An Integrated Approach of House of Quality and Multi-Criteria Evaluation in the Design of an Electric Formula Student Car

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Abstract

The House of Quality (HOQ) has been used in different industries as a tool to capture the voice of the customer and guide decision-makers and engineering teams in the development and improvement of products. But despite being improved in recent years with the use of Multiple criteria decision analysis (MCDA), some problems of the HOQ still remain and are mostly related to measurement scales. They are the assigning of weights as direct indicators of importance to Customer Attributes (CA) and their relationship to Engineering Characteristics (EC) using ordinal scales as if they were cardinal. This study applies the HOQ in the design process of a Formula Student electric vehicle integrated with the MCDA tool MACBETH to overcome the drawbacks of the HOQ. Additionally, the resource allocation software tool PROBE is applied to identify efficient portfolios of scenarios of performance for the ECs integrating the roof with the definition of EC synergies in the portfolio tool. The results are a HOQ that represents both the value perceptions of the customers and of the engineering team, and a proposed efficient portfolio of ECs specifications for implementation in the new Formula Student electric vehicle.

Keywords: House of Quality, Quality Function Deployment, multi-criteria evaluation, portfolio analysis, engineering design, MACBETH

1 Introduction

FST Lisboa, short for Formula Student Técnico Lisboa, is the Formula Student (FS) team of Instituto Superior Técnico (IST). It exists is formed entirely by bachelor and master students that must develop a formula race car every year to compete against cars from other universities' teams. As a student team, there are some weak points in project management and engineering design mostly due to the inexperience of the leadership, sometimes affecting the overall quality of the project. Some of them are expected, as the leaders have a very high technical profile, but they are not aware of the practices and tools that should be applied in design processes.

One of such tools is the House of Quality (HOQ), part of the Quality Function Deployment (QFD). It aims to capture the Voice of the Customer (VoC), as Customer Attributes (CA) and translate them into Engineering Characteristics (EC) guiding the design process to satisfy the customer in what he expects from the product/service (Hauser and Clausing, 1988). The HOQ has been used in the automotive industry for some decades and in different phases of design and development of products, often combined with other methodologies (Renzi, Leali and Angelo, di, 2017).

However, the HOQ has some issues mainly associated with the scales it uses to assign weights of importance to CAs, often using ordinal scales as if they were cardinal scales. This way, they are not meaningful and are incorrect scales (Burke, Kloeber and Deckro, 2002; Franceschini and Rossetto, 1995; Sivasamy *et al.*, 2016). Multiple criteria decision analysis (MCDA) methods have been integrated with the HOQ recently, such as the Analytical Hierarchical Process (AHP), while some authors propose Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), Operational Competitiveness Rating (OCRA) (Chan and Wu, 1998) and even Fuzzy Sets Theory (Chen, Ko and Tseng, 2013). Some of them, as the AHP, have concerning issues like the lack of consistency of the judgements (Bana e Costa and Vansnick, 2008).

This study applies the HOQ in the design of an electric Formula Student car integrated with an MCDA methodology, Measuring Attractiveness by a Category-Based Evaluation Technique (MACBETH) (Bana e Costa, Corte, de and Vansnick, 2012), and analyses the outcomes of the HOQ with a portfolio analysis tool, Portfolio Robustness Evaluation (PROBE) (Lourenço, Morton and Bana e Costa, 2012), to provide the team with a set of portfolios of specifications to implement in the new prototype.

2 The House of Quality

It is a series of tables that link together CAs and their relation to ECs, the weights of each CA, given by the customer, and the correlation between ECs. All these links allow a comparison of the product against its benchmarks in the perspective of the customers and of the engineers. Each of these different segments of the HOQ are called rooms and they are filled by different people, usually by the customer and by the business (Chan and Wu, 2002; Hauser and Clausing, 1988).

The first room is the Customer Attributes room. It captures what the customer wants from the product and inquires them about their weights (Ficalora and Cohen, 2009). The QFD team (engineers and managers of the company) then translates the CAs to ECs, that have a relationship weight to each CA, illustrating how much they affect or are important to fulfill the CA. The CAs and ECs are then benchmarked against the competition in the views of the customer and in technical terms, calculating their strategic relative weights and importance (Chan and Wu, 2002).

Then, each EC is analyzed to other ECs to assign, or not, negative or positive correlation weights in what is called the Roof of the HOQ, or correlation matrix, to help in the design trade-offs engineers face when developing a product (Yang and El-Haik, 2003).

3 Building the House of Quality

MCDA is aimed at helping a decision-maker (or a decision-making group) to address problems characterized by multiple and often conflicting criteria, typically considering several options. In spite that there are several different types of problems that may be tackled by MCDA, in this study when referred to MCDA it will be regarding methods that are used to evaluate options in the framework of Multiple Attribute Value Theory (Belton and Stewart, 2002).

MACBETH is an MCDA approach for value measurement of attractiveness of value options through a non-numerical pairwise comparison. Using qualitative judgements of difference in attractiveness, it creates value scores for the alternatives and weights for the criteria in an attempt to facilitate the work of the decision-maker (DM) in rating such differences (Bana e Costa, Corte, de and Vansnick, 2012). MACBETH uses a qualitative semantic scale with categories being “very weak”, “weak”, “moderate”, “strong”, “very strong” and “extreme” that the DM can use to express his view when comparing the different alternatives.

As it allows the creation of ratio scales to assign to the weights and relationships, and interval scales to create value functions for the alternatives, it was the chosen methodology. According to Burke, Kloeber and Deckro (2002), this is the most appropriate way of building the HOQ.

3.1 Defining CAs, their Weights and Value Functions

This process is developed for the design of the FST 10e, the 2019/20 car of the team, having the FST 09e (2018/19) as the baseline. To start it, the customer and the QFD team were defined to be the same, because it is an internal customer (FST Lisboa team). It was made of Team Leader, Mechanical Chief Engineer, Electrical Chief Engineer and Project Manager. In every step of the judgement process, they were required to answer the difference of attractiveness in the M-MACBETH software privately, not to generate an informational cascade and social influence (Wood, 2000).

The CAs were obtained from the team’s documents of their objectives and concept of the car. They were grouped into three primary level attributes, More Testing and Quality, Performance, and Simplicity, which gave origin to other secondary level attributes that became the CAs that could be qualitative or quantitative (Table 1).

To obtain the weights of the CAs, the team was then asked to provide possible performance levels and assign one to be the “Neutral” and other to be the “Good” level for each CA. It was decided that the “Neutral” should always be the performance of the FST 09e because if the FST 10e performed worse the team would get worse results in the competitions, and if the new car performed better, the team would get better results. If kept as it is, it would not make any difference for the team, thus the true definition of neutral.

The judgement process started by asking the team to do pairwise comparisons of Importance between CAs and with a fictitious alternative that performs “Neutral” in all attributes called “All Lower” using MACBETH semantic scale of “very weak”, “weak”, “moderate”, “strong”, “very strong” and “extreme”. This way they would be ordered by decreasing attractiveness. This was followed by pairwise comparisons of CAs between themselves. Questions like “what is the difference in attractiveness in improving from ‘Neutral’ to ‘Good’ in ‘Fast

Table 1 CAs and descriptors of performance

Customer Attribute	Short Name	Descriptor of performance
Mechanical Accessibility	MechAc	The easiness of mounting the car when compared to the FST 09e (see Table 3)
Reliability	Rel	% of days the car is being tested during the testing period
Good Acceleration Time	Acc	Seconds to complete a 75 m straight line
Fast and Safe Braking	Brak	Maximum longitudinal G-Force while braking (Gs)
Good Turning Abilities	Turn	Maximum lateral G-Force while cornering (Gs)
Access to Information	AccInfo	The easiness of obtaining sensitive information about the state of the car, mechanically or electronically (see Table 4)
Reduced Design, Manufactur-ing and Assembly Time	RDMA	The number of weeks of the development lifecycle, from design to first ride

and Safe Braking' compared to improving from 'Neutral' to 'Good' in 'Mechanical Accessibility'?" were asked to obtain their replies. With a complete matrix and consistent judgements, it was possible to obtain the weights on a ratio scale for each CA as shown in Figure 1.

To get a more accurate view of the team´s perception of value in the performance domain, more performance levels need to be defined for each CA to build their value scales. Thus, an intermediate level between "Good" and "Neutral", a level above "Good", and another one below "Neutral" were defined. The quantitative CAs and their performance levels can be seen in Table 2 and qualitative ones in Table 3 and Table 4.

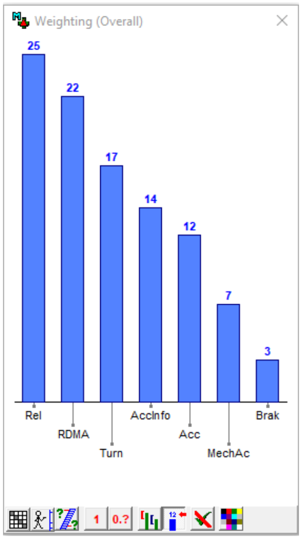

Figure 1 CA Weights

Table 2 Quantitative CAs Performance Levels

Reliability (%)	Good Acceleration Time (s)	Fast and Safe Braking (G)	Good Turning Abilities (G)	RDMA (weeks)
90.95	3.35	3.5	2.25	34.5
82 = "Good"	3.5 = "Good"	2.5 = "Good"	2 = "Good"	36 = "Good"
73.05	3.65	2.25	1.75	37.5
64.1 = "Neutral"	3.8 = "Neutral"	2 = "Neutral"	1.5 = "Neutral"	39 = "Neutral"
55.15	3.95	1.75	1.25	40.5

Table 3 Mechanical Accessibility Performance Levels

Performance Level	Short Name
Mounting easiness higher than FST 09e = "Good"	MountHigh09e
Mounting easiness like FST 09e = "Neutral"	Mount09e
Mounting easiness lower than FST 09e	MountLow09e

Table 4 Access to Information Performance Levels

Performance Level	Short Name
All access over telemetry + all mechanical parts status = “Good”	Tel+Mech
All access over telemetry + more mechanical part status than FST 09e	Tel+09eMech
Wired access to all variables + more mechanical parts status than FST 09e	Wired+09Mec h
Wired access to some variables more than FST 09e + more mechanical parts status than FST 09e	Wired09e+09e Mech
Everything like FST 09e = “Neutral”	As09e
Less than FST 09e	Less09e

Creating the value scales for CAs started with the team ranking the performance levels by decreasing order of preference, similarly to what was previously done, and then to assign judgements of difference of attractiveness for each pair of performance levels. At the end, a judgement consistency check occurred. For inconsistent judgements, the team was asked to consider the options presented by the software and to alter accordingly. After verification and results acceptance, a scale was generated using M-MACBETH for the CA. This was repeated for every CA.

3.2 Translating CAs into ECs

The process for obtaining FST Lisboa’s ECs followed a Value Focused Thinking approach (Keeney, 1992) having as starting points the CAs. For each CA the team was asked questions similar to “what influences this?” and “how can we achieve this?” in order to start building a causal map. This process was repeated for every CA and for all of their answers up to a point where it was considered to be the root cause.

From the six CAs identified by the team, it was possible to find 15 ECs. Each one of them and their measurement units can be found in Table 5.

Table 5 ECs and Their Measurement Units

Engineering Characteristics		
Rotation speed of bearings (rpm)	Internal Steel Strength on Brake Discs (MPa)	Use of More Standard Fasteners (No. of Tools)
Battery Cells' Energy Density (Wh/kg)	Controllers (No. of controller types)	Better Wing Design (Cl/cd (lift/drag) coefficient)
Total Weight of Composite Materials (kg)	Gear Ratio (ratio between outer ring and planets)	DRS that significantly reduces drag (% of drag reduction)
Total Weight of Metallic Materials (kg)	Total Weight of the Cables (kg)	Dimensional Allowance (% deviation from designed target)
Turning Radius (m)	PCBs Connected to CAN Line (% of Connected PCBs Features)	Transparency of Specific Parts (Combinations of Parts)

The team was then required to define the performance levels of each EC, with “Good”, “Neutral” and intermediate levels similarly to what was done for the CAs to obtain the value scales. Such scales allowed to compare against the competition, returning scores for each competitor car in each EC.

3.3 The Relationship Matrix and the Roof with MACBETH

The CAs, what the customer wants from the product, were related to engineering characteristics of the design that may satisfy them. The CAs were input into M-MACBETH software as criteria nodes and each EC as an option. For each CA, the ECs had to be ordered by decreasing attractiveness (as previously done) and then pairwise judgements of difference in attractiveness were undertaken by the team for each EC. This was repeated for every CA. The resulting values were the relationship weights to be used in the HOQ.

For the roof, the same process applied. The team had to define if the correlation was negative or positive, prior to the process, once they would be compared separately as different criteria.

3.4 Benchmarking Competition

To calculate the CAs strategic weights and ECs strategic importances, a benchmark was performed. The team provided four competitor teams, that were asked to tell how they performed in each of the presented CAs and ECs. With their replies, their performances were obtained from the value scales created. The team defined targets for the CAs and ECs, following the equations 1 and 2, adapted from Coelho (2017). Where sg_i is the strategic goal of CA *i*, tg_j is the technical goal of EC *j*, $v_i(X)$ is the score of the competitor X performance with X = {FP13.19e, SE18, EcoRX 2019, Thetis}.

$$sg_i = \begin{cases} max[100, v_i(FST\ 09e)], & if\ max[v_i(X), v_i(FST\ 09e)] < 100 \\ max\ [v_i(FST\ 09e), [0{,}15 \times [v(good) - v(neutral)] + max\ \{v_i(X)\}]], & otherwise \end{cases} \quad (1)$$

$$tg_j = \begin{cases} max[100, v_j(FST\ 09e)], & if\ max[v_j(X), v_j(FST\ 09e)] < 100 \\ max\ [v_j(FST\ 09e), [0{,}15 \times [v(good) - v(neutral)] + max\ \{v_j(X)\}]], & otherwise \end{cases} \quad (2)$$

Then, sale points were calculated using equation 3 (Coelho, 2017).

$$SP_i = W_i \times [v(a) - v(b)] \quad (3)$$

Where *SP* is sale points of the *ith* CA, W is the weight of the *ith* CA, obtained with M-MACBETH software tool, *v(a)* is the score in the *ith* CA for the product *a*, with *a* being the company's own product and *v(b)* is the score in the *ith* CA for product *b*, with *b* being the best performing competitor.

The results were compared by assessing the difference between the FST 09e and the strategic goal using an Unweighted Deviation – allowing to assess the scoring difference between the FST 09e and the strategic goal for that CA (equation 4) – and a Weighted Deviation – allowing to compare to the other attributes according to their weight (equation 5) (Coelho, 2017).

$$\Delta E_i = v(A_i) - SG_i \quad (4)$$

$$\Delta E_i^* = [v(A_i) - SG_i] \times w_i \quad (5)$$

Being $v(A_i)$ the score of the FST 09e in the *ith* CA, the SO_i the strategic goal of the *ith* CA and w_i its weight, these equations tell how far from the defined strategic goal the car is. If $\Delta E_i < 0$ then it has to be improved (and the lower it is, the worst). The same applies to ΔE_i^*, but it allows comparing one CA to another.

3.5 EC Importance

The importance of the ECs will be the most relevant information to extract from the HOQ in this study, as it leads the team to select the main points of improvement according to their design strategies. To obtain such scores, it was considered the relationship between CA-EC and the difference ΔE_i^*.

The EC importance were calculated following equations 6 and 7, in an unweighted and weighted manner, as proposed by Yang and El-Haik (2003).

$$ECI_j = \sum_{i=1}^{n} R_{i,j} \times |\Delta E_i^*| \quad (6)$$

$$rECI_j = \frac{\sum_{i=1}^{n} R_{i,j} \times |\Delta E_i^*|}{\sum_{j=1}^{m} \sum_{i=1}^{n} R_{i,j} \times |\Delta E_i^*|} \times 100 \quad (7)$$

Where *n* is the number of CAs, *m* is the number of ECs, $R_{i,j}$ is the relation of the *ith* CA with the *jth* EC and $|\Delta E_i^*|$ is the weighted deviation, in module, previously calculated for the CA *i.* The *ECI* and *rECI* are shown in Table 6.

Table 6 EC Importances

Engineering Characteristic	ECI	rECI
Battery Cells' Energy Density	40.736	5.78%
Total Weight of Composite Materials	64.678	9.18%
Total Weight of Metallic Materials	50.233	7.13%
Turning Radius	53.135	7.54%
Controllers	83.941	11.92%
Gear Ratio	24.401	3.46%
Total Weight of the Cables	6.709	0.95%
Dimensional Allowance	85.214	12.10%
PCBs Connected to CAN Line	20.264	2.88%
Transparency of Specific Parts	50.240	7.13%
DRS that significantly reduces drag	7.148	1.01%
Better Wing Design	97.482	13.84%
Internal Steel Strength on Brake Discs	49.096	6.97%
Rotation Speed of Bearings	19.378	2.75%
Use of More Standard Fasteners	51.767	7.35%

3.6 Portfolio Analysis

PROBE was used to analyze efficient portfolios of scenarios of performance (SP). As most of the ECs have quantitative and continuous descriptors of performances, the possibilities offered were discretized, by creating a finite set of plausible SPs for each EC. Thus, measuring the increments from one performance level to the other without having an infinite number of combinations.

The team then was asked to create different strategies, in an expanded and modified version of the two strategies proposed by Otto and Antonsson (1991). The team defined a Conservative Strategy, a Mid-Conservative Strategy, a Mid-Aggressive Strategy and an Aggressive Strategy, defining performances for each EC in each one of them.

It would be difficult for FST Lisboa to precisely estimate the cost of every SP in monetary terms (needed for portfolio analysis, but unreliable in this case), as most of the items used are provided by sponsors that are not always clear about the value of the goods provided, and workforce is voluntary. Because of this, the effort was used as it would be a more reliable source for the “cost”. So, the cost of each scenario of performance was defined using the effort approach, similarly to what was done in Bana e Costa *et al.* (2014). Using M-MACBETH, the team defined only one criterion, the “Scenarios Effort” with all the SPs as options and compared with two reference levels (100 is extreme effort and 0 is no effort) and among themselves in terms of effort (similar to the Roof).

Using PROBE, the ECs were added as criteria and their weights were the ones coming from the HOQ. Every SP was added as a project with a benefit to the related EC and with a cost. The benefits were the SPs performances scores obtained from the value scales created and the costs were the effort. Constraints were defined in the software tool to select exactly one SP for each EC.

With the use of synergies, the roof was integrated into the analysis, using the correlation weights obtained in M-MACBETH for each pair of ECs as synergies. Knowing that the correlations were not always unidirectional, being sometimes in effort, benefit or both, each benefit and cost was recalculated to consider the correlations. To identify the differences, an option graph was created (Friend and Hickling, 2005), indicating the direction of the correlation and its scope (Figure 2 exemplifies, where the dashed lines relate to the benefit, the continuous lines relate to the effort, grey background indicates the "Neutral" and the number is the correlation weight).

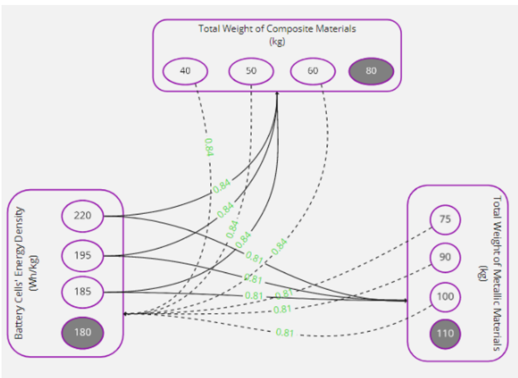

Figure 2 Correlations Between Battery Cells' Energy Density with Total Weight of Composite Materials, and Between Battery Cells' Energy Density with Total Weight of Metallic Materials

Using equations 8 and 9, the new benefit and effort were calculated for every EC.

$$NB = (1 + c) \times Bs_{kj} \qquad (8)$$

$$NE = (1 - c) \times Ef_{kj} \qquad (9)$$

Where *NB* is the New Benefit, *NE* is the New Effort, *c* is the correlation between ECs, Bs_{kj} is the benefit score of the *k*th scenario of performance for the EC *j* and Ef_{kj} is the effort of the *k*th scenario of performance for the EC *j*.

For every combination of two correlated SPs, a synergy was created in PROBE, that needed a benefit and a cost. The input into PROBE synergies had to be the difference between the new and old values. PROBE identified 138 efficient portfolios with different values of benefit and effort. They spanned from 76.46 to 1071.45 units of effort. Figure 3 shows the graph of the efficient frontier of portfolios between 76 and 106 units of effort.

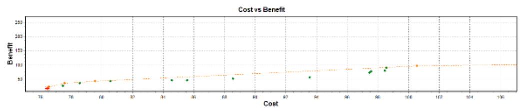

Figure 3 Efficient Frontier of Portfolios with Synergies

4 Results – Proposed Design

Having the efficient frontier of portfolios of SPs, it is possible to notice that the team is currently operating inefficiently, because four "Neutral" SPs were not selected for any efficient portfolio (and they represent the current car).

For the new design, the team said that they were willing to increase the effort by 5%, reaching an effort value of 80.283. But before selecting the affordable portfolio, the facilitator and the team analyzed portfolios with a similar effort looking at their increments in benefit/effort ratio. The portfolio with 79.57 units of effort was the most attractive because it was below the upper limit of effort and it was not worth selecting the next more expensive (in effort) portfolio, nor the previous less expensive one. Therefore, the team's selection was a convex efficient portfolio that provides 42.461 benefit units for an effort of 79.57 units. The scenarios of performance that form the selected portfolio for the FST 10e are shown in Table 7.

Table 7 The Selected Portfolio of SPs to develop in the FST 10e

Engineerig Characteristic	**Scenario of Performance**
Battery Cells' Energy Density (Wh/kg)	185
Total Weight of Composite Materials (kg)	80
Total Weight of Metallic Materials (kg)	110
Turning Radius (m)	8
Controllers (no. Of controller types)	CTRL4
Gear Ratio	On target
Total Weight of the Cables (kg)	12
Dimensional Allowance (%)	0.1
PCBs Connected to CAN Line (%)	100
Transparency of Specific Parts	ADSI
DRS that significantly reduces drag (%)	20
Better Wing Design (cl/cd)	2.8
Internal Steel Strength on Brake Discs (MPa)	200
Rotation Speed of Bearings (rpm)	5300
Use of More Standard Fasteners (no. of tools)	55

5 Conclusions

With the use of MACBETH in the House of Quality it was possible to overcome the main drawbacks of the HOQ with the use of meaningful scales in every room. The portfolio analysis is a new and unique integration to the HOQ and provided a guided and structure way to select the most efficient specifications for the car, which also included the Roof in the numerical analysis.

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