A MECHATRONIC APPROACH OF QUALITY INSPECTION AND QUALITY ASSURANCE

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Abstract. *FMECA (Failure Modes, Effects and Criticality Analysis) represents a prevention analysis method, intended to emphasize, to quantify and to classify potential risks that appear in the utilization of a product. Value Analysis is a competitive, organized and creative method that has inview customer satisfaction by taking into account the functions of the new product, as well as economical and multidisciplinary aspects involved in its manufacturing. FMECA and Value Analysis involve a great amount of design, maintenance and cost data. The paper presents a database management system (DBMS), developed by the authors in order to process available data and to obtain relevant information.*

Keywords: database management, functional, effects and criticality analysis

1. Introduction

Mechatronic systems are characterized by a high degree of integration and very good performances, as a result of cooperation among specialists in the fields of mechanics, electronics, automation systems and IT. The market economy context imposes the association between the achievement of these objectives and reasonable manufacturing costs, so it becomes peremptorily necessary that quality inspection include *statistic methods*, in order to estimate potential modifications of the inspected features.

Is no more a secret that, in contemporary society, the supply of new products is greater than needs In the same time, due to the dissemination of computer aided design (CAD) methods and information technologies, industry is in continuous progress, fact that leads to a 12-18 months period for a new product to be repaid. In such conditions, it is obvious that product success depends on the moment of its appearance, as soon as possible after the appearance of the need. In such conditions of harsh competition, delaying the launch of the product can diminish even to zero the potential benefit.

The success of a new product is connected with its capacity of answering to needs expressed by customers. Each customer has specific needs and requirements, depending on his education level, his social position and his financial power,

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needs that change in time. The association of high technologies, the open markets and the strong development of information technologies influence also the permanent evolution of needs. It is considered that 50% of the products existing after five years are not yet created. So the market success of a product depends on the ability of producers to launch it in the right moment.

Besides time constraints, the designer must consider simultaneously quality and cost price requirements. Even if a new product appears in the appropriate moment, its success is connected with its capacity of answering to needs expressed by the consumers. The designer must find the manners of transposing these needs in well-defined functions of the new product. This stage is called *functional analysis*.

On the other part, earnest companies cannot take the risk of launching a product poorly analyzed and tested. Besides time constraints, quality-related constraints also appear. It is compulsory to add cost price constraints. The simultaneous satisfaction of the three categories of constraints can be achieved only in the context of concurrent engineering. Design stages must be fulfilled simultaneously, always when possible. Increasing the speed of reaction to market needs implies the use of information technologies. All the risks related to the new product working have to be considered, together with the manners of transposing customer needs in well-defined functions of the new product.

FMECA (Failure Modes, Effects and Criticality Analysis) represents a prevention analysis method, intended to emphasize, to quantify and to classify potential risks that appear in the utilization of a product. FMECA is a methodology designed to identify potential failure modes for a product or process before they occur, to assess the risk associated with each failure mode, to rank the issues in terms of importance and to identify and carry out corrective actions to address the most serious concerns.

Corrective actions include, among others, fail-safe mechanisms, redundant controls, error-handling routines, fault-tolerance, alarms and testing activities.

Value Analysis (VA) is a structured, function oriented approach to cost control which yields savings and/or improved value without compromising quality, performance or usefulness.

The main goal of a VA effort is to supplement the work of the designers on the project in order to arrive at improved value and a better end product.

VA offers a systematic approach for searching out high cost areas in a design and arriving at the best balance between cost, performance and reliability and other key issues of the project. It is not a design review but rather an in depth cost study based on achieving the required program and functions at the lowest life cycle cost (LCC). Numerous other terms (value management, value engineering etc.)

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are also used when referring to VA. The applications of the Value Method in various fields prove its efficiency. It is normally considered that its use decreases manufacturing costs with an amount of 15% - 30%, even 40% in some cases. The VA approach assures that resources (e.g., time, money, and expertise) are directed toward the solutions that have the highest potential for meeting the customer needs at the optimum cost. Further, it attempts to obtain the largest number of creative solutions to widen the potential for better value. The process completes with the generation of a design obtaining the apparent optimum product for the customer, using engineering principles and the results of Value Analysis.

Six Sigma methodology provides the techniques and tools to improve the capability and reduce the defects in any process. Its philosophy is centred on reducing variation and taking customer-focused, data driven decisions.

The name of Six Sigma comes from the 6σ level of process capability (repeatability and consistency of a manufacturing process relative to the customer requirements in terms of specification limits of a product parameter). A capability level of 6σ corresponds to a value of 50% percent design margins for all of the key product performance specification. Six Sigma statistically ensures that 99.9997% of all products resulted in the process are acceptable. In other words, only 3.4 defects per million opportunities are allowed. It is considered that a defective unit of product can contain one or more defects. A unit of product can have thus more than one opportunity to have a defect. Increasing the process sigma means reducing process variation and leads to great customer satisfaction and lower costs. Six Sigma can be used for improving an existing business process by constant reviewing and re-tuning or to create a new process. In the first case, the specific methodology is called DMAIC (Define opportunities, Measure Performance, analyze opportunity, Improve performance, Control performance). In the second case, Design for Six Sigma (DFSS) principles is applied.

2. Statistic determination of a trend in the computer aided quality inspection of mechatronic products

Statistically treating experimental results

Statistics are founded upon probability theory principles and deal with the systematization, the treatment and the use of statistic results, in order to study aleatory mass phenomena by inductive means.

The statistic study of a population can be done by analyzing a specified feature, common to the population members, feature which can be assimilated with an aleatory variable X, considered upon the studied population.

The main advantage of statistic analysis methods is the study of small size samples, properly chosen, instead of the whole population.

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When studying product collectivities, which is the case of manufacturing processes or experimental determinations, every product unit can be concordant or not, when compared with a range of specified features.

If the manufacturing process or the experimental determination is under control, it will be affected only by aleatory factors, which can not be calculated.

The quality features are assimilated with aleatory variables following statistical repartitions that constitute the theoretical model of features behaviour.

The possible values of the features are thus correlated with the probability of their apparition, fact that allows the anticipation of quality-related events.

In the context of quality inspection and quality assurance, this advantage can be translated into economy of time and money, arguments which recommend statistic treatment every time when possible (population large enough, respectively the case of large series or mass manufacturing).

Using statistical methods in the manufacturing process prevents the ominous effects of potential disturbs, proves itself an alternative to the product sorting in the final inspection and allows the correct dimensioning of the staff involved in the inspection process.

Statistic methods of inspection require the elaboration of manufacturing process control charts. With this end in view, it is necessary to collect samples of products from the manufacturing process. The samples will be equally sized and will be collected at specified moments in time.

Technical works suggest various algorithms used in the sample selection process.

Statistically treating experimental results

The paper will consider the case of the rejected products within an inspected sample and will present comparatively a number of statistic methods used for the determination of the evolution trend of their number.

Generally speaking, trend estimation methods classify themselves in two categories:

- simple methods;
- analytical methods.

Both types of methods will be exemplified by the means of a practical situation.

It will be considered that, for a series of 50 products samples, collected at equal moments of time, the obtained results look as presented in the Table 1.

In the table, *y(i)* represents the number of rejected products from the *i*-th sample and *w(i)* its weight, compared to the sample size.

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Table 1. Experimental results

i	1	2	3	4	5	6	7	8
y(i)	3	4	3	5	2	4	1	2
w(i)	0.06	0.08	0.06	0.1	0.04	0.08	0.02	0.04
i	9	10	11	12	13	14	15	
y(i)	4	7	8	5	8	9	9	
w(i)	0.08	0.14	0.16	0.1	0.16	0.18	0.18	

Figure 1 represents graphically the variation of the number of rejected products at different moments in time. Statistically speaking, the measured number of rejects in each sample forms a chronological series of moments.

Statistic analysis requires the determination of the following indices:

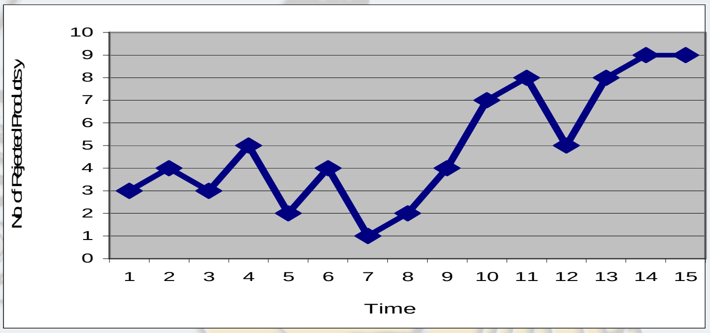

Fig. 1. Variation of the number of rejected products

a) absolute indices:
- level indices, in fact the terms of the series y_i;
- chain-based absolute modifications $\Delta_{i/i-1}$:

$$\Delta_{i/i-1} = y_i - y_{i-1} \tag{1}$$

b) relative indices:
- chain-based evolution dynamic index *I*:

$$I_{i/i-1} = \frac{y_i}{y_{i-1}} \tag{2}$$

- chain-based evolution rhythm *R*

$$R_{i/i-1} = \frac{\Delta_{i/i-1}}{y_{i-1}} \tag{3}$$

c) mean indices:
- mean level $\bar{y}$:

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$$\bar{y} = \frac{\sum_{i=1}^{n} y_i - \frac{y_1 + y_n}{2}}{n-1} \quad (4)$$

- mean absolute modification $\overline{\Delta}$:

$$\overline{\Delta} = \frac{\sum_{i=2}^{n} \Delta_{i/i-1}}{n-1} \quad (5)$$

- mean dynamic index $\bar{I}$:

$$\bar{I} = \sqrt[n-1]{\prod_{i=2}^{n} I_{i/i-1}} \quad (6)$$

Table 2. Computed values of absolute and relative indices

i	*y(i)*	*Δ(i)*	*I(i)*	*R(i)*
1	3	-	-	-
2	4	1	1.333	0.333
3	3	-1	0.750	-0.250
4	5	2	1.667	0.667
5	2	-3	0.400	-0.600
6	4	2	2.000	1.000
7	1	-3	0.250	-0.750
8	2	1	2.000	1.000
9	4	2	2.000	1.000
10	7	3	1.750	0.750
11	8	1	1.143	0.143
12	5	-3	0.625	-0.375
13	8	3	1.600	0.600
14	9	1	1.125	0.125
15	9	0	1.000	0.000

Table 3. Computed values of medium indices

Mean level $\bar{y}$ *:*	4.8571
Mean modification $\overline{\Delta}$ *:*	0.4286
Mean dynamic index $\bar{I}$ *:*	1.0816

Table 2 presents the computed values of absolute and relative indices. Table 3 presents the computed values of medium indices.

As shown above, there are two families of methods used for the statistic determination of a trend:

- simple methods;
- analytical methods**.**

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The mean absolute variation method and the mean dynamic index method belong to the first category.

The mean absolute variation method assumes a linear trend, depending upon the time moments, and proposes a simplified means of computing the slope and the intercept of the line.

It is assumed that the time dependence can be written as:

$$Y_1(i) = y_1 + t_i \cdot \overline{\Delta} \quad (7)$$

In (7), the term $\overline{\Delta}$ represents mean absolute modification, as shown above.
Equation (8) presents the results of the replacement with the computed values.

$$Y_1(i) = 3 + 0{,}4286 \cdot t_i \quad (8)$$

The mean dynamic index method $\bar{I}$ assumes an exponential variation, of type:

$$Y_2(i) = y_1 \cdot \bar{I}^{\,t_i} \quad (9)$$

Equation (10) presents the results of the replacement with the computed values.

$$Y_2(i) = 3 \cdot 1{,}0816^{t_i} \quad (10)$$

Table 4. Determination of the number of rejected products using simple methods

t_i	*y(i)*	*Y1(i)*	*ΔY1(i)*	*Y2(i)*	*ΔY2(i)*
1	3	3	0	3	0
2	4	3	1	3	1
3	3	4	-1	4	-1
4	5	4	1	4	1
5	2	5	-3	4	-2
6	4	5	-1	4	0
7	1	6	-5	5	-4
8	2	6	-4	5	-3
9	4	6	-2	6	-2
10	7	7	0	6	1
11	8	7	1	7	1
12	5	8	-3	7	-2
13	8	8	0	8	0
14	9	9	0	8	1
15	9	9	0	9	0

The result of the application of the simple trend determination methods is shown in Table 4.
The *Δ*-prefix designs the difference between estimated and measured values, when choosing one of the above-presented techniques. A more rigorous evaluation of the evolution trend can be done using analytical methods. This kind of methods involves more laborious calculations, but furnish, generally, better results.

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Nevertheless, this is not a rule, because there are many practical situations when simple methods can substitute analytical solutions, without affecting the final results. There are no general recommendations for choosing the appropriate trend determination method, but the specialists can express his option after comparing established statistic criteria.

It is assumed that the trend can be linear, exponential or parabolic.

When considering the linear trend, it is supposed that the time variation is given by (11):

$$Y_3(i) = a + b \cdot t_i \tag{11}$$

If every moment of time t_i is taken into account, the final result will be the equation system (12) and (13):

$$a \cdot n + b \cdot \sum_{i=1}^{n} t_i = \sum_{i=1}^{n} y_i \tag{12}$$

$$a \cdot \sum_{i=1}^{n} t_i + b \cdot \sum_{i=1}^{n} t_i^{\,2} = \sum_{i=1}^{n} t_i y_i \tag{13}$$

If it is also considered that the central moment of time is null, as shown in (14):

$$t_{\left[\frac{n+1}{2}\right]} = 0 \tag{14}$$

the sum of the time moments will be (15):

$$\sum_{i=1}^{n} t_i = 0 \tag{15}$$

which leads to the equations (16) and (17):

$$a \cdot n = \sum_{i=1}^{n} y_i \tag{16}$$

$$b \cdot \sum_{i=1}^{n} t_i^{\,2} = \sum_{i=1}^{n} t_i y_i \tag{17}$$

The slope and the intercept obtained as above are the coefficients of the regression line, as given by (18) and (19):

$$a = \frac{\sum_{i=1}^{n} x_i \cdot y_y - n \cdot \bar{x} \cdot \bar{y}}{\sum_{i=1}^{n} x_i^2 - n \cdot \bar{x}^2} \tag{18}$$

$$b = \bar{y} - a \cdot \bar{x} \tag{19}$$

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If the trend is assumed to be exponential, its mathematical expression will be:

$$Y_4(i) = a \cdot b^{t_i} \tag{20}$$

Similarly, the normal equation system (21) and (22) is obtained.

$$n \cdot \lg a + \sum_{i=1}^{n} t_i \cdot \lg b = \sum_{i=1}^{n} \lg y_i \ , \tag{21}$$

$$\sum_{i=1}^{n} t_i \cdot \lg a + \sum_{i=1}^{n} t_i^{\ 2} \cdot \lg b = \sum_{i=1}^{n} t_i \cdot \lg y_i \tag{22}$$

Taking into account the same facts, the final results will be the equations (23) and (24)

$$n \cdot \lg a = \sum_{i=1}^{n} \lg y_i \qquad ((23)$$

$$\sum_{i=1}^{n} t_i^{\ 2} \cdot \lg b = \sum_{i=1}^{n} t_i \cdot \lg y_i \tag{24}$$

When it is supposed that the trend presents a parabolic variation, its mathematical expression will be:

$$Y_5(i) = a + b \cdot t_i + c \cdot t_i^2 \tag{25}$$

The computing means is similar.

Parabolic trend employment is justified when chain-based second order absolute variations ($\Delta'_{i/i-1}$) present constant values, which is not the case of the application presented in the paper.

After replacements and computations, the final adjustment functions look as shown below:

- linear adjustment function:

$$Y_3(i) = 4{,}933 + 0{,}443 \cdot t_i \tag{26}$$

- exponential adjustment function:

$$Y_4(i) = 4{,}182 \cdot 1{,}09^{t_i} \tag{27}$$

Table 5 presents the result of adjusting the trend with linear and exponential functions. The table observes the same notation conventions as Table 4.

Figure 2 presents a comparison among the value series furnished by the four adjustment functions determined above and the values effectively determined in the manufacturing process.

None of the adjustment function can register the leap values obtained as a result of the measurement process.

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t_i	*y(i)*	*Y3(i)*	*ΔY3(i)*	*Y4(i)*	*ΔY4(i)*
1	3	2	1	2	1
2	4	2	2	2	2
3	3	3	0	3	0
4	5	3	2	3	2
5	2	4	-2	3	-1
6	4	4	0	4	0
7	1	4	-3	4	-3
8	2	5	-3	4	-2
9	4	5	-1	5	-1
10	7	6	1	5	2
11	8	6	2	5	3
12	5	7	-2	6	-1
13	8	7	1	6	2
14	9	8	1	7	2
15	9	8	1	8	1

Table 5. Determination of the number of rejected products using analytical methods.

Figure 3 presents the deviations from the series of the effectively determined values for each of the four adjustment functions.

The specialist has now four adjustment functions, obtained using different methods, It is important to find criteria for choosing the appropriate one.

It is reminded that the concrete situation is the only factor that imposes the final selection.

The statistical works suggest a number of means to select the appropriate adjustment function. It will be mentions only the most important ones:

- comparison between the sum of adjusted and measured terms

When applying this method, the sum of adjusted terms ($\sum_{i=1}^{n} Y_k(i)$) is compared with the sum of real terms (the measured values $\sum_{i=1}^{n} y(i)$). In theory, $\sum_{i=1}^{n}\left(y_i - Y_i\right) = 0$ if the members of the chronological series are not affected by aleatory circumstances. In fact, the sum obtained must have small values, in order to conclude that the adjustment function is appropriately chosen.

$$\sum_{i=1}^{n}\left(y_i - Y_i\right) = \min \tag{28}$$

- the least squares method:

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$$\sum_{i=1}^{n}(y_i - Y_i)^2 = \min \qquad (29)$$

- comparison of the standard deviations:

$$\sigma_{y_i/Y_i} = \sqrt{\frac{\sum_{i=1}^{n}(y_i - Y_i)^2}{n}} = \min \qquad (30)$$

- comparison of the variation coefficients:

$$V_{y_i/Y_i} = \frac{\sum_{i=1}^{n}|y_i - Y_i|}{\sum_{i=1}^{n} y_i}\cdot 100(\%) = \min \qquad (31)$$

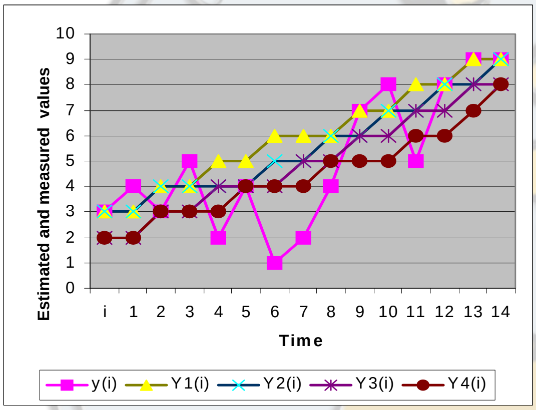

Fig. 2. Comparison among the values furnished by different adjustment functions

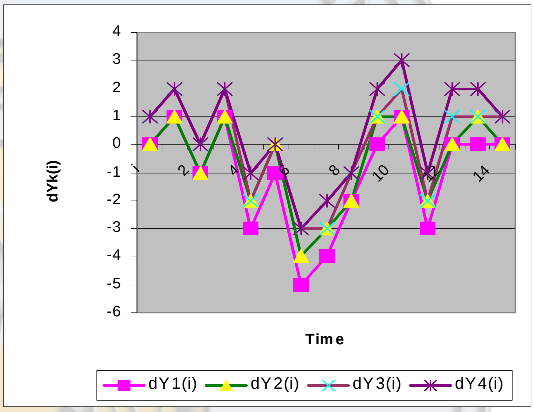

Fig. 3. Deviations from the measured values

Table 6. Criteria for appreciating the quality of the adjustment functions

	Y_1	Y_2	Y_3	Y_4
$\sum(y_i - Y_i)$	-16	-9	0	7
$\sum(y_i - Y_i)^2$	68	43	44	47
σ_{y_i/Y_i}	2,129	1,693	1,713	1,77
V_{y_i/Y_i}	29.73	25.68	29.73	31.08

Table 6 presents the results of applying the four criteria.

In the practical situation, the different criteria show that the linear adjustment function, computed using analytical methods, is the most suitable for the estimation of the desired trend. The same statistical criteria applied to another case can lead to the choice of another type of adjustment function. Obviously, it is a

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must to perform the calculations of the statistical parameters described above automatically, with appropriate software, in order to accomplish real-time estimations.

Linear adjustment function estimates that, at the instance $t = n + 1$, the number of rejected products in the sample will be $y\,(n + 1) = 8$ rejects.

3. FMECA and functional analysis

FMECA (Failure Modes, Effects and Criticality Analysis) represents a prevention analysis method, intended to emphasize, to quantify and to classify potential risks that appear in the utilization of a product. Obtaining good quality results depends on the quality of the functional analysis developed. Functional decomposition is part of FMECA analysis, as shown in Figure 4. Various methods can be applied in this stage, as fishbone diagram (Ishikawa diagram), functional analysis diagram, life cycle study, SAFE method. The next section of the paper will present such methods. It is recommended to combine all the above-mentioned methods, because even a simple product normally fulfils a great number of functions, appropriately appreciated by the customer.

In order to achieve good quality results, it is recommended for the persons who achieve the analysis to constitute a workgroup, led by an animator (*brainstorming*).

The workgroup has to include specialists in various fields, implied in marketing, design, manufacturing, distribution, maintenance, quality assurance and so on.

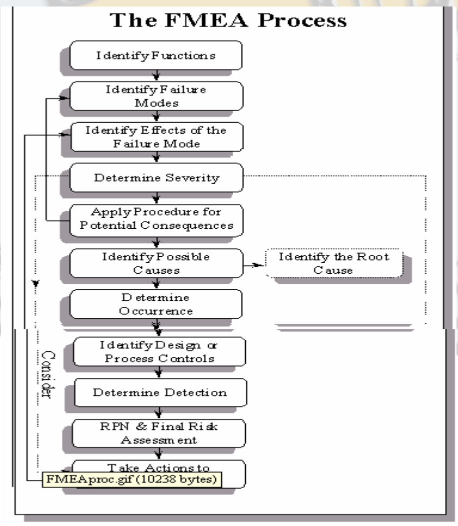

Fig. 4. The FMEA Process

As a final result, the workgroup will define the objective and subjective needs of the customer and will convert them in technical specifications.

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Normally, it is easy to transpose objective needs in measurable features. In order to describe subjective needs such comfort, elegance, esthetics or style, it is necessary to define special criteria, difficult to measure.

3.1. Functional hierarchy

Besides main functions, which reflect its role, a product is described by a great amount of other functions. Even if these functions are less perceptible, their absence can induce a state of frustration to the customer. For instance, a pair of sunglasses must fulfill 37 functions and a telephone must fulfill 47 functions.

Obviously, not all these functions have the same importance. Sometimes, the designer must select only the functions of real importance and has to neglect other facilities, less important, in order to avoid outrunning of a cost price limit. Therefore, functional hierarchy has to be used.

The most common method is to give to each function a mark, in concordance to its importance for the customer. Table 7 presents an example of attributing marks.

Table 7. A way of establishing functional hierarchy

Mark	Meaning
1	Useful
2	Necessary
3	Important
4	Very important
5	Vital

When the method presented above seems to be not efficient, it is possible to use comparison methods. Pairs of functions are compared between them and a score is attributed, proportional with the relative importance of the function.

The case of a hot or cold water meter, used in domestic applications, will be considered as an example.

Due to clarity reasons, only eight of the total functions of the water meter were taken into consideration:

- F1: To assure correct measuring;
- F2: To allow fluid passing;
- F3: To not allow fluid leakage;
- F4: To not allow indication modifying;
- F5: To be compact;
- F6: To allow rapid assembling/disassembling;
- F7: To allow easy indication reading;
- F8: To be safe.

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All these functions were considered important or very important, fact that justifies comparative hierarchy. The score accorded was the following:

- +2: more important
- +1: the same importance
- 0: less important.

It has to be specified that the score system is not unique. Each user is encouraged to promote personalized scoring rules, appropriately adopted.
The results of the comparative analysis are presented in Table 8. The function on each row is successively compared with the column functions. Total scores are computed, leading to the final hierarchy. The last column presents the final result.

Table 8. Functional comparative hierarchy

	F1	*F2*	*F3*	*F4*	*F5*	*F6*	*F7*	*F8*	Σ
F1	-	1	1	2	2	2	2	0	10
F2	1	-	1	2	2	2	2	0	10
F3	1	1	-	2	2	2	2	0	10
F4	0	0	0	-	2	2	2	0	6
F5	0	0	0	0	-	0	0	0	0
F6	0	0	0	0	2	-	0	0	2
F7	0	0	0	0	2	2	-	0	4
F8	2	2	2	2	2	2	2	-	14

3.2. Function types

A product must meet an important number of functions, therefore methods for specifying these functions have to be found. As shown before, no method is exhaustive, so their appropriate combination is recommended.

Any kind of product must satisfy four types of functions:

- main functions, which reflect the role of the product: for example, the water meter has to measure a flow;
- complementary functions, corresponding to the complementary requirements that must fulfill the product: for instance, the water meter must allow water passing;
- constraints imposed by the environment, by the users or as consequence of security reasons, norms or standards
- technical functions needed for the fulfilling of the main functions. These functions are based upon the technical solution adopted and are not intended to answer to needs specified by the customers. Technical functions cannot be established till the choice of the final manufacturing solution.

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3.3. Establishing functions

The main disadvantage of the marketing studies is that they furnish, generally, results that concern only the main functions of the new product. More information can be obtained from maintenance data on similar products, but is not enough for starting a good analysis. A number of efficient function determination methods have to be combined. The next section of the paper will present some of these methods, as well as a suggested order when applying them.

The workgroup has to start with the intuitive establishing of the functions that the new product must satisfy. The method requires brainstorming techniques and the presence of all the members of the team is required.

It is proven statistically that the method allows the determination of 50 - 60% of the required functions in the case of a new product, percentage considered insufficient. The next step consists in the study of the life cycle of the product.

The method refers to all the aspects of the existence of a good. The main advantage of the approach is the underlining of less obvious functions, needed in stages as packing, transport, stocking or recycling. The analysis is then completed with the *study of the interactions* with various factors. In this stage, it is possible to establish the functional analysis diagram. The diagram established for the water meter is shown in Figure 5.

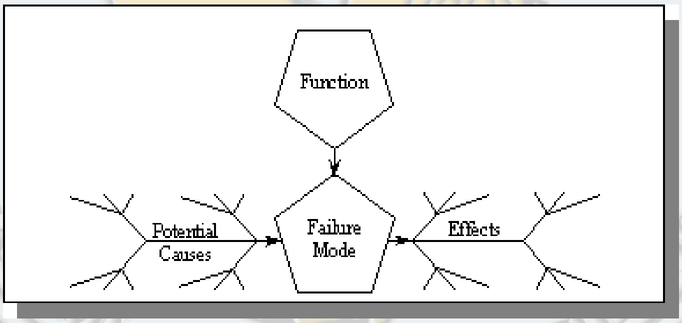

Fig. 5. Watermeter diagram

Interactions with various factors imply functions presented synthetically in Table 9. This stage is also called "*the study of the environment of the product*". "*Environment*" has here a more general meaning, including:

- persons: users or circumstantial presence;
- physical elements: nature, surrounding things, constructions, furniture, a.s.o.
- immaterial elements: norms, standards, a.s.o.
- work conditions: temperature, humidity, noise, dust, a.s.o.

It is recommended to continue with the SAFE method (*SAFE: Sequential Analysis of Functional Elements*).

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Table 9. Functions needed for the product, due to the interaction with various factors

Factor	Functions
Measured fluid	❑ To assure correct measuring; ❑ To allow fluid passing; ❑ To preserve fluid properties; ❑ To not allow condensation; ❑ To not allow fluid leakage;
Environment	❑ To not oxidize; ❑ To not pollute;
User	❑ To be visible and easy to locate; ❑ **To allow easy reading;** ❑ To not allow indication modifying; ❑ To not affect user integrity; ❑ To be silent; ❑ Attractive design;
Assembling, maintenance indication reading	❑ To allow rapid assembling / disassembling; ❑ Safety elements; ❑ To allow indication reading; ❑ To be accessible; ❑ To allow easy intervention;
Workspace	❑ To be compact;
Aggressive elements	❑ To resist to shocks produced by impurities; ❑ To resist to limestone sediments;
Norms	❑ To be in accordance with norms;
Safety	❑ To be safe.

The method starts with the study of the life cycle of the product, but its originality resides in the sequence decomposition of the product utilization. Well-defined functions are then associated with the established sequences.

For better results, the workgroup has to face the problem from the point of view of the user and has to imagine the actions that he/she does when using the product.

An example of SAFE decomposition for the case of the water meter is shown in Table 10.

Table 10. SAFE analysis of the water meter

The following of the operations	Functions to be satisfied
Water meter mounting	❑ Easy to install ❑ Compact
Water passing	❑ Allowing water passing ❑ Preserving water properties
Measuring	❑ Allowing correct measuring
Reading	❑ Allowing reading ❑ *Accessible* ❑ Visible
Verifying	❑ Allowing easy disassembling ❑ Allowing easy intervention

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The next step is the *analysis of the efforts* supported by the product. In this stage, it is possible to determine numeric values for the features that assure the strength of the new product: dimensions, material, mechanical and thermal parameters, a.s.o.

The analysis continues with the study of a reference product. The reference product can be a similar product from a related field, an existing product from the same field or a product created by a rival company.

The final stage of the functional consists in the study of the norms and standards concerning the product or the working environment.

3.4. Using databases in functional analysis

Information technologies cannot replace the contribution of the human factor in functional analysis, but can prove their advantages when organizing knowledge, elaborating functional hierarchies or estimating function-related costs.
The problem of organizing, stocking and retrieving rapidly data of interest on a specified subject constitutes the domain of information management. Databases represent software instruments developed in order to solve this problem.

A database management system (DBMS) represents the first step in developing integrated manufacturing systems, so the specialist in mechatronics must take profit of its advantages. Such a professional is asked to apply electronics, automations and IT knowledge in various fields of engineering. Quality assurance represents one of these fields.

A database that plays an important role in the functional and FMECA analysis was developed at the Department of Precision Engineering, "Politehnica" University of Bucharest, in order to underline the advantages of DBMS in quality assurance.
A great amount of maintenance data had to be processed, so the need for a DBMS maintenance-oriented appeared. Using the database, it is possible to elaborate detailed and summary maintenance reports, monthly reports, reports for a specified kind of product, for a specified kind of failure mode or exception reports (for instance, the percentage of products that fail before the mean working time).

The database allows developing an unified coding system for components, functions and their importance, failure modes, causes, effects and means of prevention. Using the database eases also the work when doing FMECA analysis, proving itself especially useful when determining RPN (Risk Probability Number), a mean for estimating criticality.

Maintenance data allow determining the percentage of failures in meeting a requirement, fact that helps when choosing the appropriate prevention means.

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It is possible also to estimate total costs for a specified function, knowing the costs of components implied in function satisfaction. This information may be useful when a it is necessary to keep costs under a certain level.

Synthetically, the advantages offered by the developed database are:

- Computation of FMECA parameters, such as RPN;
- Correlation among functions, components and costs.

Unified framework that integrates design data for the new product and maintenance data for similar products, characteristic of concurrent engineering.

4. Assessing RISK WITH FMECA ANALYSIS

Two alternative approaches may be used: a functional approach or a hardware approach. The functional approach considers sub-systems in terms of their function within the system, being often applied when hardware components cannot be uniquely identified, and the hardware approach is usually adopted when components can be uniquely identified in the system.

The FMECA procedure consists of two parts: the first part identifies failure modes and their effects (Failure Mode and Effects Analysis) and the second part ranks failure modes according to the combination of severity and the probability of that failure mode occurring (Criticality Analysis).

The following steps has to be completed: defining the system to be analyzed; building a hierarchical block diagram; identifying failure modes at all levels of indenture; assigning effects to the failure modes; assigning severity categories to effects; entering other failure mode data such as failure detection methods, failure rates and compensating provisions; ranking failure modes in terms of severity and criticality; producing reports highlighting critical failures and recommending redesign or maintenance actions to reduce them.

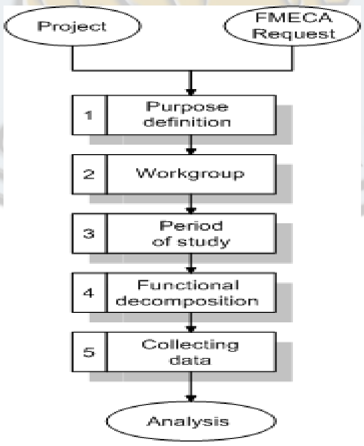

Fig. 6. Preliminary steps in order to perform FMECA analysis.

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The preliminary steps required in order to perform FMECA analysis are presented in Figure 6.
The risk associated with the potential problems identified through the analysis is evaluated, generally, by two methods: Risk Priority Numbers (RPN) and Criticality Analysis.

The Risk Priority Number (RPN) represents the mathematical product of the seriousness of a group of Effects (Severity), the likelihood that a Cause will create the failure associated with those Effects (Occurrence), and an ability to detect the failure before it gets to the customer (Detection):

$$RPN = S \cdot O \cdot D \qquad (1)$$

RPN is used to help identify the most serious risks, leading to placing priorities when planning corrective action. In order to perform RPN computation, Severity, Occurrence and Detection should be quantified. Different situations are rated on a scale sensible enough, according to consistent evaluation criteria. Scales from 1 to 10 or from 1 to 4 are generally used.

The minimum value ("no risk") is rated with 1.
The MIL-STD-1629A document describes two types of criticality analysis: quantitative and qualitative. To use the quantitative criticality analysis method, the team must:

- Define the reliability / unreliability for each item, at a given operating time.
- Identify the portion of the item's unreliability that can be attributed to each potential failure mode.
- Rate the probability of loss (or severity) that will result from each failure mode that may occur.
- Calculate the criticality for each potential failure mode by obtaining the product of the three factors:

Mode Criticality = Item Unreliability x Mode Ratio of Unreliability x Probability of Loss

- Calculate the criticality of each item by obtaining the sum of the criticalities for each failure mode that has been identified for the item:

Item Criticality = Sum of Mode Criticalities

To use the qualitative criticality analysis method to evaluate risk and prioritize corrective actions, the analysis team must:

- Rate the severity of the potential effects of failure.
- Rate the likelihood of occurrence for each potential failure mode.
- Compare failure modes via a Criticality Matrix, which identifies severity of the horizontal axis and occurrence on the vertical axis.

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4.1. Involving DBMS in FMECA Analysis

Databases represent software instruments developed in order to help organizing knowledge, stocking and retrieving rapidly data of interest on a specified subject.

FMECA involves a great amount of design, maintenance and cost data, so the need for a DBMS dedicated to quality problems appeared. In answer to this need, such a database was developed by the authors at the Department of Precision Engineering, University "Politehnica" of Bucharest.

Using the database, it is possible to elaborate detail and summary maintenance reports, monthly reports, reports for a specified kind of product, for a specified kind of failure mode or exception reports (for instance, the percentage of products that fail before the mean working time).

The created database allows developing a unified coding system for components, functions and their importance, failure modes, causes, effects and means of prevention. Using the database eases also the work when doing FMECA analysis, proving itself especially useful when determining RPN.

Severity, Occurrence and Detection are rated according to Table 11.

Table 11. Rating Severity, Occurrence and Detection

Occurence: Failure Rates	*Rank*	*Severity:*	*Rank*
Repeated failures: more than 1 in 10	10	Repairing time longer than 60 min	4
Repeated failures: under 1 in 10	9	Repairing time between 20 and 60 min	3
Repeated failures: under 1 in 50	8	Repairing time between 1 and 20 min	2
Occasional failures: under 1 in 100	7	Repairing time under 1 min	1
Occasional failures: under 1 in 200	6	*Likelihood of Detection by Design Control*	*Rank*
Occasional failures: under 1 in 500	5		
Occasional failures: under 1 in 1,000	4	No warning signs	4
Relatively few failures: under 1 in 5,000	3	Warning signs difficult to notice	3
Relatively few failures: under 1 in 10,000	2	Warning signs that could pass unnoticed	2
Failure is unlikely: under 1 in 100,000	1	Warning signs easily noticeable	1

Figure 7 presents an example of introducing service data (the same example of the water meter was considered).

Figure 8 shows an example of editing form and Figure 9 presents the form developed in order to perform FMECA analysis.

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Maintenance data allow determining the percentage of failures in meeting a requirement, fact that eases choosing the appropriate prevention means.

It is possible also to estimate costs for a specified function, using the cost function matrix.

Various libraries of components, associated with their costs, allow the comparison of solutions, in order to select the most appropriate one from the point of view of life cycle costing.

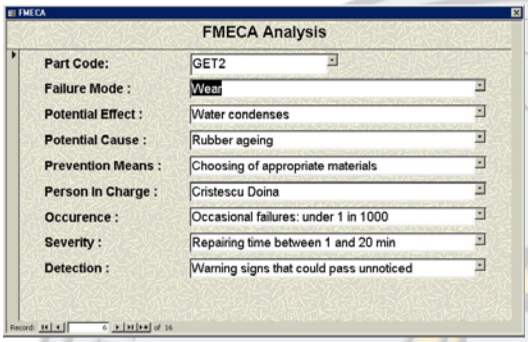

Fig. 7. Form allowing introducing service data

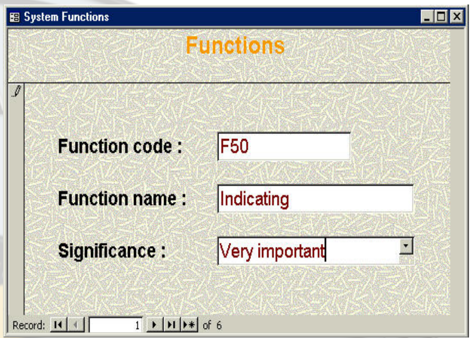

Fig. 8. Form used for editing functions information

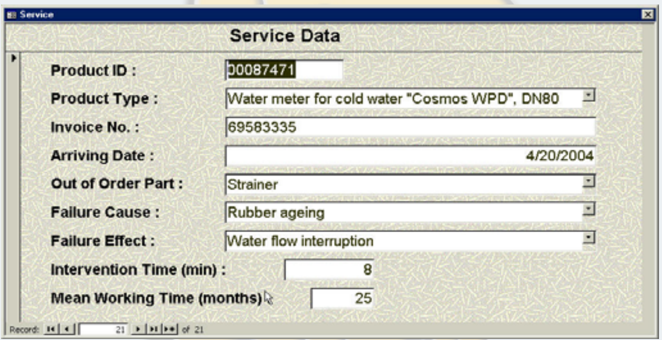

Fig. 9. Form developed in order to perform FMECA analysis

Synthetically, the advantages offered by the developed databases are:

- computation of FMECA parameters, such as RPN;
- correlation among functions, components and costs;
- unified framework that integrates design data for the new product and maintenance data for similar products, characteristic of concurrent engineering.

5. Value analysis, component part of the design of mechatronic products

The VA approach assures that resources (e.g., time, money, and expertise) are directed toward the solutions that have the highest potential for meeting the customer needs at the optimum cost. Further, it attempts to obtain the largest number of creative solutions to widen the potential for better value. The process

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completes with the generation of a design obtaining the apparent optimum product for the customer, using engineering principles and the results of Value Analysis.

5.1. Recommended procedures for applying value analysis

A Value Analysis study must be composed of a succession of compulsory steps, which can be summarized as follows:

1. Defining Purposes;
2. Finding Information;
3. Functional and Cost Analysis;
4. Finding Ideas and Solutions;
5. Solution Analysis and Recommendations;
6. Presenting Reports;
7. Implementing Results.

5.1.1. Defining purposes

This step establishes the purpose of the analysis, as well as objectives and conditions. The workgroup structure is established as well. Independence of the value study team is crucial in order to obtain the most from the value study process, for the design or process teams have often been working on the project for a long time.

In this phase, team members become familiar with the requirements of the project. They obtain and review technical and cost data, coordinate timing and establish a productive relation with the design and process teams. Any limitations or constraints on the study must be specified at this time.

5.1.2. Finding information

During the Information Phase, the VA team solicits comments on the technical and cost data to develop an overall understanding of the project's functions and requirements and gains as much information as possible about the project design, background, constraints and projected costs.

The designer team should present the evolution of the project in order to facilitate the work of the VA team. The quality and organization of the data presented are important since these factors directly impact the usefulness of the VA recommendations.

It is important for the VA team to understand the designer point of view for the project's development, including the assumptions used to establish the design criteria and select the materials and systems.

The VA team should identify and review the alternatives considered by the designers.

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5.1.3. Functional and cost analysis

The function analysis approach is used in value engineering to arrive at the basic purpose of building systems and sub-systems. It aids the VA team in determining the least costs to perform primary functions and peripheral or support functions and identifying costs that can be reduced or eliminated without affecting the performance or reliability of the facility. The basic function of an item is the specific task or work it must perform. Secondary functions are those functions that may be desired but are not actually required to perform the specific task or work. Required secondary functions are absolutely necessary to accomplish the specific task or work, although they do not exactly perform the basic function.

In function analysis, it is important to identify functional areas sequentially since the functions vary according to the selected area. The main disadvantage of the marketing studies is that they furnish, generally, results that concern only the main functions of the new product. More information can be obtained from maintenance data on similar products, but is not enough for starting a good analysis. A number of efficient function determination methods have to be combined. The VA team has to start with the intuitive establishing of the functions that the new product must satisfy. The method requires brainstorming techniques. It is proven statistically that the method allows the determination of 50-60% of the required functions in the case of a new product, percentage considered insufficient.

The next step consists in the study of the life cycle of the product. The method refers to all the aspects of the existence of a good. The main advantage of the approach is the underlining of less obvious functions, needed in stages as packing, transport, stocking or recycling. The analysis is then completed with the study of the interactions with various factors. In this stage, it is possible to establish the functional analysis diagram. Figure 10 presents an example of such a diagram established for the case of a water meter.

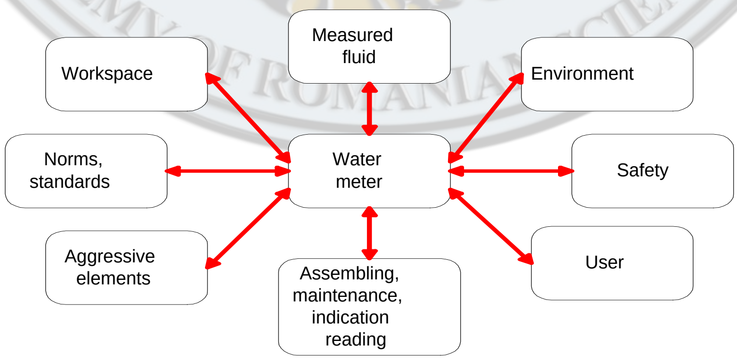

Fig. 10. Functional analysis diagram

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Interactions with various factors imply functions presented in Table 12.

Table 12. Functions needed for the product, due to the interaction with various factors

Factor	*Functions*	*Factor*	*Functions*
Measured fluid	To assure correct measuring; To allow fluid passing; To preserve fluid properties; To not allow condensation; To not allow fluid leakage;	User	To be visible and easy to locate; To allow easy reading; To not allow indication modifying; To not affect user integrity; To be silent; Attractive design;
Assembling, maintenance, indication reading	To allow rapid assembling / disassembling; Safety elements; To allow indication reading; To be accessible; To allow easy intervention;	Aggressive elements	To resist to shocks produced by impurities; To resist to limestone sediments;
		Norms	To be in accordance with norms;
		Workspace	To be compact;
Environment	To not oxidize; To not pollute;	Safety	To be safe.

This stage is also called “the study of the environment of the product”.

“Environment” has here a more general meaning, including persons (users or circumstantial presence), physical elements (nature, surrounding things, constructions, furniture), immaterial elements (norms, standards) or work conditions (temperature, humidity, noise, dust). It is recommended to continue with the SAFE method (SAFE: Sequential Analysis of Functional Elements).

The method starts with the study of the life cycle of the product, but its originality resides in the sequence decomposition of the product utilization. Well-defined functions are then associated with the established sequences.

For better results, the VA team has to face the problem from the point of view of the user and has to imagine the actions that he/she does when using the product.

Table 13 shows an example of SAFE decomposition for the case of the water meter.

As part of the function analysis, the VA team must associate specific costs to each function performed by the system, in order to rank costs of systems and sub-systems and to identify potential high cost areas. The cost analysis has to start with the cost function matrix.

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Table 13. SAFE analysis of a water meter

The following of the operations	*Functions to be satisfied*	*The following of the operations*	*Functions to be satisfied*
Water meter mounting	Easy to install Compact	Reading	Allowing reading Accessible Visible
Water passing	Allowing water passing Preserving water properties		
Measuring	Allowing correct measuring	Verifying	Allowing easy disassembling Allowing easy intervention

The matrix is designed to cost an existing product, service or system by function, in addition to the cost of component parts.

By this approach it is possible to determine if second order functions are costing the most to achieve. An additional advantage from costing by function is that is forces the value analysts to rigorously examine and understand the nature of the product being investigated.

The cost function matrix includes all the different components and sub-assemblies of the product in the left vertical column and all the functions to be satisfied across the top.

Using the matrix allows determining which components satisfy a required function.

Because, generally, a component contributes towards more than one function, the proportion of the component cost affected to the demanded function has to be determined and filled in the corresponding case.

Applying this method, it is possible to sum the costs implied by each function, in order to start the cost analysis.

The VA team must estimate all the cost imposed by the use of the product or system, during its entire life. This part of the study is called the Life Cycle Costing (LCC).

Life cycle costing (LCC) is the development of all significant cost of acquiring, owning and using an item, system or service over a specified length of time. The time period used is the projected effective useful life of the item

Costs of repairs, operations, preventive maintenance, logistic support utilities, depreciation and replacement, in addition to capital cost, all reflect on the total value of a product to a user.

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Calculation of LCC for each alternative during performance of a VA study is a way to judge whether product quality is being maintained in sufficient degree to prevent degradation of necessary reliability, performance, and maintainability.

The results obtained at this step allow the start of solutions searching.

5.1.4. Finding ideas and solutions

The search for solutions has to be oriented to three directions:

1. Market: listening and analyzing the reactions that the functions generate among customers, manufacturers and competition;
2. Experience: studying similarities with other cases previously analyzed;
3. Research Centers: exploring various technological domains and combinations of them in order to find the appropriate solution.

The ideas should be listed by system, sub-system and component, in order to facilitate effective organization of the study. The participation of all team members must be encouraged.

It is important to develop as many ideas as possible and also to look for associations of ideas, because a function can be often performed by a technique currently applied to another area or industry.

All ideas must be recorded as they are developed.

5.1.5. Solution analysis and recommendations

During this phase, the ideas developed previously are examined to assess which have the best opportunity for implementation, cost savings and value improvement.

The VA team evaluates the feasibility of each idea by identifying its advantages and disadvantages. The ideas are then rated on a scale of one to ten. A ten represents either the best technical idea or the one with the greatest potential for cost savings and value improvement.

When ranking ideas, the VA team should consider the following aspects:

- Are the aesthetic, performance, quality and reliability requirements met or exceeded?
- Will excessive redesign or project delay be created?
- Does the solution improve operation and maintenance?
- Will life cycle cost savings be achieved?
- Does the idea have a reasonable chance of acceptance and implementation?

The ranking of ideas leads to a hierarchy of selected solutions.

Subsequently, the VA team researches and develops preliminary designs and life cycle cost comparisons for the original designs and the proposed alternative ideas.

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During this phase, the technical expertise of the team becomes very important. Frequently, it is necessary to consult outside experts, vendors, and reference sources.

5.1.6. Presenting reports

The results of the VA study must be presented to the design and manufacturing team, as a written and oral report. The final evaluation has to be done by the producers, because the choice of the accepted solutions belongs to them.
For each proposed solution, the report must highlight the economic evaluation, advantages and disadvantages, potential opportunities or dangers in relation with the environment, conditions to be satisfied when implementing the solution.

5.1.7. Implementing results

The implementation of the selected project is the responsibility of the producer, assisted by some of the members of the VA team. The experience acquired during the study must be stored in order to be accessible for future analyses.

5.2. Value analysis and databases

Information technologies cannot replace the contribution of the human factor in value analysis, but can prove their advantages when organizing knowledge, elaborating functional hierarchies or estimating function-related costs.

Databases represent software instruments developed in order to help organizing, stocking and retrieving rapidly data of interest on a specified subject.

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Various libraries of components, associated with their costs, allow the comparison of solutions, in order to select the most appropriate one from the point of view of life cycle costing.

6. Forecasting performance in DFSS

6.1. Methodology of DFSS

The methodology of DFSS requires determining the critical parameters and optimizing their variability, in order to increase performance, manufacturability and reliability.

The main tools used in DFSS include QFD – Quality Function Deployment, FMEA – Failure Mode and Effects Analysis, DOE – Design of Experiments and simulation techniques.

It is known that the quality of a product or process is affected by its behavior in presence of parameter variation. A robust design means reducing the sensitivity of the product/process to the variation sources.

Robust design can be obtained by minimizing the performance variability. This can be done by either minimizing the sensitivities (derivatives of process functions) or minimizing variability of design variables.

There are many methodologies to accomplish DFSS: DMADV (Define, Measure, Analyze, Design, Verify), DCCDI (Define, Customer, Concept, Design, Implementation), IDOV (Identify, Design, Optimize, Validate), DMEDI (Define, Measure, Explore, Develop, Implement).

In the manufacturing world, a methodology that constantly has gained popularity is IDOV. It consists of four phases: *Identification* of the customer and of the specifications (CTQ variables and specification limits), *Design* in order to translate customer CTQs into functional requirements, *Optimization* using advanced statistical tools and models and *Validation* of the conformance to customer's requirements.

The identification stage allows establishing Critical-to-Quality (CTQs) parameters and setting technical requirements and quality targets. It is important to have the appropriate means to gather the Voice of the Customer (VoC), as well as to develop a team able to perform competitive analysis.

The key tools used in this stage are: QFD, FMEA, SIPOC (Supplier, Input, Product, Output, Customer product map), IPDS (Integrated Product Delivery System), target costing, benchmarking.

The design phase consists of identifying functional requirements, developing alternative concepts, evaluating alternatives, deploying CTQs and predicting

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sigma capability. Research has shown that decisions made during the design period determine 70% of the cost of the product, while decisions made during production influence only 20% of the product's cost. Decisions made in the first 5% of product design could determine the vast majority of the product's cost, quality and manufacturability characteristics.

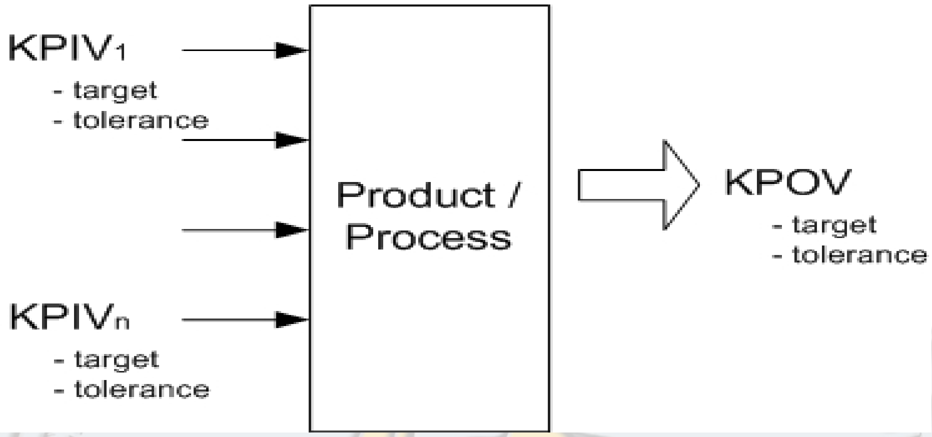

Fig. 11. Defining the transfer function between Key Process Input Variables (KPIV's) and Key Process Output Variables (KPOV)

This stage implies identifying design parameters associated to each technical requirement, assessing potential risks, establishing manufacturing and procurement plans, developing transfer functions between KPIV's - Key Process Input Variables and KPOV's - Key Process Output Variables (Figure 11).

The key tools used in this stage are: smart simple design, risk assessment, FMEA, engineering analysis, materials selection software, simulation, DOE, systems engineering, analysis tools.

In the optimization phase, the designed system is analyzed and optimized in terms of robust performance, manufacturability and reliability. If the transfer functions between inputs and outputs are non-linear, it is possible to reduce output variation by adjusting the average of the inputs, in order to achieve a behaviour less sensitive to the variation of inputs, in other words a more robust product. In most cases it is less expensive to adjust inputs that to tighten tolerances, so the search for a better set of parameters must have the highest priority in product optimization.

An efficient way of identifying the most appropriate set of values is the Design of Experiments (DOE). Tightening input tolerances has to be performed only after this stage. The tolerance intervals to be decreased should be decided using cost and efficiency criteria.

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6.2. Analysis is eased by the use of Monte Carlo simulation

This method consists in allocating a number *N* of values for each input variable, according to a previously established distribution pattern. *N* values of the output are thus obtained, allowing the computation of various statistical parameters, such as mean or standard deviation of the distribution.

The cost has also to be optimized in this stage. The key tools involved are: manufacturing databases, design for manufacturability, process capability models, robust design, Monte Carlo methods, smart tolerancing, Six Sigma tools.

The validation phase allows assessing performance, by the use of prototype test and validation, as well as establishing and maintaining control plans for critical parameters. The key tools needed for validation are accelerate testing, reliability engineering, FMEA, disciplined New Product Introduction (NPI). Feedback of requirements should be shared with manufacturing and sourcing and improvements should be noted.

Conclusions

(1) The market success of a product relies on its ability to satisfy customer needs, specified or implicit, as well as on its moment of appearance in the market.

Considering these reasons, mechatronic specialists involved in the design of new products have to transpose customer needs in functions satisfied by the new product. Thus, the need for *functional analysis* appears.

Database management systems represent convenient ways for organizing, stocking and retrieving data required for the functional analysis. It is estimated that the role of IT in activities that involve creativity and decision power will extend in the future, as a consequence of the development of expert systems.

(2) *Functional analysis and FMECA represent two fields that benefit of the advantages of database management systems.* Mechatronic specialists have to consider all the aspects presented in the paper when developing high complexity computer-aided quality assurance systems.

Even if a new product appears in the appropriate moment, its success is connected with its capacity of answering to needs expressed by the customers. The designers must find the manners of transposing these needs in well-defined functions of the new product.

(3) *Value Analysis* represents an organized effort directed to the analysis of the functions performed by a system, equipment, facility or service, for the purpose of achieving the essential functions at the lowest life cycle cost, associated with the required performance, reliability, quality and safety.

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The use of the developed DBMS facilitates significantly the work of a VA team. Among the advantages offered by the database can be mentioned:

- Correlation among functions, components and costs;
- Computation of FMECA parameters, such as RPN;
- Unified framework that integrates design data for the new product and maintenance data for similar products, is characteristic of concurrent engineering.

DFSS allows forecasting and optimizing processes using various methodologies. IDOV, a very popular one, is often used in the manufacturing world in order to increase performance, manufacturability and reliability.

A crucial step in the application of the method requires determining the critical parameters and optimizing their variability.

If the transfer functions between inputs and outputs are known, it is possible to simulate the performance of the product without the need of prototypes, using Monte Carlo methods. The obtained values constitute the initial data for the optimization phase of the IDOV cycle. The optimization has to start, when possible, with the adjustment of input parameters, in order to achieve a more robust behaviour. Tolerance intervals have to be tightened only for the inputs that produce the most significant variation of the outputs.

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