1,0272	3,95
x_5	7,6050	1	7,6050	29,22
x_1x_2	0,0200	1	0,0200	0,08
x_1x_3	0,0939	1	0,0939	0,36
x_1x_4	0,0050	1	0,0050	0,02
x_1x_5	0,6422	1	0,6422	2,47
x_2x_3	0,0035	1	0,0035	0,01
x_2x_4	1,2535	1	1,2535	4,82
x_2x_5	1,9012	1	1,9012	7,30
x_3x_4	0,1901	1	0,1901	0,73
x_3x_5	0,0235	1	0,0235	0,09
x_4x_5	1,3612	1	1,3612	5,23
Residual	4,1644	16	0,2603	
Total SS	19,8365	31		

$R^2 = 0.790$; $\alpha = 5\%$; $F(1,16,0.05) = 4.49$

From Tables 3, 4 and 5, according to Axiomatic Design [5], the design equation for the rubbercock product is:

$$\begin{bmatrix} T \\ C \\ R \end{bmatrix} = \begin{bmatrix} \mathrm{X} & 0 & \mathrm{X} & \mathrm{X} & \mathrm{X} \\ \mathrm{X} & \mathrm{X} & \mathrm{X} & \mathrm{X} & 0 \\ 0 & \mathrm{X} & 0 & \mathrm{X} & \mathrm{X} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_3 \\ x_4 \\ x_5 \end{bmatrix}, \quad (2)$$

where T, C and R are the tensile strength, the compressibility and the recovery responses of the rubbercork product, and the symbols X and 0 represent high and low significance of the associated design variables.

As one can see, Eq. (2) represents a coupled design. In brief, this means that when designing a new rubbercork product, it would be impossible to set the design variables to fulfil all the functional requirements simultaneously. In addition, it would be impossible to set most of the responses without disturbing the other responses. Because of this, setting the design variables of such a product should be done in an iterative way, and the success of this expensive and time-consuming process is not guaranteed.

Since one of the goals of this research was to find out relationships that could be helpful in genuine industrial product design, one had to understand what design variables should be made constant so that the design equation becomes decoupled.

This means that two variables should be selected for setting them to constant values, so that we can have a design equation with three functional requirements, three design variables and a 3x3, diagonal or triangular design matrix. In fact, the AD's Independence Axiom states that the functional requirements of a design should be fulfilled an independent manner, and Theorem 4 states that in an ideal design the number of design variables equates to the number of functional requirements [5]. Noting that uncoupled and decoupled designs are acceptable design solutions and have, respectively, diagonal and triangular matrices [5], one could conclude that a possible approximation to a decoupled design that one could obtain from Eq. (2) is given by:

$$\begin{bmatrix} T \\ C \\ R \end{bmatrix} = \begin{bmatrix} \mathrm{X} & 0 & \mathrm{X} \\ \mathrm{X} & \mathrm{X} & 0 \\ 0 & \mathrm{X} & \mathrm{X} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \\ x_5 \end{bmatrix}, \quad (3)$$

which means that the design variables x_3 (relative plasticizer quantity) and x_4 (relative inert filler quantity) must be set to some specific values, in order to satisfy Theorem 4. Therefore, taking in account the attained experimental results and the historical of the producer, it was decided to set those variables to values that were supposed to satisfy most of the targeted customers.

Anyway, note that Eq. (3) does not represent either an uncoupled or decoupled design, which means that the difficulty described above could not be completely surpassed.

In an industrial point of view, however, the cork granule size range (c.g.s.r.), x_5, is treated in a different way than the other two design variables, since the cork granulate usually comes in only two size ranges, sometimes three. Moreover, the granule size range selection is usually made at the outset of development process, and sometimes the costumer imposes the value for this design variable.

In our case, the available granule size ranges were 1~2 mm and 2~4 mm. Thus, we decided to make separate performance analyses in a second experimental phase for the two granule size ranges that were available to us. This corresponds solve two distinct decoupled designs — one for each granule size range — according to the following design equation:

$$\begin{bmatrix} T \\ C \end{bmatrix} = \begin{bmatrix} \mathrm{X} & 0 \\ \mathrm{X} & \mathrm{X} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, \quad (4)$$

a condition that is acceptable in the light of Axiomatic Design.

In fact, this condition allows attaining the required compressibility by adjusting only the relative cork quantity. Then, one can set only the in-mould mass per volume unit to fulfil the required compressibility without disturbing the previously attained tensile strength. In the end, one has just to check if the resulting recovery is within the required range.

The main goal of the second phase was to accurately analyze the relationships between the responses and the selected design variables, including the study of the possible cross-effects. This was achieved through a second set of experiments, which also aimed finding out a phenomenological model represented by a second-degree polynomial function of the type

$$Y = \beta_0 + \sum_{i=1}^{n} \beta_i x_i + \sum_{i=1}^{n} \beta_{ii} x_i^2 + \sum_{j=0}^{n} \sum_{i<j}^{n} \beta_{ij} x_i x_j + \varepsilon, \quad (5)$$

where Y is the response under analysis, β_0, β_{ii}, β_{ij} are the polynomial coefficients, n is the number of coded explanatory variables, x_i, x_{ii}, x_{ij}, and ε is the experimental random error.

Thus, a central composite design (c.c.d.) model with two variables at five value levels was used. The influence of the in-mould mass per volume unit, X_1, and of the relative cork quantity, X_2, were studied for each granule size range separately, totalling 20 experiments. The results for the first 10 experiments — related to the granule size range 1~2 mm — are presented here.

Table 6 displays the real and the coded values for the design variables, and Table 7 shows the results of the experiments. Tables 8~9 show the ANOVA tables, and Tables 10~11 show the coefficients of regression, standard deviation and *t* values.

Table 6. Values of the design variables (2nd phase)

Variables		x_i *Levels* -√2	-1	0	1	+√2
In-mould mass per volume unit (Kg / m³)	X_1	659	680	730	780	801
Relative cork quantity (PHR)	X_2	128	140	170	200	212

Table 7. Design of experiments and results (2nd phase)

x_1	x_2	*Tensile Strength* (MPa)	*Compression* (%)
-1	-1	2,40	37,5
-1	+1	2,52	32,9
+1	-1	2,85	30,3
+1	+1	3,09	27,6
-√2	0	2,35	36,5
+√2	0	3,08	26,4
0	-√2	2,61	35,5
0	+√2	3,03	27,6
0	0	2,75	32,4
0	0	2,88	29,8

Table 8. ANOVA table relative to tensile strength (2nd phase)

	Sq. sum	*DoF*	*Mean square*	*F*
x_1	0.5261	1	0.5261	110.34
x_1^2	0.0174	1	0.0174	3.65
x_2	0.1102	1	0.1102	23.11
x_2^2	0.0005	1	0.0005	0.11
$x_1\,x_2$	0.0021	1	0.0031	0.66
Residual	0.0191	4	0.0048	
Total SS	0.6774	9		

$R^2 = 0.972;\ \alpha = 5\%;\ F(1,4,0.05) = 7.71$

Table 9. ANOVA table relative to compressibility (2nd phase)

	Square sum	*DoF*	*Mean square*	*F*
x_1	89.8623	1	89.8623	57.15
x_1^2	0.3889	1	0.3889	0.25
x_2	42.5505	1	42.5505	27.06
x_2^2	0.5779	1	0.5779	0.37
$x_1\,x_2$	0.8815	1	0.8815	0.56
Residual	6.2895	4	1.5724	
Total SS	140.2704	9		

$R^2 = 0.955;\ \alpha = 5\%;\ F(1,4,0.05) = 7.71$

Table 10. Coefficients of regression for tensile strength

	Coefficient	*Std deviation*	*t*
Indep. coeff.	2.8150	0.0488	57.654
x_1	0.2564	0.0244	10.504
x_1^2	-0.0617	0.0323	-1.912
x_2	0.1174	0.0244	4.808
x_2^2	-0.0106	0.0323	-0.329
$x_1\,x_2$	0.0281	0.0345	0.813

$R^2 = 0.972;\ \alpha = 5\%;\ |t|>2.776$

Table 11. Coefficients of regression for compressibility

	Coefficient	*Standard deviation*	*t*
Independent term	31.1111	0.8867	35.087
x_1	-3.3516	0.4433	-7.560
x_1^2	0.2917	0.5865	0.497
x_2	-2.23063	0.4433	-5.202
x_2^2	0.3556	0.5865	0.606
$x_1\,x_2$	0.4694	0.6270	0.749

$R^2 = 0.955;\ \alpha = 5\%;\ |t|>2.776$

From Tables 10~11, one can find the following estimate expressions:

$$T = 2.82 + 0.26x_1 + 0.12x_2 \qquad (R^2{=}0.97) \tag{6}$$

$$C = 31.1 - 3.4x_1 - 2.3x_2 \qquad (R^2{=}0.96) \tag{7}$$

From Eq. (6) and Eq. (7) one can conclude that the design equation for the 1~2 mm cork granule size range is

$$\begin{bmatrix} T \\ C \end{bmatrix} = \begin{bmatrix} \mathrm{X} & \mathrm{X} \\ \mathrm{X} & \mathrm{X} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}. \tag{8}$$

Eq. (8) denies the decoupled nature of the design that was stated by Eq. (4), and this discrepancy is easy to explain: Eq. (4) derives from a two-level DoE, which gives a linear model, and Eq. (8) comes from a five-level DoE, which yields to a more accurate polynomial model of the 2nd order.

Figures 2 and 3 show graphical representations of Eq. (6) and Eq. (7).

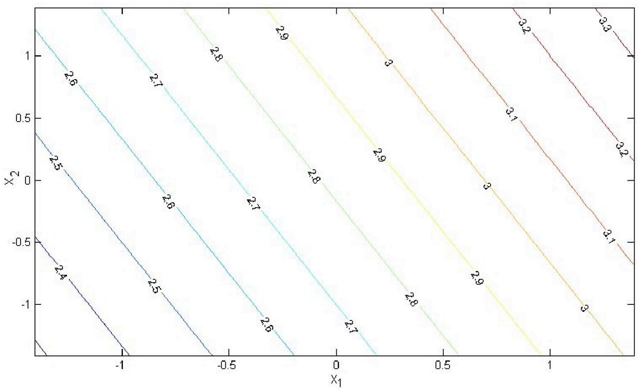

Figure 2. Projection of the tensile strength (MPa) surface over the plane x_1Ox_2

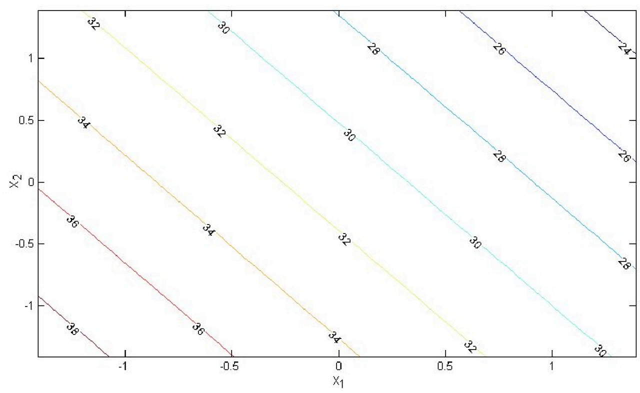

Figure 3. Projection of the compressibility (%) surface over the plane x_1Ox_2

A short validation procedure was carried out to appraise the quality of the predictions that one can obtain through Eqs. (6) and (7). Table 12 shows the experimental conditions used for the validation tests, and Table 13 contains the results that were attained.

Table 12. Experiments for the validation of the models

Exp.	c.g.s. (mm)	x_1 (X_1)	x_2 (X_2)	Tensile strength (Mpa)	Compressibility (%)
1	1-2	-0.8 (690)	0.4 (182)	2.47	35.9
2		0.3 (745)	-0.9 (143)	2.8	32.2
3		0.1 (735)	0.8 (194)	2.78	30.7
4		0.9 (775)	-0.5 (155)	2.94	30.4

Table 13. Calculated and experimental responses

Exp.	Tensile strength (Calc.)	Tensile strength (Exp.)	Var. (%)	Compr. (Calc.)	Compr. (Exp.)	Diff. (%)
1	2.66	2.47	7.7	32.9	35.9	-8.4
2	2.79	2.80	-0.4	32.2	32.2	0.0
3	2.94	2.78	5.8	28.9	31.7	-8.8
4	2.99	2.94	1.7	29.2	30.4	-3.9

One can see that the difference between the calculated and the experimental results is always less that 10%.

3.3 COST ANALYSIS

The cost function in Euro/m³ of a rubbercork composite mixture, C_M, at 2003 prices, is given by [7]

$$C_M = X_1 \frac{C_1 + 0.01 \cdot C_C \cdot X_2}{C_2 + 0.01 \cdot X_2} \tag{9}$$

where C_1 and C_2 are constants that represent, respectively, the cost per kg of rubber and the weight per kg of rubber of all the raw materials except cork, C_C is the cork cost per kg of rubber, X_1 is the in-mould mass per volume unit, and X_2 is the relative cork quantity.

For the 1~2 mm cork granule size range, there is:

C_1 = 1.839 EUR/kg of rubber,

C_2 = 2.313 kg/kg of rubber, and

C_C = 1.950 EUR/kg of rubber.

Thus, the cost per cubic metre of the studied mixture is given by [7]

$$C_M = X_1 \frac{1.8390 + 0.0195 \cdot X_2}{2.3130 + 0.0100 \cdot X_2}, \tag{10}$$

In order to have Eq. (10) expressed in terms of coded variables, it is necessary to make the same variable transformations that were used to build Table 6:

$$x_1 = \frac{X_1 - 730}{50}, \tag{11}$$

$$x_2 = \frac{X_2 - 170}{30}. \tag{12}$$

Therefore, the cost of the studied mixture expressed in terms of coded variables is given by

$$C_M = \frac{937.558 + 64.216 x_1 + 106.417 x_1 x_2}{1 + 0.075 x_2}. \tag{13}$$

Eq. (13) is graphically represented in Figure 4.

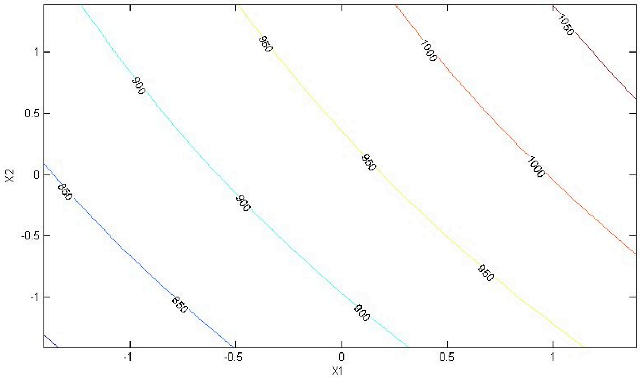

Figure 4. Projection of the mixture cost (Euro/m³) surface over the plane x_1Ox_2

3.4 PERFORMANCE AND COST INTEGRATION

We are now in position to find out interesting zones in terms of variables — i.e., zones where one can find out some suitable response values at different costs. This can be done by superposing the tensile strength surface (Fig. 2) with the compressibility (Fig. 3) and the mixture cost (Fig. 4) surfaces, as shown in Figure 5.

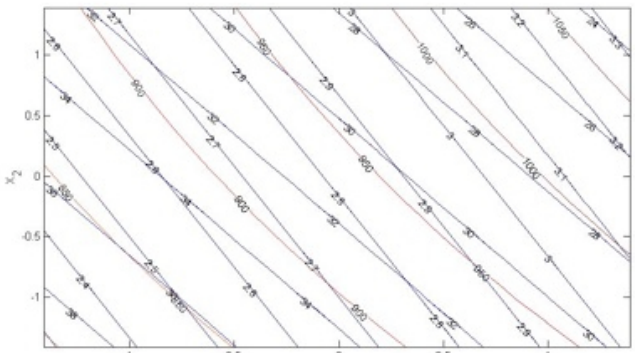

Figure 5. Simultaneous projection of the tensile strength, compressibility and cost surfaces over the plane x_1Ox_2

A brief example shows how to proceed.

Let us suppose that one has to manufacture two different rubbercork composites — Product 1 and Product 2 — for which one knows the required minimum tensile strength and the compressibility range:

Product 1: T_{min} = 2,8 MPa; C = 25~30 %.

Product 2: T_{min} = 2,7 MPa; C = 30~35 %.

These specifications for the functional requirements should be achieved at the lowest possible cost. Notice that the relative plasticizer quantity, X_3, the relative inert filler quantity, X_4, and the cork granule size range, X_5, were kept constant — i.e., at the usual values for the production line.

The light grey zones of Fig.s 6~7 show the pairs of values (x_1, x_2) that accomplish both functional requirements. The dark grey zones indicate the lower possible cost for both products. For both products, the minimum manufacturing cost is below 900 Euro/m^3.

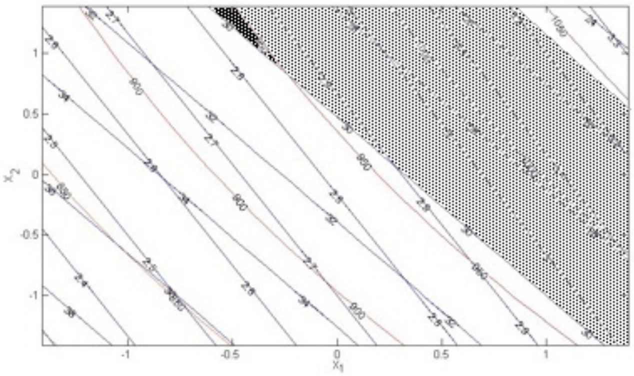

Figure 6. Tensile strength, compressibility and cost ranges for Product 1

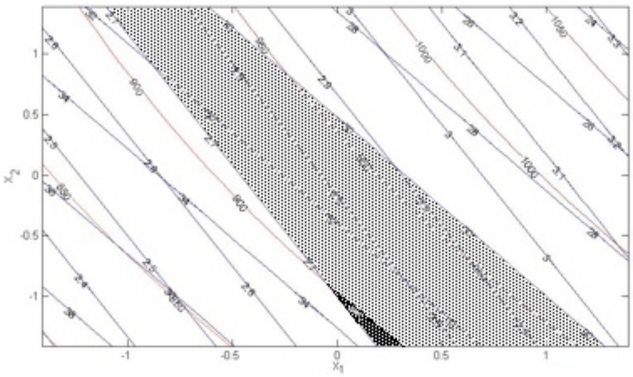

Figure 7. Tensile strength, compressibility and cost ranges for Product 2

The given examples show a maximum possible cost variation of 8,7% for Product 1 and 6,3% for Product 2, which cannot be neglected if one wants to achieve the minimum cost for the required performance.

4 CONCLUSIONS

In an economy where doing it "right at first time" is critical, the existing of predictive tools is very important, especially when there are not scientific laws for modelling the response of the products under design.

This paper presented a methodology that promotes the integration of data from the product the development, the manufacturing and the costs departments of a small company. The integration was attained by using AD as a means to interpret the results of design of experiments, in order to minimize the costs of products which designs are coupled through early, time-saving decisions on how the manufacturing variables should be set by taking in account the independence axiom.

The design tactics consists in using design of experiments to detect the variables that are causing couplings, so that they can be "frozen" in a systematic manner.

The proposed methodology allows for:

- acquiring a better perception on the behaviour of the production processes;
- finding out solutions that are compatible with the application of simultaneous criteria for decision-making, especially to take in account functional performance and economical requirements.
- expressing costs in terms of the considered manufacturing variables;
- coming upon suitable cost response zones that correspond to certain value ranges of the considered manufacturing variables.

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