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AN AXIOMATIC APPROACH TO MANAGING THE INFORMATION CONTENT IN QFD: APPLICATIONS IN MATERIAL SELECTION

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ABSTRACT

Material selection takes on a strategic importance to meet the highest level standard of a product/process design. The evolution of legislative, regulatory and functional needs makes this selection extremely complex as it is the result of several compromises involving the consumer. Choosing the wrong material produces product failures, reliability problems and high costs. On the other hand, the many compromises needed during product design are often responsible for a non-optimal final design and for a reduction in the design process efficiency (delays in schedule or a rise in the cost). In the material selection process, the designer has to deal with a lot of trade-offs. These are often caused by a failure to identify the functional specifications that are related to the materials (i.e. limited weight, ability to conduct heat, wear resistance, etc.). In many cases, however, the designer has correctly understood the functional specifications but there is a deficiency in the mapping of the connections between the functional specification and the physical characteristics (i.e. density, thermal conductivity, hardness, etc.). A systematic strategy to drive the designer to discover and map the correlation between the different physical characteristics is also missing. This paper shows how, using the Information Axiom of Axiomatic Design Theory, the designer can clearly define the functional specifications as functional requirements (FRs) and identify the mutual correlation between the different physical characteristics (the design parameters used in Axiomatic Design). In this way, material selection during the development of new product can be made more effective and innovative.

Keywords: MADM problems, materials selection, Information Axiom.

1 INTRODUCTION

Over the years, various attempts have been described which aim to provide a structured support in the selection of optimum materials for projects. The algorithms developed tried to help assess material performance based on several critical aspects (selection attributes) minimizing the needs of high level competences.

It is important to observe that each of the selection attributes usually has a specific and different impact on the product quality and on the ideality of the solution so that an effective weighting method has to be adopted to consider all attributes during the material selection process. The correct definition of the different weights for selection attributes among many alternatives is still an open topic. Many of the proposed methods define a precise and complete structured methodology to overcome the problems of weighting evaluation (e.g. AHP method [Mayyas *et al.*, 2011], Entropy Weighting Method, etc.) but at the same time they appear as extremely rigid frameworks with complex procedures that are usually not sustainable for application in the real industrial environment. In fact, the rigidity and the time consuming characteristics of these methods mean that the decision making process still used in many industrial environments is a structureless approach completely based on the expertise, and built on the trust, of the technicians and engineers who are members of the project team.

With the aim of developing a formal approach, without sacrificing the inventing contribution to the selection process, a study of the authors [Cavallini *et al.*, 2013] proposed the use House of Quality (HoQ) as a preliminary aid in the material selection process. In this model, the correlation between the selection criteria is still not considered during the criteria weights calculation and this aspect can sometimes produce an incomplete understanding of the optimal weight that has to be assigned to each criteria. In other words, in articulate systems it is very important to estimate as soon as possible the complexity of the development phase of a new product. A large part of this complexity (as clearly shown in Axiomatic Design) is often due to the correlation between the design variables.

The aim of this study is to develop a simplified model to quantitatively take into account this coupling in the weighting estimation for the selection criteria. The proposed method considers that the evaluation of the weight of each criterion has to be dependent on the following two points:

- the ability to represent the functional needs of the product (i.e. to translate effectively the informal description of what the material has to sustain during the product lifecycle);
- the number of degrees of freedom available for the optimization of each criteria, to avoid sacrificing the other criteria or more probably facing with trade-off problems.

The proposed methodology can be optimally and simply integrated with Multi Attributes Decision Making algorithms (MADM) to span the whole process of material selection.

To better explain the research topic, a brief case study is presented at the end of this paper.

2 PROPOSED METHODOLOGY

The proposed method wants to introduce an approach based on the second axiom of Axiomatic Design [Suh, 1990] that is the Information Axiom. This axiom says that the best design alternative among all is the one that minimizes the information content. It's simple to understand that the larger the quantity of data necessary to complete the task, the greater the probability that something goes wrong. Therefore, less necessary information means a high probability of optimization of the task. Our aim is to deploy this concept in the study of the correlations between the characteristics of the materials and then use the results to better evaluate the different solution in the material selection problem.

Figure 1 shows the typical scheme of the first HoQ (based on the QFD cascade).

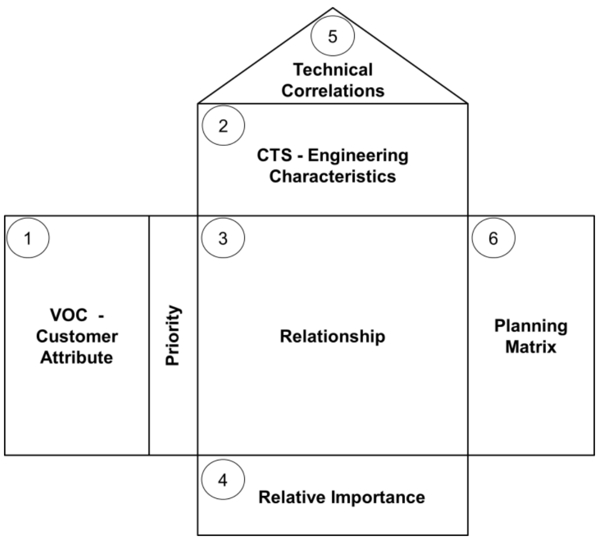


Figure 1. Scheme of the first HoQ.

The methodology to compile this graphical design tool is largely shown in literature [Hulrich, *et al.*, 2008] and many possible integrations with Axiomatic Design have been developed during the years (e.g. [Rizzuti, *et al.*, 2009]). For the aim of this paper we focus particularly only on two aspects of the HoQ:

- The weighting method for the Critical to Satisfaction (CTS);
- The signification of the roof of the first HoQ.

In the traditional HoQ algorithm the weight (w_{Rj}) for each CTS is computed as (4).

$$w_{Rj} = \sum_{i=1}^{n} (v_i * x_{ij}) \quad (4)$$

Where:

- v_i is the weight of the *i*-th Voice of Customer (VOC);
- x_{ij} is the correlation coefficient between the *j*-th CTS and the *i*-th VOC;

This relative importance weight computed for the *j*-th CTS can be normalized as follows:

$$W_{Ri} = \frac{w_{Rj}}{\sum_{j=1}^{m} w_{Rj}} \quad (5)$$

The roof of the first HoQ shows the correlations between the CTSs. This part of the HoQ is the real theme of interest for the approach proposed in this paper. Usually the correlation between CTSs is considered in a qualitative manner. With this approach the design team can clearly show and understand intuitively the kind of correlation between the CTSs during the design phase. The data reported in the roof of the first HoQ are although very seldom used in a quantitative or semi-quantitative manner as a design driver to improve the project.

This paper proposes a new approach to integrate the data collected in the roof of the first HoQ in the weighting process of the CTS. In this context is very important to explore the different kinds of mutual correlation that can be found between two different CTSs.

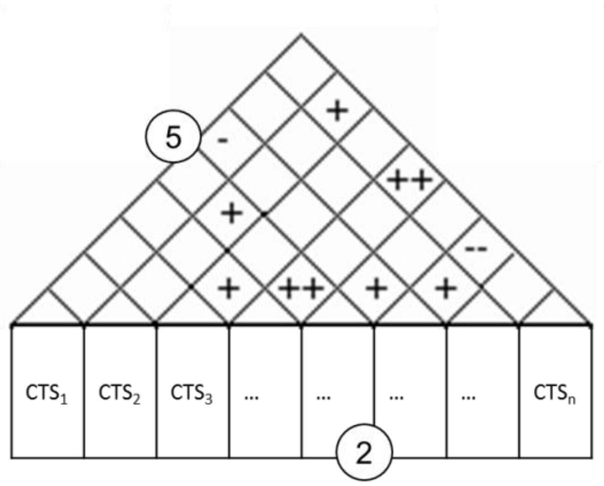


Figure 2. Highlight of the roof of the first HoQ.

Three types of correlation can be enumerated through a simplified taxonomy (see Figure 2):

- No correlation;
- Positive correlation;
- Negative correlation.

The meaning of *no correlation* is clear. *Positive correlation* means that two CTSs are correlated in a sense that the improvement of one involves the improvement also of the other. Finally *negative correlation* means that between the two CTSs there is a trade-off situation: i.e. the improvement of the one involves the worsening of the other. It is intuitive to understand that among the three alternative types of correlation, the only critical for the design activity is the negative correlation.

The proposed axiomatic approach to manage the information content in QFD wants to take into account the negative correlation among the different CTSs in the weighting process. As mentioned in the introduction, the weight of each selection criteria (the CTS using the terminology of QFD), has to be dependent not only on the representation of the VOCs, but also on the correlation grade among the selection criteria. A quantitative and extremely simple method to manage the correlation among the selection criteria can be introduced with the aid of the Information Axiom.

In particular we define the following values for the correlation among the selection criteria:

- 0 for no correlation;
- +1,+3,+9 for positive correlation;
- -1,-3,-9 for negative correlation.

These data should be used to fill in the roof of the HoQ and to fix in what manner each selection criteria interact with the other. If we assume as *n* the number of the selection criteria, the total number of correlations that each selection criterion can develop is *n-1*. The probability that the *j*-th selection criterion shows a non-negative correlation in the design activities can be calculated as:

$$P_j = \frac{(n-1) - \#Negative\ correlation\ of\ the\ j-th\ selection\ criteria}{(n-1)} \quad (6)$$

The expression (6) defines an indicator able to "quantify" the correlation developed by the *j*-th selection criterion. The use of a probabilistic approach is useful because many of the correlations should have a stochastic behaviour. The partial content of information of the *j*-th selection criterion can then be defined as follows:

$$I_{pj} = -\log_2 P_j \quad (7)$$

The Expected Value of Negative Correlation $(EVNC)_j$ can be introduced to consider the magnitude of the negative correlations among the *j*-th selection criterion and the other. $EVNC_j$ is defined as follows:

$$EVNC_j = \sum_{k=1}^{(n-1)} (\alpha_k * \delta_k) \quad (8)$$

where:

- α_k is the probability that the *k*-th correlation for the *j*-th selection criterion is negative;
- δ_k is the negative weight associated with the *k*-th correlation for the *j*-th selection criterion.

Finally, it can be defined the complete content of information for the *j*-th selection criterion as:

$$I_j = I_{pj} * abs\,(EVNC)_j \quad (9)$$

The correlation weight for the *j*-th selection criterion is then defined as:

$$W_{Cj} = \frac{1/I_j}{\sum_{i=1}^{n} 1/I_j} \quad (10)$$

where

$$0 \le W_{Cj} \le 1 \quad (11)$$

When the number of negative correlations made by the *j*-th CTS is zero then $W_{Cj} = \infty$. This condition can be easy managed by the assumption shown in Table 1 (where *k* is the number of CTSs that have non-negative correlation).

Table 1. Summary of the proposed method.

Condition	Results	Assumption
$\#NC_j = 0$	$W_{Cj} = \infty$	$I_j = \max(I_j) * n - k$
$\#NC_j = (n-1)$	$W_{Cj} = 0$	

The W_{Cj} should then be combined with the W_{Rj} from (5), to obtain a unique importance weight for the *j*-th selection criterion. With the aim to conjugate formal treatment and intuitive simplicity, the answer to the aforementioned question can be found in.

$$W_j = \frac{W_{Rj} * W_{Cj}}{\prod_{j=1}^{n} (W_{Rj} * W_{Cj})} \quad (12)$$

where

$$0 \le W_j \le 1 \quad (13)$$

On the basis of what has been described, the most important selection criterion is the one that satisfied better the combination of the two following tests:

- Is more representative to the VOCs array.
- Is more "independent" or uncoupled with the other selection criteria.

The proposed approach considers a negative correlation between the CTSs as a negative element for the research of the best solution for the system. The motivation of this assumption is based on a high number of real application experiences (in particular connected with material selection for mechanical applications) that have shown many problems in finding a good optimization for the material performance in presence of many trade-off situations.

3 CASE STUDY: THE MATERIAL SELECTION PROBLEM

In the proposed case study, the task is the selection of the optimal material for an engineering product. The product is the structural frame of a road bicycle, like the one reported in Figure 3.

Figure 3. Frame for a road bicycle used as Case Study.

The conceptual design starts with the collection of the Voices of the Customer expressed in the example as functional requirements. The biker (customer) will use this road-bicycle had expressed the following desires for his/her bicycle:

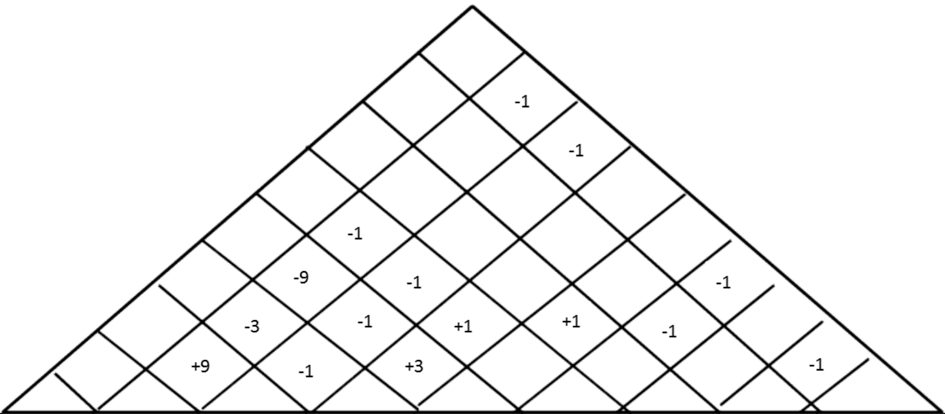
A. Should be light;
B. Should be strong;
C. Should be resistant to repeated loads;
D. Should have ductile rupture (the rupture has to be not sudden).

These desires should be integrated with the needs identified by the design team, of which the most important are:

i. The frame has to be produced with a metal alloy, so that it can be easy joinable;
ii. The material should be correctly stiff to avoid transmitting excessive forces to the biker;
iii. The material should withstand to atmospheric agents;
iv. The material should have a limited cost (the target market is formed by amateur bikers).

In Figure 4 it is shown the first HoQ through which the Voices of the Customer and the design team needs are systematically traduced in technical terms.

According to the proposed method, the parameters computed from (5) to (9) are shown in table 2.



VOC	Priority	Density	Rm	Fatigue strength	Toughness	A%	Weldability	E	Salty fog hours	Cost
A	3	+9								
B	5		+9	+3						
C	3		+3	+9						
D	3				+9	+3				
i	4						+9			
ii	2							+9		
iii	4								+9	
iv	4		+1	+1						+9
score		*27*	*58*	*46*	*27*	*9*	*36*	*18*	*36*	*36*
W_{rj}		**0.1**	**0.2**	**0.15**	**0.09**	**0.03**	**0.12**	**0.06**	**0.12**	**0.12**

Figure 4. HoQ of structural frame for a road bicycle.

Table 2. Summary of the calculated parameters.

Parameters	Density	Rm	Fatigue Strenght	Thoughness	A%	Weldability	E	Salty fog hours	Cost
$\mathbf{P_j}$	1	0.5	0.5	0.75	0.75	0.5	1	0.87	0.5
$\mathbf{I_{pj}}$	0	1	1	0.41	0.41	1	0	0.19	1
$\mathbf{EVNC_j}$	0	-4	-2	-3	-7.5	-2	0	-0.87	-2
$\mathbf{I_j}$	28	4	2	1.24	3.11	2	28	0.17	2
$\mathbf{W_{Cj}}$	0.004	0.03	0.06	0.09	0.04	0.06	0.004	0.66	0.06
$\mathbf{W_j}$	0.008	0.124	0.186	0.16	0.021	0.145	0.004	0.16	0.145

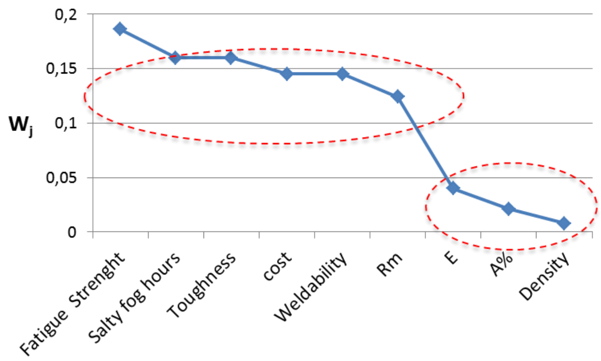


Figure 5. CTSs Importance Ranking with the proposed method.

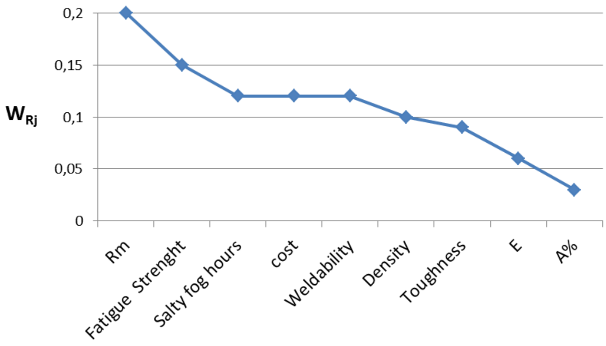


Figure 6. Importance Ranking without correlations.

The importance rating W_j of CTS is shown in Figure 5 and it can be easily deduced that the set of CTSs can be divided into two groups:

- High importance CTSs (on the left);
- Low importance CTSs (on the right).

The high level CTSs contain the maximum level of customer satisfaction and design optimization probability. Due to this consideration it is fundamental for the design team to focus its attention on these CTSs as the main drivers in the material selection for the system. For comparison in Figure 6 it is shown the importance rating of the CTSs deduced by the use of the HoQ without considering the correlation among the CTSs (W_{Rj}). From the comparison between Figure 5 and Figure 6 two aspects can be highlighted:

- In Figure 6 no importance class can be identified through the CTSs array;
- No design complexity evaluation is considered in Figure 6.

The proposed weighting method can be finally integrated in the advanced MADM algorithms to conclude the material selection problem [Cavallini, *et al.*, 2013] and identify the best solution for the system.

4 CONCLUSIONS

In every engineering or management system there is the need to operate with the system complexity. This complexity can be declined in a lot of different project features: data, information, number of people involved, quantity of material resources consumed and so on. However it is important to note that the system complexity is due to "single objects" only to a limited degree instead a great contribute to this complexity is produced by the interaction of many "single objects". Interaction is the key to manage and improve the performance in an organization not only at the *top-notch* level, but in every single design task. Axiomatic Design recognizes this strategic feature.

This paper has shown how the second axiom of Axiomatic Design can be used as an important step to manage the system complexity. The proposed approach represents a first attempt of the authors to use the concept of the Information Axiom in integral aided method for material selection based on Quality Function Deployment and MADM algorithms. In this context, the Information Axiom is used to evaluate in a quantitative manner the degree of correlation trough the CTSs.

Thanks to this approach a total importance rating can be assigned to each CTS based both on:

- The degree of Voice of Customers and Design Teams Needs representativeness and
- The number and magnitude of correlations through the CTSs array.

This second aspect should result in a key factor to correctly evaluate the project optimization complexity that the design team must deal with during product development. The presented case study shows the conceptual soundness of the method while leaving interesting open ideas of research.

5 REFERENCES

[1] Cavallini C, Giorgetti A, Citti P, Nicolaie F, *Integral aided method for material selection*, 2013, Materials and Design 47, 27–34

[2] Hulrich KT, Eppinger SD, *Product design and development,* 2008, McGraw-Hill.

[3] Jahan A, Ismail MY, Sapuan SM, Mustapha F, *Material screening and choosing methods – a review*, 2010, Mater Des, 31:696–705.

[4] Jahan A, Mustapha F, Sapuan SM, Ismail MY, Bahraminasab M, *A framework for weighting of criteria in ranking stage of material selection process*, 2012 Int J Adv Manuf Technol, 58:411–20.

[5] Mayyas A, Shen Q, Mayyas A, Abdelhamid M, Shan D, Qattawi A, *Using quality function deployment and analytical hierarchy process for material selection of body-in-white*, 2011, Mater Des, 32:2771–82.

[6] Rizzuti S, De Napoli L, Giampà F, Lonfranco F, "Axiomatic design as a means to find contradiction in an integrated approach for product design", *Fifth International Conference on Axiomatic Design, ICAD2009*, Campus de Caparica (Lisbon) – March 25-27, 2009.

[7] Suh NP, *The Principles of Design*, New York: Oxford University Press, 1990. ISBN 0-19-504345-6.

[8] Suh NP, *Axiomatic Design: Advances and Applications*, New York, Oxford University Press, 2001, ISBN 978-019513466.

