VIRTUAL QUALITY MANAGEMENT ELEMENTS IN OPTIMIZED NEW PRODUCT DEVELOPMENT USING GENETIC ALGORITHMS

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Abstract:
The contribution of this paper is placed in the field of vQM (virtual Quality Management) supposing the use of software techniques in product and its manufacturing process planning. The research was focused on laying out a framework, which brought together quality techniques used in competitive design (VOCT, AHP, QFD) and mechanisms inspired by biological evolution (genetic algorithms), achieving in the same time customer oriented development and optimization of new product characteristics. Both quality techniques and genetic algorithm were deployed in the virtual environment based on specialized software tools (Qualica, Genesis). The methodology supposes as stages: "Acquiring and ranking customer knowledge" (VOCT and AHP in identifying customer requirements and their degree of importance); "Turning requirements into characteristics" (cascaded QFD is translating successively customer requirements into technical characteristics of product and its components) and "Product optimization" (genetic algorithm optimizes the component characteristics). The genetic algorithm itself contains several constraints derived either from the customer requirements or product functionality. Thus, each component's shape, size and fitness is determined by the objective function, formulated within the genetic algorithms code. By complying with the above described framework, each component is optimally designed to constitute a product that will best serve customer needs. The proposed methodology is illustrated on the development of furniture industry products that cover diverse design situation. The product optimization and the objective function derived were focused on minimizing the product mass, implicitly its raw material consumption.

Keywords: new product development; information technology; genetic algorithms; virtual quality management

1. INTRODUCTION

In the context of virtualization, product design and manufacturing companies rely more and more on complex computational systems, which are capable to respond to situations already predicted through simulations performed in the virtual environment, based on information obtained from all devices involved in the manufacturing process.

As the need grows for ever increasing productivity, current manufacturing systems are not capable to manage the huge amount of data needed to reach the required level of productivity. Industry 4.0 can offer a solution to this problem as it is based on Cyber Physical System-enabled manufacturing. This means that the virtual information flow between the actual product and the processes related to it (including supply, shipping and customer feedback) will be enhanced and all information will be linked up as a Cyber-Physical System (CBS) (Lee, Bagheri, & Kao, 2015).

The concept of vQM (virtual Quality Management), in addition to this, takes into account also the environmental issues and any other factors that can influence the final product (i.e. Quality Knowledge and Process Knowledge) and with the help of “Design of Virtual Experiments” and “Quality Oriented process models”, through modelling and simulation the so called “Quality Parameters” and process parameters are obtained. The latter ones can be further processed in the sense that they can be optimized, this way obtaining the best possible solution, which can be implemented and used in real-life scenarios (Bookjans & Weckenmann, 2011).

This paper proposes to out lay a framework for new product development by deploying tools used in vQM, in the same order and structure in which the concept was first formulated (Figure 1), but slightly modified and adapted strictly to product development.

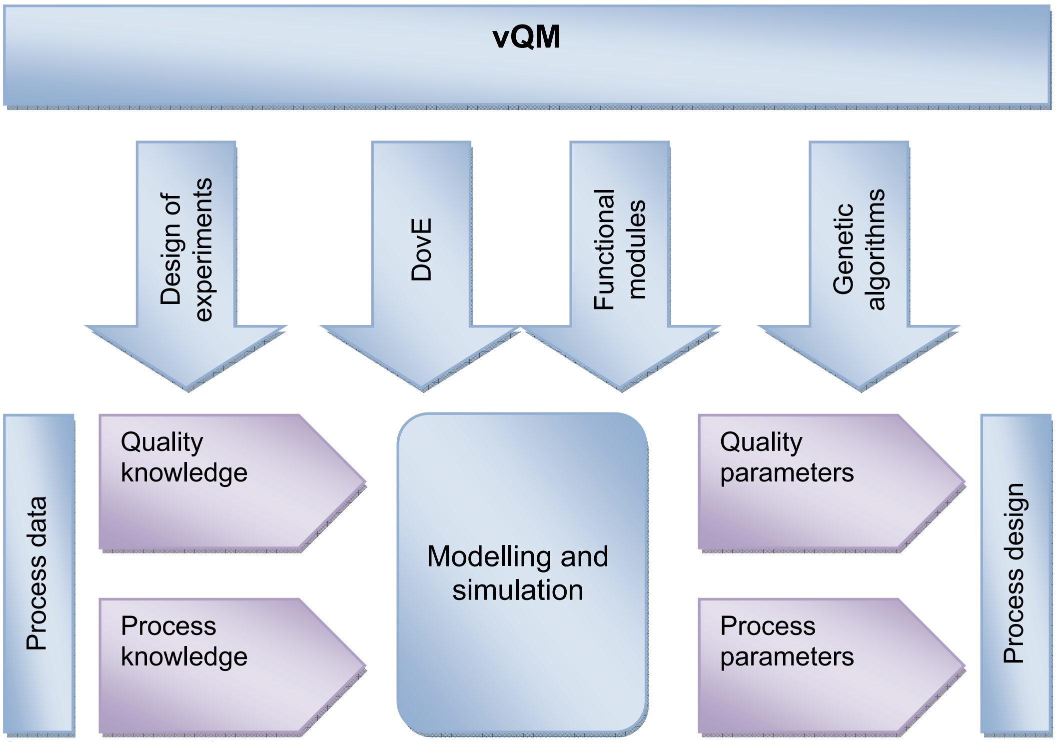
The framework presented in this paper will be illustrated by a simple example that will refer to a common household item. The product in question will be put through all the stages of the framework and the results will prove its effectiveness.

2. THEORETICAL FRAMEWORK AND LITERATURE REVIEW

The concept of virtual Quality Management is based on, but not limited to simulation studies, which are efficiently deployed for the sole purpose of “generating resilient knowledge and dimensioning quality techniques” (Bookjans & Weckenmann, 2010) that can be applied either to products or processes, before they physically exist. By doing so, products and processes reach a certain level of maturity in the planning stage, so they can be introduced straight into production, having an increased level of performance compared to ones developed using conventional methods.

An overview of the vQM concept is depicted in Figure 1, with interactions between its elements.

Figure 1: Elements of virtual Quality Management



Source: (Bookjans & Weckenmann, 2011, p. 17)

Figure 1 shows that starting from the information that describes ideal processes (process knowledge) and taking into consideration factors that are environment related or come up due to other external influences, which make the process not to behave in an ideal way (quality knowledge), through simulations, highly accurate, close to real-life scenarios can be obtained, as well as prognosis regarding the stability, capability and predictability of a modelled process (Bookjans & Weckenmann, 2011).

The main advantage of this concept is that by increasing the accuracy of the process models there will be no surprises when implementing them into production. This way highly precise resource allocation can be made, which in term reduces overall costs.

Keeping this in mind, the proposed framework is based on the architecture of vQM, having three main stages: “Acquiring and ranking customer knowledge” (e.g. Voice of the Customer Table (VOCT) and Analytical Hierarchy Process (AHP) in identifying customer requirements and their degree of importance); “Turning requirements into characteristics” (e.g. cascaded QFD is translating successively customer requirements into technical characteristics of product and its components) and “Product optimization” (e.g. genetic algorithm optimizes the component characteristics), corresponding to the stages of vQM.

VOCT is a broadly used and simple method for identifying the needs or preferences of the customer. (Roman, 2010) It can also be deployed for better understanding how the customer perceives the product (Hanjun, JinYoung, & Yongmoo, 2014, p. 207). In the field of product development, the VOCT is applied to improve the fitness of the product that is developed to the customer needs for which it is intended.

The VOC analysis is mainly deployed either by subjecting each formulated customer requirement to a 5W1H analysis (Bradlow, 2010) or by determining relationships between complaints and requirements (Pyon, Woo, & Sang, 2010). When dealing with small scale applications the first one is more convenient, as it does not require data mining and huge amount of data processing.

The VOCT is followed by the ranking of identified customer requirements, regardless if they are intrinsic or expressed. For this purpose the authors propose the use of the AHP method, which ranks and weighs criteria in a systematic way, by pair wise comparison (Guo-Niu, Jie, & Jin, 2015). The scale attribution to each comparison integrates not only qualitative, but quantitative aspects as well (Yanlai, Jiafu, Xinggang, & Jie, 2009) for determining the relative importance.

The outputs (the ranked customer requirements) from the first stage, which constitute the "Quality knowledge", enter the next phase, where they will be analyzed and transformed into product characteristics through a cascaded QFD deployment. The two QFD matrices are formed out of Ranked *Customer Requirements*, *Technical Characteristics (CTQs)* and Individual *Components* of the product.

It has to be noted that QFD is a powerful tool for "continuous product improvement" bringing forth innovation (Cor, 2001) and creative ways for solving conflicts between the technical characteristics.

Another advantage and argument for incorporating QFD in the proposed framework is that this method keeps in focus what the customer wants throughout the development process (Bouchereau & Rowlands, 2000). In its extended form the QFD process involves 4 steps: Product planning: house of quality; Product design: parts deployment; Process planning; Process control (Bouchereau & Rowlands, 2000). Because the authors focused mainly on product development, the framework will include the deployment's extent only to the first two matrices.

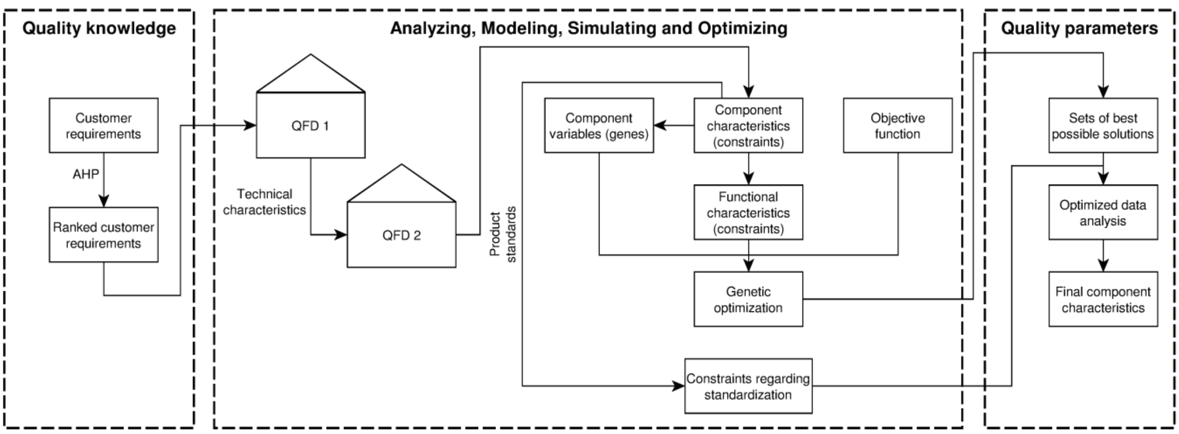
After verifying the correlations in the second QFD and obtaining the importance of each component their optimization can begin. At this point each component can be described by its characteristics (each with its own value interval), which are consistent with the customer's requirements. The optimization is done through evolutionary algorithms, by defining a single objective function (fitness function), which is either minimized or maximized, depending on the product in question and the desired outcome. First, individuals (values) are selected randomly from the defined value intervals. By applying the two fundamental evolutionary operators, which will affect those individuals and genes, the crossover and mutation (Chan, Kwong, & Wong, 2011), new possible solutions are obtained. A solution is found to be suitable, if all defined constraints are satisfied. That solution is returned and for it, it is calculated the value of the objective function. It will also serve as parent for the next generation. After re-iteration, the value of the objective function is recalculated and it is compared to the previous iteration. If the value is smaller (or greater – depending on the defined objective function) than the previously obtained one the new value is returned. It can be stated that it has a better fitness than the last one (Syberfeldt & Gustavsson, 2014). This cycle continues until the minimum (or maximum) value of the objective function is reached (Chan, Kwong, & Wong, 2011). It has to be noted that during a single objective optimization multiple values can be optimized concurrently.

3. RESEARCH

3.1. Methodology

An overview of the methodology is depicted in Figure 2:

Figure 2: Proposed framework for optimized product development



The proposed methodology begins with the customer requirements collected from potential customers by deploying numerous virtual tools such as: online surveys and questionnaires, VOCT or by analyzing trending features for the product in question, identified with the help of the internet.

The collected set of customer requirements have to undergo further finishing within established brainstorming sessions to which members from the product development team participate. This way, redundant requirements are eliminated and the remaining ones are grouped into categories for making it easy to keep track of them. This step also facilitates knowledge sharing between members and further understanding of the requirements by those that are directly connected to the product development process, thus ensuring that all ambiguity is lifted and the formulated requirements by the customer are not vague.

After this process, the final and concise set of requirements are obtained, which can undergo the prioritization process. There are lots of ways for ordering the requirements by importance, starting from traditional conjoint analysis to fuzzy logic ranking. However, arguably, the most widely used tool for prioritization is the Analytical Hierarchy Process (AHP). For this reason the presented methodology will also rely on this solution, but it can be replaced with more sophisticated tools, depending on the product in question and its complexity.

The next step is the Quality Function Deployment (QFD). The proposed methodology contains two QFD matrices interlinked in a cascaded way. The first matrix brings together the customer needs with the technical attributes. The second one verifies the correlation between technical attributes or specifications and components. This way, starting from the customer requirements we obtain technical specification for each component.

Before entering the optimization stage a few crucial steps have to be made in order to ensure the smooth running of the optimization process. This is called also as defining the optimization problem. Firstly, it is imperative to define the objective function. Depending on the application and the desired outcomes the objective function lays out the path through which the optimization is made. Secondly, the genes (variables) that are optimized in the light of the objective function have to be stated, so it is clear, which are the critical areas upon which the optimization is performed. These genes are the actual information that describes each component (length, width, height, etc.). It should also be noted that the genes have to be present as variables in the mathematical form of the objective function. It is also accepted if a new variable is used, that was earlier defined with the help of the gene in question.

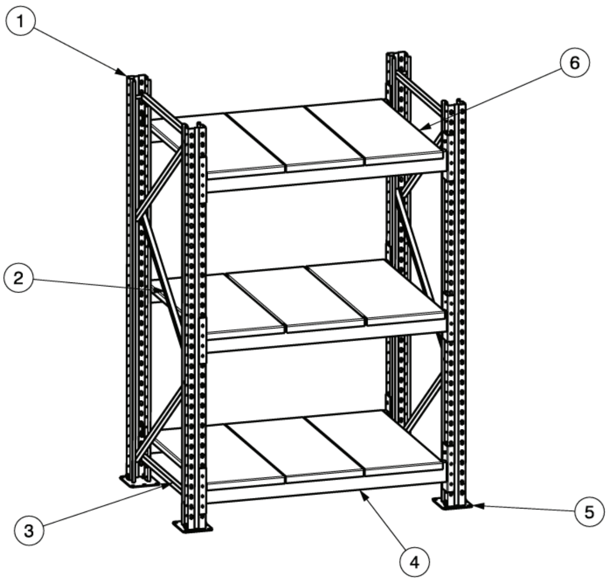
Finally, it is important to define the constraints, which are given by the component and functional characteristics of the product.

Next, the genetic algorithm can be easily deployed for each component of the product with its own objective function, constraints and genes. By deploying the genetic algorithm we obtain an optimized set of genes (i.e. component characteristics) or set of best possible solution. This set of data has to be further analyzed and compared to product standards that contain standardized information regarding the shape, size, or even form of the product. This is done because even if an “optimized variable” is obtained, incorporating it in the product could prove more costly than to use a standardized dimension.

3.2. Illustrative case study

The methodology described above is illustrated on a simple example. The product in question (modelled using a 3D CAD solution – Figure 3) is a common household shelf that was optimized regarding its mass. It was desired that the product should serve the same needs in the same way or better, but with less material consumption. Thus, the objective function was formulated taking account the weight of each product component.

Figure 3: The modelled optimized product (Note: part denomination can be seen in the second QFD matrix)



The first step was the requirement identification and hierarchization, which was possible using a specialized software tool called “Qualica QFD”:

Figure 4: Ranked customer requirements

Group: **Top Level ITEMS** — Output — Completed: ☑

AHP Toplevel Matrix

9	9,00	an order of magnitude more important
8	8,00	absolutely more important (8x as important)
7	7,00	demonstrated more important
6	6,00	demonstrated more important (6x as important)
5	5,00	essentially more important
4	4,00	essentially more important (4x as important)
3	3,00	considerably more important
2	2,00	twice as important
+	1,50	somewhat more important
○	1,00	Equally important
-	0,67	somewhat less important
½	0,50	half as important
⅓	0,33	clearly less important
¼	0,25	essentially less important (other item 4x as important)
⅕	0,20	essentially less important
⅙	0,17	demonstrated less important (other item 6x as important)
⅐	0,14	demonstrated less important
⅛	0,13	absolutely less important (other item 8x as important)
⅑	0,11	an order of magnitude less important

Input	1 the shelf should be modular	2 open access to every item on the shelf	3 easy and fast assembly	4 it should bear a weight of 60 kg/ stand	5 it should be made out of steel	6 it should fit into a space with a volume of 1200x600x2000 mm	7 it should be light	8 it should have minimum two stands	9 the stands should be at least 500 mm apart	Importance in group
1 the shelf should be modular		3	3	¼	½	¼	⅓	2	4	8,8%
2 open access to every item on the shelf			½	⅕	⅓	⅕	½	½	-	3,6%
3 easy and fast assembly				¼	½	¼	-	○	2	5,7%
4 it should bear a weight of 60 kg/ stand					3	-	4	4	5	25,1%
5 it should be made out of steel						-	⅓	3	3	11,1%
6 it should fit into a space with a volume of 1200x600x2000 mm							3	4	4	23,7%
7 it should be light								2	2	12,5%
8 it should have minimum two stands									2	5,5%
9 the stands should be at least 500 mm apart										3,9%

Importances / Sorted ITEMS 1	Calculated Importance %	Final Importance %
4 it should bear a weight of 60 kg/ stand	25,1%	23,1%
6 it should fit into a space with a volu...	23,7%	22,0%
7 it should be light	12,5%	12,3%
5 it should be made out of steel	11,1%	11,1%
1 the shelf should be modular	8,8%	9,2%
3 easy and fast assembly	5,7%	6,5%
8 it should have minimum two stands	5,5%	6,3%
9 the stands should be at least 500 m...	3,9%	4,9%
2 open access to every item on the shelf	3,6%	4,6%
Most important item:	25,1%	
Least important item:	3,6%	

After the pair wise comparison between the requirements (Figure 4 – left) the ranked customer needs are obtained (Figure 4 – right). As it can be seen in the above figure the two most important needs are related to the dimensions of the shelf and its load capability.

The information obtained after the AHP constitute inputs for the phase, for the cascaded QFD deployment.

In Figure 5 it is depicted the first QFD matrix, which analyzes correlation between needs and technical characteristics (which constitute the CTQs). This is the first step in transforming customer requirements into component characteristics. Based on the calculated importance of the needs, by verifying correlation between needs and CTQs, one can calculate the importance of the later ones. In this sense, as expected, the most important two CTQs describe the top two customer requirements, ranked during the AHP.

The second QFD matrix (Figure 6), which is interlinked with the first one (calculated CTQ values are the same), analyzes correlations between CTQs and product components. Thus, alongside the importance of each component we also obtain information about their characteristics (dimensions, load that it should withstand, etc.). For a simple illustration the authors focused only on optimizing the top two most important components (i.e. the *shelf* – no. (6) and the *shelf support beam* – no. (4))

When it is established which components are suitable for optimization, the problem must first be formulated. In our case the most suitable components that should undergo optimization are the shelf and the support beams upon which the shelf is placed. This selection is based on data obtained from the QFD process, thus, in a broader sense, based on customer requirements.

Next, it has to be established which variables, that characterize the component, will serve as genes. In the case of the first component we are looking for the thickness of the metal sheet and the height of the shelf's side reinforcement. After that the objective function is formulated: in this case it is the mass of the shelf, which is expressed by multiplying height, width, length and material density. It is imperative that the objective function has to contain all of the genes (optimized variables) or other variables that are expressed with the help of them. Finally, the restrictions have to be expressed by inequations, that will serve as limits for the optimization.

Figure 5: First QFD matrix

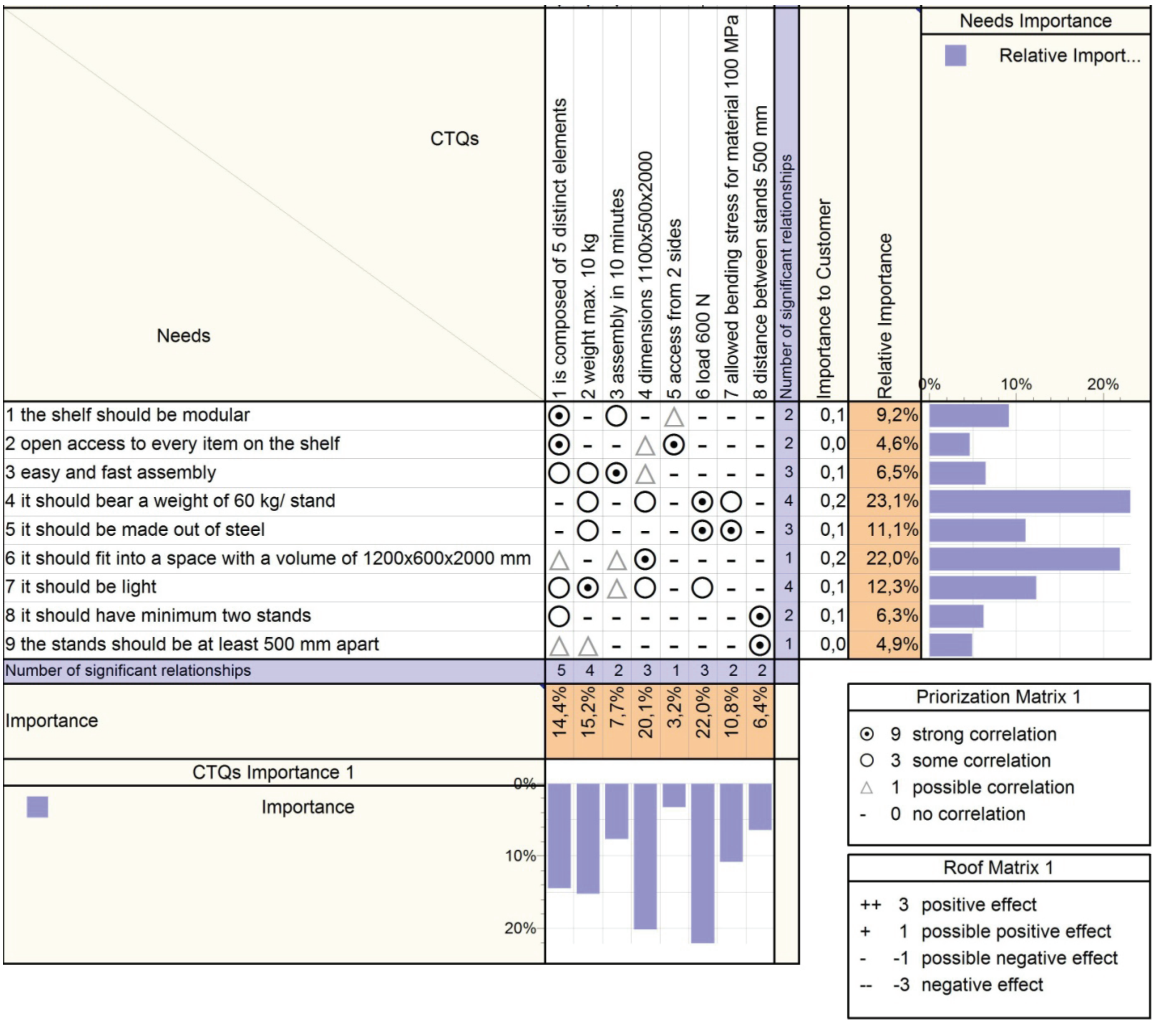
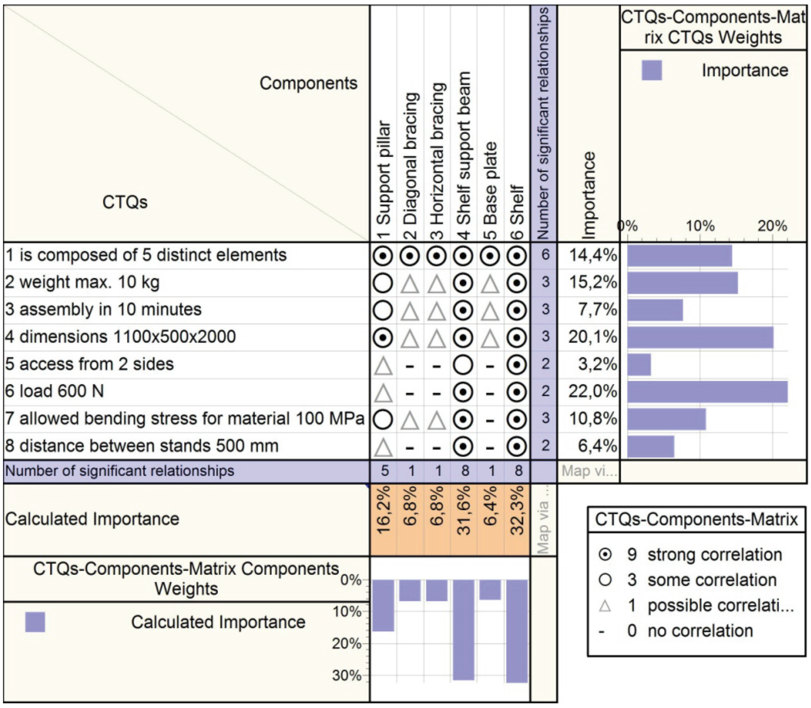


Figure 6: Second QFD matrix



The main concern when designing a product is dimensioning of components. When employing classic methods a “pre-dimensioning” is done, which will make sure that the component will withstand the stress that is subjected to. In many cases the allowable bending stress for the material is not optimally used because the component is oversized (more material is put into the component without need). In the case of optimal design the “pre-dimensioning” is replaced with iterations, meaning that the solution is not calculated exactly, but looked for within an interval. This way the obtained solutions are closer to an ideal case, because they are found according only to the established restrictions.

Keeping all this in mind, the input data for optimizing the top two components are presented in table 1 and 2:

Table 1: Entry data for the optimization for the “*shelf*” component

Known variables		Searched variables (genes)	Objective function	Restrictions
Load: F=600 N (≈60 kg)	Material density: r=7.87*10^{-6} kg/mm^3	Metal sheet thickness: t	Mass: M=r*(h*t+w*t)*l	1. Bending verification: $\sigma_i \le \sigma_{ia} \rightarrow R_1 = \frac{\sigma_i}{\sigma_{ia}} - 1 \le 0$
Length: l=1000 mm	Allowed bending stress: σ_a=100 MPa	Height of the shelf reinforcement: h		2. Metal sheet thickness should be at least 0.7 mm: $t \ge 0.7$ mm $\rightarrow R_2 = \frac{0.7}{t} - 1 < 0$
Width: w=400 mm				3. The height of reinforcement should be at least 20 mm; $h \ge 20$ mm $\rightarrow R_3 = \frac{20}{h} - 1 < 0$

Table 2: Entry data for the optimization of the "support beam" component

Known variables	Searched variables (genes)	Objective function	Restrictions
Load: F=650 N (≈65 kg)	Height of the beam: H	Mass: M=r*(H*B-h*b)*l	1. Bending verification: $\sigma_i \leq \sigma_{ia} \rightarrow R_1 = \frac{\sigma_i}{\sigma_{ia}} - 1 \leq 0$
Length: l=1200 mm	Width of the beam: B		2. Wall thickness should be at least 2 mm: $t \geq 2$ mm $\rightarrow R_2 = \frac{2}{t} - 1 < 0$
Material density: $r=7.87 \cdot 10^{-6}$ kg/mm^3	Wall thickness: t		3. The width should be smaller than the height $B < H \rightarrow R_3 = \frac{B}{H} - 1 < 0$
Allowed bending stress: σ_a=100 MPa			4. The width should be at least 2 times smaller than the height: $B \geq H/2 \rightarrow R_4 = \frac{H}{2*B} - 1 \leq 0$

All this information obtained until this point is introduced in a specialized software tool, called Genesis, which will perform the actual optimization in the manner described in the previous chapter (the information is transformed into a C++ code).

As outputs we obtained a set of solution, which was then compared to product standards for both components (i.e. standardized thickness, standardized width, standardized length, etc.), according to (EN 10025, 2004), (EN 10219, 2006), (EN 10305-5, 2010).

For better illustrating the effectiveness of the described framework the authors also calculated the values for the component characteristics using classic design methods. A comparison between the two is shown in Table 3.

Table 3: Obtained results

Classic product development			Optimized product development		
t – 1 mm	h – 20 mm		t – 0.7 mm	h – 28 mm	
Mass: 3.305 kg			**Mass: 2.358 kg**		
H – 50 mm	B – 40 mm	t – 3 mm	H – 70 mm	B – 30 mm	t – 2 mm
Mass: 3.966 kg			**Mass: 3.022 kg**		

In the case of both components significant reduction of mass is obtained: 29% and 24% respectively.

4. CONCLUSIONS

The purpose of the vQM concept is to generate resilient knowledge either for product or processes by deploying tools and instruments used in the virtual environment. The end scope is to develop the necessary information for those products/processes that will enable implementation into production with an increased performance and with a higher degree of predictability. The concept of vQM was slightly adapted for the product development process, thus obtaining a new framework that relies on customer requirements throughout the entire process and it offers optimized data for the component characteristics of the products' constitutive elements.

By deploying instruments that are simple to use (e.g. VOCT, AHP and cascaded QFD) and more advanced ones (e.g. genetic algorithms) in the structure described within the framework, product optimization can be achieved without compromising or neglecting the initial customer requirements.

The framework was subject to a common household item, which was optimized from its mass perspective, but it can also be applied to more complex products, with a different optimization perspective. For the optimized product an overall 27% mass reduction was obtained.

Future work can go as far as the extent of process modelling.

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