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ENHANCED INTEGRATED SENSITIVITY ANALYSIS IN MODEL BASED QFD METHOD

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Abstract

This manuscript presents a methodology to mathematically calculate the relation between the technical customer requirements and the technical product characteristics. This methodology is used to fill the house of quality tool of the quality function deployment method during the product design and development. In addition, the critical to quality characteristics of the product are identified. Further, the direction of optimization of the characteristics is determined. The sensitivity method is used to calculate the relations namely the elements of the transfer matrix by means of an analytical model of the product. The proposed method is applied to a model of a Segway consisting of kinematic/dynamic relations as well as actuation and control unit models.

Keywords: QFD, Requirements, Sensitivity analysis, New product development, Product modelling / models

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1 INTRODUCTION

The main purpose of the modern engineering design is to systematically plan different levels of the design process. Here the correlation between different branches with different prospects such as mechanical engineering, electrical engineering, computer science, etc should be synchronised so that the least possible effort in time and finances are spent. In addition to the technical characteristics of the product the requirements and constrains set mainly by the customer, economic, legal, environment, etc should be considered and planned within the design process, (Pahl and Beitz, 2013b). One key tool enabling the design team to integrate the customer requirements into the design process is the quality function deployment (QFD) method.

The QFD methodology emerged during 1970s (Akao and Mazur,2003). Upon its success in japan the QFD was within two decades widely known. This methodology has been under development ever since and many interpretations where made by different companies from different fields (Zhang et al., 2014). The House of quality (HoQ) is the core tool by this method (Raharjo, 2013). Here the weighted customer requirements matrix is used to determine the weighted product characteristics. The house consists of a matrix relating input data to the outputs. Some later renditions include the competitor's position matrix and the interrelationships among product characteristics which is in the form of a triangular matrix on top of the HoQ namely the roof.

In QFD one of the fundamental steps is to determine to what extent the product characteristics are related to the customer requirements. This is usually done in the QFD Workshops consisting of experienced engineers and managers whom will predict and estimate the strength of the relationships one by one (Fehlmann and Kranich, in press). This might take several iterations as the resulting relationship matrix is based on predictions. Within the QFD process not all of the product characteristics are relevant and just a specific group known as Critical to Quality (CtQ) are considered (Ostrowski, et al., 2001). This categorisation is the outcome of the QFD workshops based on the determined weight of the product characteristics. The more complex the product is, the more effort is needed to detect the right product characteristics as CtQ and to estimate the strength of relationship of these characteristics to the customer requirements.

According to Sivasamy et. al. (2016), in most cases the QFD is seen as a complex procedure for non-QFD experts. Additionally, determining the relationships between 'WHATs' and 'HOWs' is not accurate and the results analysis is based on a subjective way causing inconsistencies in the final decision.

In this work, a new method to calculate the strength of the relationships in the HoQ is presented. Non-QFD experts can apply this analytical way instead of the traditional subjective way within the design procedure and it makes less inconsistency in the final decision. Here the sensitivity methodology upon an analytical model of a product is used in order to find the relation of each technical characteristic (from here just characteristic) to the analytically expressed technical customer requirements (from here just customer requirements). The determined sensitivity values are inserted into the HoQ for further analysis. This way selecting the right characteristics as CtQ in complex products with many characteristics is executed accurately within the HoQ. Additionally, the direction of the relationship can be determined as well. This is useful in the case of further optimization of the product as it shows whether a specific product characteristic should be minimized or maximized. The proposed methodology is applied to a model of Segway.

In the following section 2 the new advances in QFD are described. Next, on section 3 the method derived by the authors is explained. In section 4 the proposed approach is applied to an example. Last but not the least the results are concluded in section 5.

2 BACKGROUND AND MOTIVATION

The new ISO 16355 standard on QFD was introduced in 2015. It defines QFD as a statistical method versus the former qualitative definition (ISO 16355-1, 2015).

QFD method benefits from different tools at different design levels and it is specifically tailored for each project. The QFD method in engineering design applications starts with defining customer requirements namely the Voice of Customer (VoC), Figure 1. There are several techniques to identify the VoC such as verbatim analysis and etc (Brown, 1991). In addition to identifying the VoC the weighting of each requirement should be defined by the customer. Determining the VoC and assigning the weights to each

VoC is one of the main challenges in QFD as most of the time the customer itself does not know exactly which requirements are needed nor the importance of them.

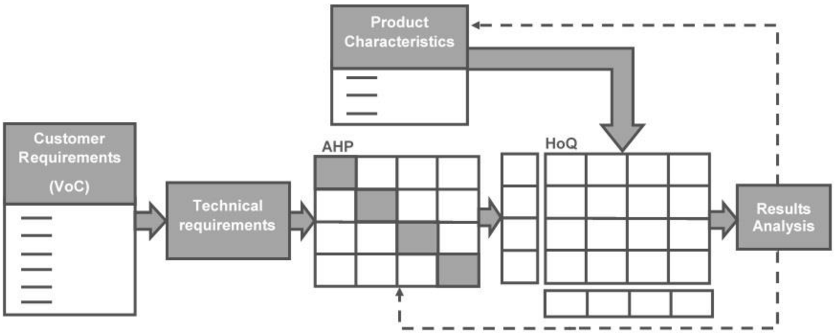

Figure 1. QFD Process

One of the tools to categorize and rank VoCs is the Kano Analysis. With the help of this tool the requirements which lead to higher customer satisfaction and require less technical excellence are identified. The accuracy of this method is based on the expertise of the technical and sales staff who participate in Kano workshops (Chaudha, et al., 2011).

Once the customer requirements are categorized and ranked, these are weighted with the help of Analytic Hierarchy Process (AHP). This method was introduced by Saaty (2003) to address the complex, multi objective decision problems. In the application of customer requirements analysis, the pairwise comparison of the requirements, instead of general comparison with all requirements at once, results in solutions with the most acceptable trade-off among the requirements. The pairwise comparison is conducted in QFD workshops and is based on expertise perception. In order to prevent inconsistencies in the perceptions of the comparisons, after each AHP process a consistency analysis is done and upon its results the expertise perceptions may need to be improved.

At this point the product characteristics which have an influence on the customer requirements namely CtQ should be found. It is important to note that not just the characteristics that directly have an effect on a requirement are important but the characteristics that maintain the functionality and other basic features of the product are as well important.

In modern QFD the relation matrix in HoQ was replaced by the transformation matrix (transfer function) which maps mathematically the inputs to the outputs (Fehlmann and Kranich, 2011). The transfer function $f: \mathbb{R}^n \rightarrow \mathbb{R}^m$ which transforms the product characteristics profile (in the rest of the manuscript just product characteristics) $x \in \mathbb{R}^n$ to customer requirements profile (in the rest of the manuscript just customer requirement) $y \in \mathbb{R}^m$ is defined as:

$$y = f(x) \tag{1}$$

It is important to note that in reality the product characteristics will result in customer satisfaction and not vice versa. Thus the customer requirements are a function of product characteristics. Assuming the function f to be a linear function, the matrix $A \in \mathbb{R}^{n\times m}$ is defined as the gain in the Equation (2).

$$y = A.x \rightarrow \begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_m \end{pmatrix} = \begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & & a_{2n} \\ \vdots & & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mn} \end{pmatrix} . \begin{pmatrix} x_1 \\ x_2 \\ \vdots \\ x_n \end{pmatrix} \tag{2}$$

Here, the main challenge is to find the product characteristics x leading to customer requirements y. In practice usually the latter is known, this leads to calculating x in most cases by try and error and within several iterations. The main approach is to calculate x from the requirements using the Equation (3).

$$x = A^T.y \tag{3}$$

The resulting x is not necessarily the solution to Equation (1). If the calculated x is used to determine the customer requirements back, Equation (4), the results is equal to the original customer requirements if and only if the vector y is an eigenvector of the matrix $A.A^T$.

$$y' = A.x = A.A^T.y \tag{4}$$

Hereby the vector y' represents the achieved customer requirement vector.
The quality of the estimated x and the transfer function A is measured via the convergence gap. The convergence gap is the Euclidean Distance between y and y', Equation (5).

$$Convergence\ Gap\colon \|y - y'\| = \sqrt{\sum_{i=1}^{m}(y_i - y'_i)^2} \tag{5}$$

The critical limit for the convergence gap is 20% leading to convergence limit of 0.2. Large convergence gap implies that the product is unable to fulfil the customer requirements.
Analysing the inconsistencies in the transfer function may lead to new customer requirement or even hidden customer needs. In this context tools like the convergence gap can light the need for search on missing requirements or characteristics.

3 MODEL BASED QFD WITH ENHANCED INTEGRATED SENSITIVITY ANAYSIS (MBQFD-EISA)

Acquiring the right product characteristics as CtQ and evaluation of their relationship with customer requirements is one of the main tasks in QFD. The method proposed by the authors addresses this issue by introducing a modelling based QFD shown in Figure 2.
In this method the relationship between all product characteristics which are implanted in an analytical model of the product and the customer requirements are determined using sensitivity analysis. Naturally in the QFD workshops the technical experts use product models to get an accurate estimation of the weighting of the relationship of a specific characteristic to a specific requirement. The advantage of the proposed method compared to the traditional one is that, first, there is no need to categorize the product characteristics into CtQ and non CtQ in advance. The CtQ characteristics are determined based on their weighting (profile). Second, the relationship of the characteristics and requirements is accurately calculated and not estimated.

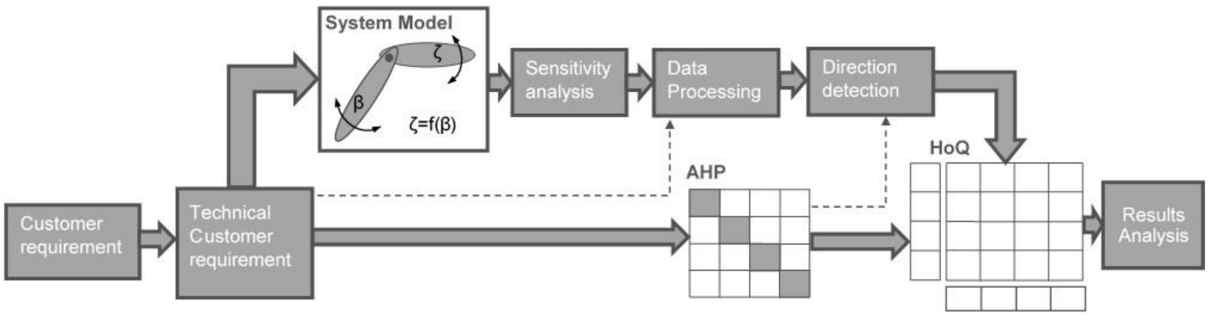

Figure 2. Model based QFD with the integrated sensitivity analysis

It is important to note that this method is not designed to replace the QFD workshops and the need for the expert's opinions but as a tool to assist them in the decision making process.
As this methodology is aimed to address the complicated mechatronics products, as part of the sensitivity analysis methods the linear regression is used to calculate the relationship of the characteristics and requirements.
Initially, an analytical model of the product needs to be prepared. This is the same model being used by the experts in the QFD workshops. The model can be a very simple at one hand due to the fact that in the first stages of the design few parameters are known to the engineers. At the other hand as the design process proceeds the model can get more complicated. In the case of mechatronics products, the model is comprised of parameters from different disciplines such as mechanical engineering, electrical engineering and controls.

3.1 Linear regression

Once the model is prepared as a first step in Regression method a training set (sample set) should be prepared. This is done by defining the range of each feature (characteristic). Then within the defined range a random value is selected. Based on these values the analytically defined requirements *y*s are calculated.
Next in the regression method, the hypothesis h in Equation (6) is defined to calculate a specific requirement from a linear equation of the features (Eslami, 1994).

$$h_i = \theta_0 + \theta_1.x_1 + \theta_2.x_2 + \cdots + \theta_{n-1}.x_{n-1} + \theta_n.x_n\ , i = 1 \ldots m \quad (6)$$

Here θs are the parameters (gains) of each feature. These parameters will define the sensitivity of each feature (characteristic) to each hypothesis (requirement). Naturally the more the population of the training set, the more general the hypothesis would be.

The goal of the linear regression is to find the parameters θ in the hypothesis h so that h and y are close to each other. This can be mathematically represented as minimizing a defined cost function J. In this approach the square error function of the h and y is selected as the cost function in Equation (7).

$$J_i(\theta_0, \cdots, \theta_n) = \frac{1}{2s}.\sum_{j=1}^{s}(h_j^i - y_j^i)^2\ , i = 1 \ldots m \quad (7)$$

Here s denotes to the population of the training set. The h_j^i indicates the ith hypothesis calculated based on the jth member of the training set population.

There are different optimization methods to obtain the parameters θ that minimize the cost function J such as gradient descent method, particle swarm method, etc. Here the gradient descent method is used as it can easily be combined with linear regression.

3.2 Gradient descent

In this method, the value of θs are updated in each iteration based on the constant descent rate α and the gradient of the cost function J with respect to θs, Equation (8).

$$\theta_k = \theta_k - \alpha_i.\frac{\partial}{\partial\theta_k}J_i(\theta_0, \cdots, \theta_n), i = 1 \cdots m, k = 1 \cdots n \quad (8)$$

Here selecting the right value for the descent rate α is important. If α is too small, the gradient descent can be slow on minimizing the cost function. If α is too large, the gradient descent may fail to converge to a minimum or even diverge.

3.3 Processing the parameters for QFD

The resulting parameters θs of the gradient descent method have to be processed before filling the transformation matrix.

Primarily, it is needed to define the direction of optimization by each requirement y. Does the customer want a specific requirement to be minimized or maximized. This step is important, as there might be a parameter with negative sign, which is incorporated to desired minimization of a specific requirement y. Here increasing the parameter will decrease the requirement which is considered to be a positive value sensitivity.

At the next stage the parameters matrix should be filtered for the noisy values. These are the very small parameters calculated through the regression process and due to the non-linearity in the data set. According to ISO 16355, the ratio between the highest and lowest semi-subjective and quantified relation levels is about 20. Here the same ratio is used to find the lower threshold of acceptable parameters based on the maximum value of the parameters for each calculated hypothesis of the requirements.

After filtering and before categorizing the parameters into positive and negative, the parameters for each requirement should be standardised so that they can be compared to each other in the HoQ. In the standardisation process the parameters of each requirement are subtracted from their mean value and divided by their standard deviation (Grus, 2015), Equation (9).

$$\theta_i^k = \frac{\theta_i^k - \bar{\theta}_i}{\sigma_{\theta,i}}, i = 1 \cdots m, k = 1 \cdots n \quad (9)$$

Here θ_i^k is the kth parameter of the ith requirement. The $\bar{\theta}_i$ and $\sigma_{\theta,i}$ are the mean and the standard deviation of the parameters of the ith requirement respectively.

Once the parameters are standardized they can be divided into positive and negative parameters.

3.4 Evaluation of the direction of optimization

The direction of the optimization of the product characteristics is a key information during the product design procedure. As a result, in some versions of the HoQ a row indicating the direction of optimization is inserted between the roof and the transfer function. In the traditional QFD Workshops the direction of optimization is being estimated by the experts.

In the proposed procedure, this optimization direction is obtained from positive and negative sensitivity matrices. The positive sensitivity matric contains the positive parameters and the negative sensitivity matric the negative parameters. Hereby the characteristics profile (normalized weights) for each positive and negative sensitivity matrices are calculated. For each characteristic between positive and negative sensitivity the one with the largest profile value is selected, Figure 3.

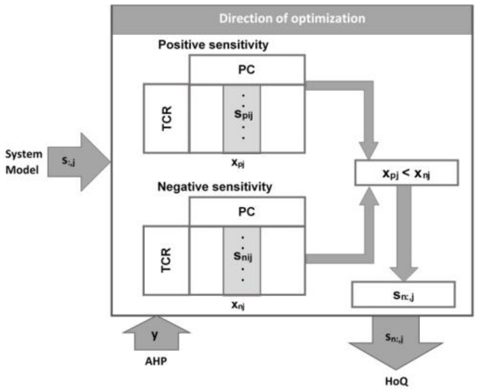

Figure 3. The process of determining the direction of optimization, here $A^T(j,:)$.is the jth row of the A transpose matrix

It is important to note that HoQ accepts only positive values. This means for the negative sensitivity only the absolute value of sensitivity is set in the matrices and the sign of the parameters are inserted in a separate vector as a reference.

3.5 HoQ and the convergence check

Once the direction of the optimization for each characteristic is selected, the parameters with the same sensitivity are selected. At this point, the matrix of the parameters can be viewed as the transformation matrix in the HoQ.
Based on the characteristics profile, the CtQ characteristics can be identified. These are the characteristics with the highest profile value. In this procedure the same relation levels of the ISO 16355 is applied to the characteristics profiles. The CtQs are the characteristics with the level of "strong" and above that.
In addition, the convergence gap tool is used to measure the state of the achievable customer requirements from the model compared to its desired value from the AHP analysis. The presence of a large convergence gap indicates that the model cannot fulfil the customer’s weighted technical requirements. Customer requirements or the model itself can cause this. In the case of customer requirements, the problem may rely on non-realistic customer requirements for the model, wrong analytical definition of the technical customer requirements, dependency of the technical customer requirements on the non-technical product characteristics etc. In the case of model, the large convergence gap might be due to poor modelling of the product functionality, missing product characteristics etc.

4 MBQFD-EISA ON A SEGWAY MODEL

In this section the proposed QFD method is applied to the design process of a Segway. With the help of QFD the main technical characteristics of the Segway which may have a large influence on customer requirements are identified.
At the beginning the model of the Segway is explained. Next the customer requirements on this product are discussed. At the end of this section the resulting HoQ is illustrated.

4.1 Segway model

Segway is selected as an example on the implementation of the proposed method due to its detailed studied design process in the "development of mechatronic products" course at Ruhr University Bochum. During this course the students are required to design a Segway based on the methodologies learned for engineering design. The Segway is meant to have a special role. To be able to stay balanced having a plaque with the logo of the exhibiting company attached to it during an exhibition. In addition,

it should be able to recover from an impact while the visitors are asked to participate in a game and through a ball to the Plaque. The game is designed with the purpose of advertisement.
The schematic design shown in Figure 4 illustrates the main parts of the Segway. The main control unit, driving unit and batteries are mounted on the assembly plate. The plaque is connected to the main body via a rod. The rod is connected to the assembly plate via a fix joint with no degrees of freedom.

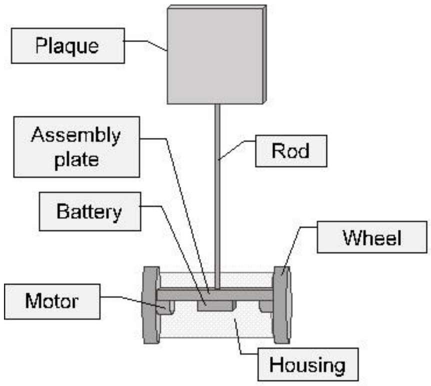

Figure 4. The schematic design of the Segway, showing the main parts

4.2 Customer requirements

The customer requirements on the Segway are determined from a survey held within the colleagues of the Institute of product development at Ruhr University Bochum. These were categorized using the main characteristics list (Haupt Merkmalliste), Pahl et al. (2013). The technical requirements were identified and later weighted and analysed using AHP. The main requirements with the highest profile value are then selected, Table 1.

Table 1. Costumer Requirements

#	Customer requirement	Profile value
1-2	Quick balancing	0.48
3-4	Easy transportation	0.09
5	Advertisement readable	0.19
6	Long operation duration	0.48
7	Compensation of a ball impact	0.48

Knowing the main requirements, these have to be defined analytically so that their value can be calculated from the model.

- The requirement "quick balancing" was analytically expressed as low oscillation time and low oscillation distance. The oscillation time, is the time required for the Segway to compensate an impulse. The oscillation distance, is the distance the Segway travels back and forth until it compensates the impulse.
- "Easy transportation" is defined as both the weight and volume of the Segway. By volume, the volume of a rectangular box the Segway is inscribed in is selected.
- The area of the Plaque is the term defining the Advertisement readability. This requirement does not only dependent on the defined technical characteristic but on non-technical characteristics as well such as the font size, colouring, etc.
- The duration of the operation is calculated based on the time needed to discharge a 2500mA battery with the assumption of one ball hit every hour.
- The ball impact compensation is defined by the changes in the rod angle with respect to the normal vector to the ground. If this angle is 90° that means the Segway has fallen on the ground. Thus the less the angle change of the rod, the more successful the Segway is in compensating the impact.

4.3 Model properties

The Segway is analytically described through equations of motion of the main parts. These forward dynamic equations of motion, simplified with the kinematic dependencies of the parts, were inserted in the Simulink environment of MATLAB.

In addition to the Segway, the model consists of a brushed DC motor model as well. The model of the motor is inserted via the electrical equations of the DC motors. Based on the input voltage the motor model calculates the actuation momentum on the wheels.

The voltage signal required for the motor model is provided by the control unit. The control unit is the third main part of the model. The controller follows the PID architecture. This unit's goal is to keep the Segway upright at all times, thus minimising the angle of the rod with respect to the ground normal vector.

The assumptions made in the modelling phase are as follows:

- No losses due to the friction at the joints
- Slip-free contact of the wheels to the ground
- Noise-free signalling
- No plastic/elastic deformation of the parts during the motion

The impact of the ball to the plaque is modelled with an impulse momentum at the motor joints.

4.4 Linear regression

For this model a training set with the population of 478 is made and the requirements for each set are calculated from the model. 38 product characteristics in different fields including geometry, electrical and control variables are identified (see Appendix).

In the gradient descent process the descent rates are adjusted to the requirements. This way by the same number of iterations the optimal value is found. The number of iterations in this example is set to be 2500.

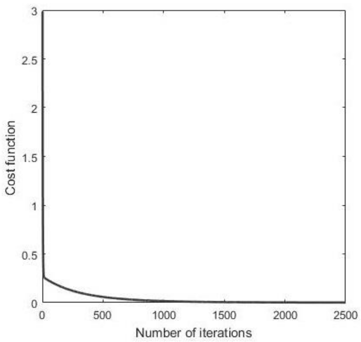

Figure 5. Cost function of the requirement easy transportation(volume)

Figure 5 shows the result of the linear regression for the 4th cost function "easy transportation (volume)". Here the cost function reaches low values in vicinity of zero. This means that this requirement has a linear relationship with specific parameters. In some cases, the requirement does not have a linear relationship with the parameters and just a local minimum based on the selected initial values can be found. In order to have linear relationship, the gradient of the best fitted function at the operation point can be found. If the operation point is not known and the range of the variable cannot be limited, still the main influential parameters on the requirement can be found with the help of the fitted line to the data.

4.5 HoQ of the Segway

First by processing the parameters, they are filtered, standardised and categorised into negative and positive sensitivity. The achieved customer requirement profile has a convergence gap of 0.16, which is within the range of the convergence limit. This means that the product characteristics are able to address the desired requirements.

Figure 6 shows the final version of the HoQ including only CtQ characteristics. The complete list of the Segway characteristics is in the Appendix.

Customer requirements	y	W. diameter	H. length	R. length	P. length	P. width	P. weight	M. length	M. torque const.	M. resistance	G. ratio	PID con. P	PID con. I	y‘
Quick balancing (time)	0.48	0.31	0.39	1.73	0	0	0.27	0.44	0.75	1.46	1.1	4.67	2.18	0.49
Quick balancing (distance)	0.48	0	0.45	1.73	0	0.63	2.16	1.06	0.31	0.91	1.17	3.83	2.16	0.49
Easy transportation (volume)	0.09	0.08	3.85	4.02	0	0.16	0.42	0	0.31	0	0.4	0	0	0.23
Easy transportation (weight)	0.09	0	0	0	0.39	0	0	0	0.37	0	0.33	0.3	0	0.08
Advertisement readable	0.19	0	0	0	4.18	4.08	0	0.46	0	0.45	0	0	0	0.13
Long operation duration	0.48	2.37	0.47	1.86	0	0.17	0.19	0	3.44	0.65	3.56	0	0	0.44
Compensation of a ball impact	0.48	1.4	0.69	0	0.48	0	2.37	0.74	3.2	2.37	2.73	0.69	0	0.49
		0.2	0.14	0.3	0.11	0.12	0.25	0.12	0.39	0.28	0.43	0.46	0.22	
		⇩	⇩	⇩	⇧	⇧	⇧	⇩	⇧	⇩	⇧	⇧	⇩	

⇧ Maximize
⇩ Minimize

Figure 6. HoQ of the Segway with the requirements and CtQ characteristics profile values and the direction of the optimization.

Here it can be seen that not just the physical, electrical or control design of the Segway is important in the engineering design but also their combination. This way the interaction between different prospects of the design on each other are considered in the design process.

The main characteristics with the highest profiles belong to the motor and control unit models. Naturally, in every mechatronics product the selection of the right actuation and control parameters determines if the system fails to conduct its tasks or fulfils them.

Based on the results of the QFD, the gearbox ratio is among most important characteristics of the Segway. Higher gearbox ratio increases the torque inserted in the system. This will result in faster impact compensation, which will lengthen the operation duration. It is important to note that the weight of a gearbox increases with the increase in its ratio. Thus makes the Segway heavier. The relation between the weight and the ratio depends on the gear type and is different from one manufacture to another, thus this relationship is not integrated in the model.

The motor constant has almost the same effect as the gearbox ratio. This is due to its effect on the main requirements, which are the impact compensation and operation duration. The more this characteristic is, the motor provides more torque which helps the control unit to act more robustly.

The proportional part of the PID controller is its backbone. Although proportional gains larger than the critical limit results in unstable performances, increasing the proportional gain reduces the rise time as well as the steady state error.

Within the geometry parameters, the rod length and the wheel diameter have the highest profile value. Decreasing the rod length in addition to decreasing the volume of the Segway will increase the Segway moment of inertia meaning that the body of the Segway absorbs most of the impact energy and therefore less effort is needed in balancing the Segway. Decreasing the wheel diameter influences the duration of the operation and response time to the impact as the motor needs to provide less torque and therefore more rotational speed to rotate the wheels.

5 CONCLUSION

The proposed enhanced model based QFD with the integrated Sensitivity analysis calculates the transfer matrix of HoQ based on an analytical model of the product. This method considers only the technical requirements and characteristics of the product. The proposed methodology was applied to the design process of a Segway. An analytical model of the Segway was made including the kinematic and dynamic model of it as well as the actuation and control unit models. The relations between analytically formulated technical requirements and the technical characteristics of the product were calculated with the help of the linear regression method. The results show an acceptable convergence gap between the goal requirements and achieved requirements profile value. This indicates that the proposed methodology is able to address the need to calculate the transfer matrix accurately in contrast to the traditional subjective methods. In addition, it can determine the right CtQ characteristics. Here the effect of non-linearity in the model and between the technical requirements and characteristics needs further study.

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APPENDIX

The Segway characteristics used in the model are summoned in the table 2.

Table 2. Segway characteristics list

1	W. diameter	2	W. width	3	W. weight	4	H. outer diameter	5	H. inner diameter
6	H. length	7	H. weight	8	H. CoM dis.	9	AP. length	10	AP. width
11	AP. height	12	AP. CoM dis.	13	R. outer diameter	14	R. inner diameter	15	R. length
16	R. weight	17	P. length	18	P. width	19	P. thickness	20	P. weight
21	M. diameter	22	M. length	23	M. weight	24	M. CoM dis.	25	M. torque const.
26	M. speed const.	27	M. inductance	28	M. resistance	29	G. ratio	30	B. length
31	B. width	32	B. height	33	B. weight	34	B. CoM dis.	35	PID con. P
36	PID con. I	37	PID con. D	38	PID con. N				

Here are the acronyms used in the above table.
W.: Wheel, H.: Housing, AP.: Assembly plate, R.: Rod, P.: Plaque, M.: Motor, G.: Gearbox, B.: Battery, PID con.: PID controller, CoM dis.: distance from Centre of Mass of the part to the rotation axis