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

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Declaração

Declaro que o presente documento é um trabalho original da minha autoria e que cumpre todos os requisitos do Código de Conduta e Boas Práticas da Universidade de Lisboa.

Declaration

I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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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. Some problems with the traditional application of the HOQ are well known in the literature 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.

In recent years, the HOQ was improved with the use of quantitative methods, especially from multiple criteria decision analysis, in an attempt to solve such issues. However, the approaches used did not solve the scaling problems associated with the HOQ. This thesis applies the HOQ in the design process of a Formula Student electric vehicle integrated with the multiple criteria decision analysis tool MACBETH to overcome the drawbacks of the techniques formerly applied in the HOQ.

Additionally, besides proposing a methodology that can address the most critical shortcomings of the HOQ, the resource allocation software tool PROBE is applied to identify efficient portfolios of scenarios of performance for the ECs. The roof of the HOQ is also integrated in the quantitative analysis 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

Resumo

A Casa da Qualidade (House of Quality – HOQ) tem sido usada em diversas indústrias para capturar a voz do cliente e guiar engenheiros e decisores no processo de desenvolvimento e melhoria de produtos. Alguns problemas da HOQ são bem conhecidos na literatura na maioria relacionados com escalas de mensuração. Eles são a atribuição de pesos como indicadores diretos de importância dos atributos do cliente (Customer Attributes – CA) e sua relação com as características de engenharia (Engineering Characteristics – EC) usando escalas ordinais como se fossem cardinais.

Recentemente, a HOQ foi melhorada com o uso de métodos quantitativos, especialmente de análise multicritério, numa tentativa de resolver tais problemas. Contudo, as abordagens usadas não resolveram os problemas das escalas associadas com a HOQ. Esta dissertação aplica a HOQ no projeto de um carro elétrico de Formula Student integrada com a metodologia de análise multicritério MACBETH de modo a ultrapassar as lacunas encontradas na HOQ.

Além de propor uma metodologia que pode resolver os erros mais prementes da HOQ, também é proposto o uso da ferramenta para alocação de recursos PROBE, que permite identificar portfólios eficientes de cenários de desempenho para os ECs a serem implementados no novo veículo. O telhado da HOQ é integrado na análise quantitativa através da definição de sinergias no software de análise de portefólios. Como resultados obtém-se uma casa da qualidade que representa os juízos de valor dos clientes e da equipa de engenharia, e propõe-se um portfólio eficiente de características técnicas para o novo carro elétrico de Formula Student.

Palavras-chave: Casa da Qualidade, Função Desdobramento da Qualidade, avaliação multicritério, análise de portfólios, design de engenharia, MACBETH

Index

1 Introduction 1

1.1 Problem Context 1

1.2 Objectives 1

1.3 Thesis Organization 1

2 The Management Challenges in Formula Student 3

2.1 Introduction 3

2.2 Formula Student 3

2.3 FST Lisboa and the Car Design 4

2.3.1 The Design Phase 5

2.3.2 The Manufacturing Phase 6

2.3.3 The Testing Phase 6

2.3.4 Design Phase Implications in Manufacturing 7

2.3.5 The Decision Makers at FST Lisboa 8

2.4 Chapter Conclusions 9

3 A Review of Engineering Design Practices in the Industry 10

3.1 Introduction 10

3.2 Engineering design 10

3.3 A Review of the Quality Function Deployment 11

3.3.1 The House of Quality Applications 12

3.3.2 Walking Through the Rooms of the House of Quality 15

3.3.3 Analysing HOQ results 21

3.3.4 The HOQ Benefits and Points of Improvement 22

3.3.5 Numerical Approaches 23

3.4 Decision Support Methods 24

3.4.1 Multiple Criteria Decision Analysis 24

3.4.2 MACBETH 25

3.4.3 PROBE 26

3.5 Conclusions on Engineering Design Practices 27

4 The Application of HOQ at FST Lisboa's Design Phase 28

4.1 Introduction 28

4.2 Selecting the QFD Team 29

4.3 Integrating MACBETH into the House of Quality 29
4.3.1 MACBETH in the Customer Attributes 30
4.3.2 MACBETH in the Roof 31
4.3.3 The Relationship Matrix with MACBETH 31
4.3.4 Technical Benchmark for MACBETH Results 32
4.4 The Effort Coefficient Using MACBETH 32
4.5 Integrating the Roof in the Analysis 32
4.6 Conclusions on the Proposed HOQ Application for FST Lisboa 33
5 Implementing the HOQ 34
5.1 Introduction 34
5.2 Obtaining CAs, Their Weights and Value Scales 34
5.2.1 Obtaining Customer Attributes' Weights Using MACBETH 36
5.2.2 Implementing MACBETH in the Competitive Assessment Room 39
5.3 Translating the Voice of the Customer into Engineering Characteristics 41
5.3.1 Technical Benchmark Using MACBETH 43
5.4 The Relationship Matrix Using MACBETH 45
5.5 Correlating ECs in the Roof Using MACBETH 48
5.6 Benchmarking Competition with MACBETH 49
5.6.1 Strategic and Technical Goals 50
5.6.2 Sale Points 53
5.6.3 Deviations 54
5.7 The Importance of the Engineering Characteristics 55
5.8 Welcome Home – Chapter Conclusions 56
6 One Step Further – The Efficient Selection of ECs 58
6.1 Introduction 58
6.2 Defining Portfolio Options 58
6.3 The Effort of the Scenarios of Performance 60
6.4 Defining PROBE Projects 61
6.5 Defining Constraints 63
6.6 The Efficient Frontier of SPs Portfolios 63
6.7 Creating Synergies Between ECs 66

6.8 The Efficient Frontier of Portfolios with Synergies 69
7 Results Analysis of the New Car (FST 10e) 70
7.1 Introduction 70
7.2 Looking at the House of Quality 70
7.3 The Suggested Portfolio of ECs for the FST 10e 71
8 Conclusions, Limitations and Future Study 74
8.1 Conclusions 74
8.2 Limitations 76
8.3 Future Study 76
References 77
Appendix A 82
Appendix B 84
Appendix C 85
Appendix D 86
Appendix E 87
Appendix F 88
Appendix G 89

List of Figures

Figure 1 Formula Student Germany 2019. Source: Photo by Formula Student Germany 3

Figure 2 The FST 09e during Endurance at Formula Student Germany 2019. Source: Photo by Formula Student Germany 5

Figure 3. Formula Student car development phases 5

Figure 4 FST Lisboa Leadership Hierarchy..................... 8

Figure 5 Impact vs Cost by product development stage. Adapted from Yang et al. (2003) 10

Figure 6 Phases and tools for engineering design process 11

Figure 7 The four QFD houses adapted from Hauser and Clausing (1988) 12

Figure 8 The House of Quality Rooms 16

Figure 9 FST 10e requirements proposed by the team 35

Figure 10 CAs M-MACBETH weighting matrix..................... 38

Figure 11 CA weights histogram 38

Figure 12 "Good Turning Abilities" judgements matrix and value scale..................... 40

Figure 13 The FST 10e causal map of requirements..................... 42

Figure 14 HOQ Relationship Matrix 47

Figure 15 The Roof..................... 49

Figure 16 UPC EcoRacing's EcoRX 2019. Photo by UPC EcoRacing 50

Figure 17 Aristurtle's Thetis. Photo by Aristurtle 50

Figure 18 WHZ Racing Team's FP13.19e. Photo by WHZ Racing Team 50

Figure 19 Superior Engineering's SE18. Photo by Formula Student Germany 50

Figure 20 Competitors' Scores for CAs..................... 50

Figure 21 Performance Options for Each EC..................... 59

Figure 22 Scenarios of Performance Efforts - Extract 1..................... 61

Figure 23 Scenarios of Performance Efforts - Extract 2..................... 61

Figure 24 PROBE's Benefit Value Tree 62

Figure 25 M-MACBETH Table of Performances for Each Strategy 62

Figure 26 M-MACBETH Table of Scores for Each Scenario of Performance 62

Figure 27 Battery Cells' Energy Density (Energy) Scenarios of Performance Scores in PROBE 63

Figure 28 Battery Cells' Energy Density (Energy) Scenarios of Performance Costs 63

Figure 29 Group Constraint Example - Battery Cells' Energy Density (Energy) 63

Figure 30 PROBE Efficient Frontier of Possible Portfolios 64

Figure 31 Suggested portfolios within possible boundaries of effort of the team 64

Figure 32 Correlations Between Battery Cells' Energy Density with Total Weight of Composite Materials, and Between Battery Cells' Energy Density with Total Weight of Metallic Materials 66

Figure 33 Costs of the First Three Possible Combinations of Energy and Composites 69

Figure 34 New Benefits of the First Three Combinations of SP for Energy and Composites 69

Figure 35 Efficient Frontier of Portfolios with Synergies 69

Figure 36 List of Similar Portfolios and Their Values 72

Figure 37 Full HOQ with FST 10e in the Technical Benchmark 73

List of Tables

Table 1 Fields of applications of HOQ 12

Table 2 Customer attributes hierarchy 36

Table 3 CAs and Descriptors of Performance 36

Table 4 "Neutral" and "Good" Levels of CAs 37

Table 5 Quantitative CAs and the performance levels used to create value functions 39

Table 6 Mechanical Accessibility performance levels used to create value function 39

Table 7 Access to Information performance levels used to create value function 40

Table 8 Engineering Characteristics and measurement units 42

Table 9 Transparency of Specific Parts Performance Levels 44

Table 10 Controllers Descriptor of Performance 44

Table 11 Gear Ratio Descriptor of Performance 45

Table 12 Quantitative ECs Performance Levels needed for creating the value functions 45

Table 13 Scores and Strategic Goals 51

Table 14 EC Scores, Benchmark and Technical Goals 52

Table 15 Sale Points of the FST 09e in each CA 54

Table 16 CA Deviations 55

Table 17 EC Importance and Weighted Importance 55

Table 18 Trade-off Strategies 59

Table 19 Efficient Portfolios of SPs Without Synergies (each row corresponds to a portfolio) 65

Table 20 New Benefit and New Effort for the Correlation Battery Cells' Energy Density (Energy) with Total Weight of Composite Materials (Composites) 68

Table 21 The Selected Portfolio of SPs for the FST 10e 72

List of Abbreviations

AHP – Analytical Hierarchical Process

CA – Customer Attribute

CAD – Computer-Aided Design

DM – Decision Maker

DRS – Drag Reduction System

DSS – Decision Support System

EC – Engineering Characteristics

FMEA – Failure Mode and Effect Analysis

FS – Formula Student

HOQ – House of Quality

IDCR – Interactive Design Characteristic Ranking

IST – Instituto Superior Técnico

MACBETH – Measuring Attractiveness by a Category-based Evaluation Technique

MCDA – Multiple Criteria Decision Analysis

OCRA – Operational Competitive Rating

PCP – Production Control Plan

PROBE – Portfolio Robustness Evaluation

QFD – Quality Function Deployment

RDMA – Reduced Design, Manufacturing and Assembly

SAE – Society of Automotive Engineers

SP – Scenario of Performance

TOPSIS – Technique for Order Preference by Similarity to Ideal Solution

TRIZ – Teoriya Resheniya Izobretatelskikh Zadatch (Theory of Inventive Problem-Solving)

VoC – Voice of the Customer

1 Introduction

1.1 Problem Context

FST Lisboa is the Formula Student team of Instituto Superior Técnico (IST). It exists since 2001 and 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.

Since its foundation, the team's management practices have improved and have become more professional as has the entire Formula Student environment. However, there are some weak points that remain 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.

Most of the noticed problems that occur in later stages of development are originated in the beginning, during the design phase. Poor planning, inefficient meetings, lack of communication between departments and unclear goals lead to delays in manufacturing, in research and development, and in a reduced number of testing hours.

The awareness of those issues and the knowledge of some of the industry's practices that were developed long ago to solve exactly this type of issue motivated the topic of this project.

1.2 Objectives

In a year where the team has been through a significant renovation, with more than 80% of the 2018/19 season team members leaving FST Lisboa, it was the perfect moment for the implementation of new practices in the project management and to set objectives. From those who stayed, most took over managerial positions coming from technical roles reinforcing the need for guidance.

The main objectives of the work are:

1. Help the team improve its decision-making process in an attempt to solve recurrent issues that affect the performance of the car;
2. Apply adequate value measurement techniques together with the House of Quality, to avoid common mistakes found in the application of this technique;
3. Propose the use of a resource allocation methodology to help the team to select an adequate portfolio of specifications for the car;
4. Propose a design for the FST 10e, which is the car that was being developed by the team during this work.

It is also expected to provide the team with tools and methodologies to make the decision-making process clearer and more efficient.

1.3 Thesis Organization

The remaining part of this document is divided into seven chapters.

Chapter 2 expands on the topic of the problem, contextualizing FST Lisboa and its history, what is Formula Student, what are the main problems in the team, how the team is structured and how its workflow is.

Chapter 3 takes on the observations made in the previous one, doing a literature review on the engineering design practices and the most important tools that could be useful for the team to use. The main topic is a review on the House of Quality (HOQ) of the Quality Function Deployment (QFD) methodology, going through its history, how it is built, where it has been being used and in what industries, pointing out what the main issues associated with the tool are, as well as the main strengths and how advanced models have improved it.

Chapter 4 describes the methodology to be applied in the study.

Chapter 5 describes a step-by-step application of the selected methodology. It starts identifying the team's objectives, adjusting them to the House of Quality application, and how to obtain the technical specifications to be used. Then, the MACBETH methodology is applied, and the House of Quality is filled.

Chapter 6 proposes the application of PROBE as the resource allocation tool, integrating the technical correlation matrix of the House of Quality to the quantitative analysis. A set of efficient portfolios of technical specifications is then obtained.

Chapter 7 analyzes the results obtained, and Chapter 8 presents the conclusions, limitations and some suggestions for future work.

2 The Management Challenges in Formula Student

2.1 Introduction

In this chapter a brief explanation of the history of Formula Student will be presented in section 2.2 as well as its challenges. Then, in section 2.3 FST Lisboa's history will be briefly explained with special focus on the challenges that arose over the years and with the transition to the development of a car in a single academic year. The team's structure, workflows and the three different development phases of a car will be explained, with section 2.4 presenting conclusions of the main problems that can be addressed.

2.2 Formula Student

Formula Student (FS) is a global competition that was created in the early 1980s in the United States under the name of Formula SAE (Society of Automotive Engineers). It is aimed towards university students from different engineering courses that want to apply their theoretical knowledge into the real world while at their academic lives.

Its main objective consists in making a formula race car to compete at different competitions worldwide against other teams from different universities and countries. Team members are encouraged to design and manufacture as much as possible of the car by themselves, enabling them to apply skills and acquire new ones in the process.

From its beginning to current age, FS has grown rapidly and has now presence in every continent and has become the largest competition for students in the world, mobilizing around 2500 people per event (Figure 1 illustrates the event dimension). There are over 700 teams able to participate in such events across the globe, divided into three categories: Internal Combustion; Electric; and recently added, Driverless. Each university can have more than one team and participate in more than one category.

Figure 1 Formula Student Germany 2019. Source: Photo by Formula Student Germany

Each competition is split into static and dynamic events. Most of all, this is an engineering competition, and besides presenting a car and racing with it, the yet-to-be engineers must address judges in three static events: Engineering Design Event; Cost and Manufacturing Event; and Business Plan Presentation. In these three the team's knowledge and design considerations are evaluated, being requested to understand concepts like prototyping and mass production, the process of starting a business with an economically viable idea, and even management practices during design and construction phases. When it is time to get the wheels rolling in the dynamic events, all the hard work of the year, or years, are put to the test in Acceleration, Skidpad, Autocross and Endurance and Efficiency. Besides being called a competition, this is a learning opportunity for everyone. Unlike professional motorsport, there are no secrets among competing teams and boxes are free for people to walk around and learn with fellow students and their cars.

The teams are managed and organized without any external support from professors or entities, being restricted to advise. This means that members must design, build and test a car, prepare for the events and at the same time manage finances, human resources and logistics. It resembles a normal company, varying in its professionalism level from team to team. The number of team members ranges from less than 10 to over 100, from diverse degrees such as Mechanical, Electrical, Aerospace, Industrial, Computer, Naval, Civil Engineering and others.

Some of the members are taken outside of the engineering practices to assume managing positions, assuring that an actual vehicle appears and that its development is efficient. This is specifically important when working with budgets rounding hundreds of thousand euros and large groups of people. These are challenging tasks, which to be successful require: resources (financial support from the university and sponsors); and good management practices.

2.3 FST Lisboa and the Car Design

Instituto Superior Técnico has a long-lasting team that has been evolving year over year and has reached a high level that allows it to think in bigger leaps in the near future. FST Lisboa, short for Formula Student Técnico Lisboa, exists since 2001 and has changed name twice since then. Seven students from the Mechanical Engineering course decided to join the recently arrived European version of the Formula SAE. Their endeavor lasted four years from design to racing, originating the FST 01.

Since that time the team has grown, now having eight cars in its portfolio, five being electric, and counting with 40 team members in the 2019/20 season. From the FST 01 to the FST 09e (shown in Figure 2), 18 years have passed, and technology evolved, as well as the processes and management capabilities of the team.

Such expertise allowed to take a step forward to join the top teams in FS, which was the creation of a new car every year. Previously, the vehicles were made in two years, being one devoted to design and the other to manufacturing. The FST 08e was the first car to be completed in a single academic year (September 2017 to July 2018). This was only possible due to the design phase minimization.

Indubitably this was the way to go, but it forced the team to work around inefficiencies in the entire development throughout the year, and in some cases, worsening or highlighting issues that were before attenuated by the longer period for construction.

Figure 2 The FST 09e during Endurance at Formula Student Germany 2019. Source: Photo by Formula Student Germany

Instances of this occurrences are the critical delays to car completion due to manufacturing undertaken at sponsoring companies and mistakenly chosen parts that needed to be later replaced. The first example is common in a one-year project, but it has a root cause in the design phase. The latter was an actual happening, where the whole set of bearings had to be reordered after a change in design still when cars were made over two years.

In order to make a vehicle in 10 months (from September to June) the first measure was to reutilize and improve the previous design to save time. However, critical errors or decisions in the design phase were not mitigated, simply avoided by playing it safe and limiting innovation. Being innovation one of the mottos of Formula Student, it is only an option to limit it for transition years and must not be neglected in a team with high aspirations and resources. Figure 3 shows the three phases of a FS car construction.

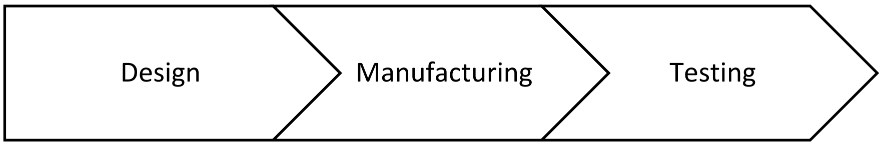


Figure 3. Formula Student car development phases

2.3.1 The Design Phase

The design phase officially starts in September, at the beginning of the new academic year. However, work has already begun during the summer with early conceptualization and scratches of ideas based on other teams' cars. It is in this phase that design trade-offs are considered for the entire year.

During this phase, several considerations are made, such as the behavior of the car and its systems in the previous season, integration issues (interferences, tolerances, available parts in the market, etc.), time and resources constraints and team objectives. Heads of the different departments discuss overall design objectives and then bring to their own departments such considerations for further development of ideas and solutions.

As time progresses and deadlines come closer, the team needs to pick up pace and several sprints are undertaken. They range from requirements sprints to computer-aided design (CAD) sprints. During these sessions, the entire team and all departments are in one room for two or more days working on the design. Such approach is done to solve inter-department communication issues and to facilitate decision-making taking advantage of the physical presence of every member in one place.

It can be challenging to conciliate the different “design freezes”, starting date from which no design change should be made to start review and production, for different departments. Less critical subassemblies of the car have the design process taken further through the year, while more critical ones have it pulled back in the timeline. The challenge lies in changes that may affect other subassemblies, for example, if a suspension A-Arm support needs to be changed after the chassis design is “frozen” or under production. This could lead to a more expensive solution or one that can dramatically affect the overall performance of the car due to interferences or weight addition.

2.3.2 The Manufacturing Phase

After a department’s design is “frozen”, reviewed and approved, the parts are compiled alongside with their requirements for material, production method, workforce and deadlines for each one. This process usually takes less than a week in November, possibly October for critical subassemblies or January for less critical ones.

The compilation of such parts generates a list of items that are then distributed to sponsoring companies when they need to be manufactured outside the university. For simpler or composite parts, this process occurs between January and March, possibly extending to April and May, where students themselves put their hands to work. As the parts, components and materials arrive from sponsors and production, they begin to be assembled in the car. If everything arrives on time, the process takes no more than a month, usually between May and June. Depending on delays the assembly can start in March but only be completed by the end of June.

2.3.3 The Testing Phase

After the car is assembled and has the minimum requirements to start running by its own means, the tests begin. This phase is the least predictable in terms of time, as it lasts from the moment the car runs for the first time until a few days before the first competition.

During this period the car is put to run gradually, as many parts are not fully functional, to test its systems, integration, parameters and performance. As it gets all its systems fully integrated and functional, optimization for performance start to be undertaken as well as training drivers for the different events.

The teams with better performance in a season normally get over 500 km of testing before the first competition, which can be translated to a little over an entire month of preparation. However, some even break the mark of 1000 km.

2.3.4 Design Phase Implications in Manufacturing

By being dependent on sponsorship to manufacture complex metal parts, delays in the car design would often lead to delays in manufacturing. It is not known the exact multiplier due to the lack of data, but a small delay in obtaining a final version of a car component can lead to a bigger delay in its manufacturing. This is because the sponsored parts are manufactured according to the availability of the sponsor company to fit the team's parts. If the manufacturer had a "time window" in its production line in a certain week, and the design is delayed in this same week, it would take an undetermined time to have a new opportunity to manufacture that part again. This illustrates how important focusing efforts is when trying to find the best solution for the new vehicle, concentrating resources in what will indeed have an impact and do it in a shorter time.

Some cases may require ongoing tests and validation through the design and even manufacturing phases of the project to reach a conclusion, that may not be positive. As the first iterations arise, new discussions are brought to the table to consider if it is worth or not investing time developing them or if they have unforeseen implications. This last step may be frustrating since some work might be scrapped out and more time needs to be invested in other solutions. The process continues and if the ongoing validation of some engineering concepts shows themselves as unworthy or not cost-beneficial, the time that has been spent may have severe implications later.

The key success factors in Formula Student are the testing time span, the car reliability and the transition of knowledge from one team to the next. All three of them have some relation to the design phase. Some are more direct while others have some indirect impact.

The testing time span is the most indirectly correlated with the design phase, with it being the number of weeks between the moment the car is first considered "ready to race" and the rehearsal of the first competition's travel day. As previously explained, small delays during the design can lead to greater delays in manufacturing. Consequently, delays in the second phase (manufacturing) lead to a delay in the car completion date, reducing the number of testing weeks and thus creating a snowball of delays and shortage of time to properly test the car before the first competition.

This is also related to the reliability factor, meaning that if the car is not reliable enough it does not run enough, and testing is not done in exchange for repairing hours. Reliability can also be assured during the first phase (design) and spending too much time for this purpose may originate delays that could be mitigated by speeding up manufacturing. However, this approach can be dangerous, once poorly machined parts might break or damage, affecting reliability. It is a vicious cycle that is difficult to interrupt.

The transfer of knowledge from one year to another plays a major role in the overall quality and evolutions of a car since the average life expectancy as a FS team member is of around two years. The high turnover makes it hard to evolve, becoming an important task to ensure that the knowledge stays institutionalized and does not go away when team members leave. Design documentation, besides helping with the process itself, is crucial to assure the transition and allow the next generation of members to learn from previous mistakes and improve upon them. By allowing this information to be used in the next prototypes, there is a higher chance that the new generations will suffer less from the common issues, decreasing the time it takes to build a new car.

The design phase, as seen, has several implications to the overall outcome of a Formula Student car in a season. However, it is just one of the many variables that are present in this process. If it is carefully analyzed, some of the common mistakes can be avoided and targets can be set, enabling an improvement in the results. The source of those mistakes lies mostly in the inexperience of the decision-makers.

2.3.5 The Decision Makers at FST Lisboa

As already explained section 2.2, the members of a FS team are university students that have the job to not only build the car but to manage the team and the project. For most of them, managing positions are a new experience and it is expected that difficulties come from this. It is important, then, to have very clear leadership in the team that will decide upon the design concepts of the car as well as everyday matters. This hierarchy for FST Lisboa is shown in Figure 4.

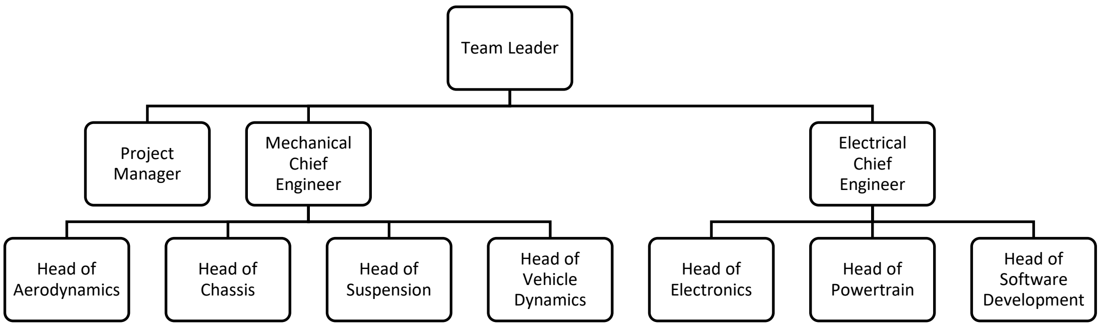


Figure 4 FST Lisboa Leadership Hierarchy

The decision-making process within the team occurs in two different ways, depending on the matter to be discussed: meetings between the Team Leader, the Project Manager and both Chief Engineers; and meetings of all the Heads of Departments with the three previously mentioned.

During the design and conceptualization of the new prototype, the entire leadership is involved and bring to the table for discussion the ideas each department has. They discuss if the suggested changes match the team’s goals for the season and how they interact with the remaining of the car, analyzing possible implication in time and budget as well as in the needed workforce.

With the lack of a structured overview, such meetings can take up to four hours and sometimes be unproductive and tiring. The lack of experience in management and knowledge of successfully applied methods in the industry are some of the causes for the long hours, but as will be presented, there are methods to give this overview.

2.4 Chapter Conclusions

Up to this point, the different processes of making a Formula Student car have been presented, as well as some of the associated issues with each one of them. The main problems identified are:

- Problems with communication between different departments in the design and manufacturing phases;
- Lack of proper, complete, structured and standardized documentation of the design process, either from past years (what would help improve current design timings) and of the current year (what would help next generations design and manufacturing as well as inter-communication);
- Lack of a structured decision-making process, heavily relying on subjective analysis of possible outcomes during long and inefficient meetings of the head of departments;
- Lack of full consideration of all possible outcomes, leading to a change in design or parts selection in late stages of design, manufacturing and even testing phases;
- Lack of a formal structured overview document of the entire process status and implications of one design solution into another department;
- Lack of transparency in decision-making, seldom inviting other team members to discuss certain issues;
- Difficulty integrating different departments knowledge base and workflow for the development of a common sub-assembly (the battery serves as an example, where at least three different departments have a say on its final design and integration);
- Besides knowing overall target specifications needed to be changed from the performance analysis of the past season, there is no formal definition of how much time and effort should be directed to each one of them.

Those problems make most of the everyday life of a Formula Student team, and therefore causing inefficiencies that if corrected, could lead to a higher level of performance on the track as well off it. Being at a top engineering institution, technical knowledge is not the weakness of FST Lisboa, but the presented list enlightens where they really are: management practices for engineering design.

3 A Review of Engineering Design Practices in the Industry

3.1 Introduction

This chapter is divided into four following sections. Section 3.2 explains briefly what the main concepts of engineering design and its implications on the later stages of development of a product are. Section 3.3 introduces the Quality Function Deployment (QFD), and reviews in depth the House of Quality (HOQ), its applications in the industry as a design tool, how it works, what are the common mistakes practitioners make when using it and numerical approaches that are commonly integrated with the HOQ. Section 3.4 presents two new decision support methods that can be used integrated with the HOQ. Section 3.5 concludes about the engineering practices and the integrated methods.

3.2 Engineering design

Engineering design is an activity that puts together both what it is wanted to be created as well as how it can be done, normally selecting from a set of alternatives. It questions whether the process or product can be improved with no consensus over what the best practices are. It is known that the human factor is extremely important in any design context and that the process of choice depends on that same context of application (Reich, 2010). It is also an iterative process for the solution, which is generated as the understanding of the problem evolves, that requires engineers to make trade-off decisions on multiple variables (Clarkson and Eckert, 2005).

Within this process, designers must be very resilient on their approach, because it is affected by different aspects such as the origin of the task, the organization they are in, the novelty of the problem, if it is adaptive or a variant design, the batch size of the order, the branch of engineering it relates to and the goals of the project (Pahl *et al.*, 2007).

With all these variables associated with engineering design, it does not surprise the fact that this is the most important stage in the development lifecycle of a new product. Figure 5 precisely illustrates this importance, with the design being the most impactful stage and at the same time less costly to make changes.

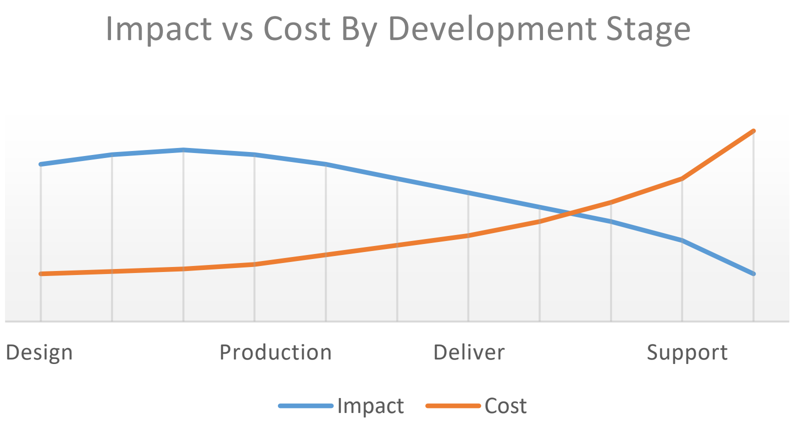


Figure 5 Impact vs Cost by product development stage. Adapted from Yang *et al.* (2003)

With that in mind, this study will focus on the design phase, that is divided according to Yang *et al.*, (2003) into four phases, as shown in Figure 6.

The Identify phase is where the gathering of requirements from the customers occurs, while in Characterize they are translated into engineering solutions to fulfill the desires of the potential users of the product. Optimize and Verify focus on improving the obtained solutions and planning of the production process. This chapter will cover some of the tools used in Identify and Characterize phases as they are the early stages of development.

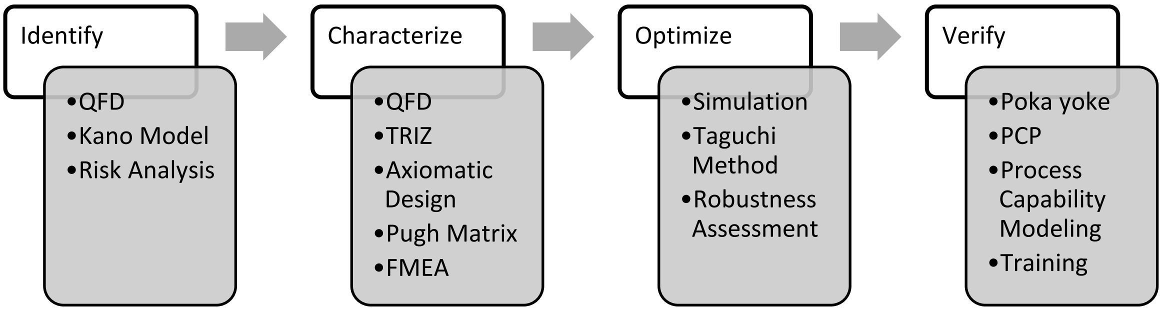


Figure 6 Phases and tools for engineering design process

3.3 A Review of the Quality Function Deployment

Quality Function Deployment (QFD) was firstly introduced in 1966 in Japan in a time the world was emerging from World War II, and quality control has been increasing to be an important part of businesses. It was made to be an addition to Total Quality Control, as a more a structured methodology that uses management and planning tools to design new processes and products aiming quality. It evolved at Mitsubishi's Kobe shipyard site, where the quality chart was made public for the first time, and six years later it got its current look. It was later improved by Toyota Auto Body and its suppliers to meet the requirements of the auto industry (Akao and Mazur, 2003).

The QFD has four subdivisions, or steps, that are represented by charts that resemble houses. The first step is the House of Quality (HOQ), which sets plans to manufacture and then to market products and services, making people join forces and discuss the different problems since the early stages of design and conception (Hauser and Clausing, 1988). To achieve such goal, the HOQ takes into account the attributes given by the customers that must be a part of that product, or simply Customer Attributes (CA), and translates them to Engineering Characteristics (EC), the engineering language for those attributes. For the ECs, a QFD team is assigned, that must be as diverse as possible, including marketing, technical and other relevant departments to have different perspectives on the design and its influences on the final result (Hauser and Clausing, 1988). The following houses take on the results of the previous one iteratively, advancing through the development lifecycle of the product. The second house, called Parts Deployment, takes the engineering characteristics of the House of Quality and uses them as requirements to be expanded into part-specific engineering characteristics. This process is repeated for

Process Planning and Production Planning, as Figure 7 shows with the upper part becoming "Customer Attributes" of the next House. The following subdivisions of this chapter will go through each part of the HOQ.

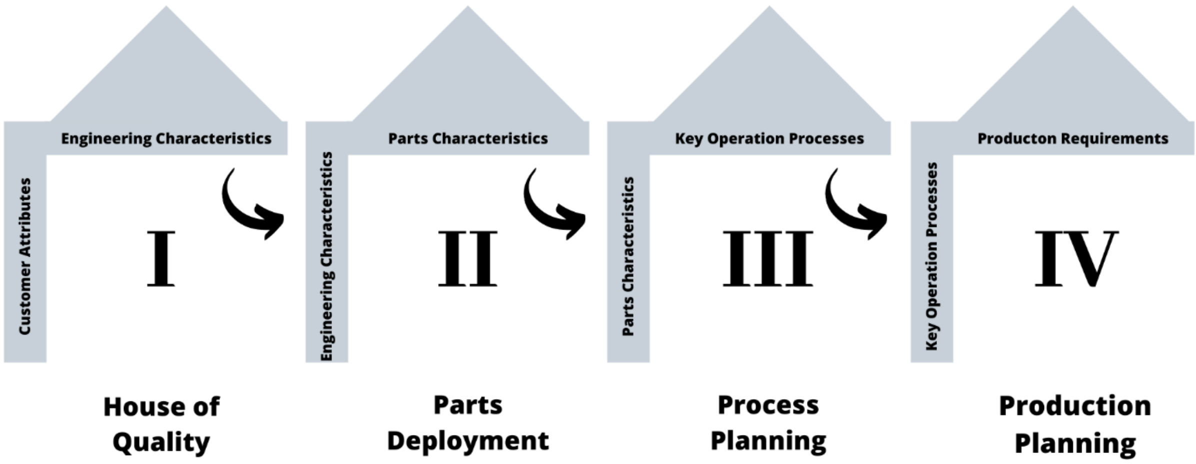


Figure 7 The four QFD houses adapted from Hauser and Clausing (1988)

3.3.1 The House of Quality Applications

It started in a shipyard in 1966, was taken to the automotive industry soon after and in recent years have been introduced in many different fields. Its introduction to the West began in 1983 (Akao, 1997), and in 1993 Hauser wrote an article about the implementation of HOQ in a medical equipment manufacturer and by that time many other industries were already using the approach, in the 2000s it entered education (Bier and Cornesky, 2001) and as a technology and software development arises in our society it started to be proposed to be used in application development Chen *et al.* (2017) and even fashion industry (Kiill Santos, Paulo de Souza and José Borges, 2019). According to the reviewed literature, it is used as a design and quality improvement tool in the fields shown in Table 1.

Table 1 Fields of applications of HOQ

Field of Application	Author	Description
Technology Selection	Ramírez, Cisternas and Kraslawski (2017)	Selection of water pretreatment technology
	Yang *et al.* (2015)	Evaluates the best coal pyrolysis polygeneration technologies using HOQ
	Bhattacharya, Sarkar and Mukherjee (2005)	Uses HOQ for selecting robots

(continues)

Table 1 Fields of application of the HOQ (continued)

Field of Application	**Author**	**Description**
Technology Selection	Kusumawardani *et al.* (2019)	Uses the HOQ to select a knowledge management system for private banking
Logistics	Rajesh and Malliga (2013)	Selection of suppliers
	Ho *et al.* (2012)	Selection of third-party service providers
	Sharma and Singhi (2018)	Uses HOQ to assess management expectations on Vendor Managed Inventory in a healthcare supply chain
Automotive	Arora, Kapoor and Shen (2018)	Design improvement in battery packs for electric vehicles
	Kang *et al.* (2018)	Applies HOQ in the development of minicars to validate the proposed integration of methods
Construction	Malakouti *et al.* (2019)	Uses HOQ to identify key characteristics of housing quality and flexibility components
	Ismail *et al.* (2017)	HOQ applied to designing a platform for boiler inspection
	Adinyira, Kwofie and Quarcoo (2018)	Applies the HOQ to determine the requirements in building energy-efficient mass housing
Food industry	Sularto, Wardoyo and Yunitasari (2015)	User requirement analysis for a restaurant
	Park, Ham and Lee (2012)	Improving promotion of Korean beef barbecue abroad
Furniture	Homkhiew, Ratanawilai and Pochana (2012)	Design of new furniture using HOQ

(continues)

Table 1 Fields of application of the HOQ (continued)

Field of Application	**Author**	**Description**
Healthcare	Fernandes Volpato *et al.* (2010)	Improving quality in Family Health Units using HOQ for patients' requirements
	Wood *et al.* (2016)	Use of HOQ for green design to plan a Hospital construction meeting patient demands
Services	Bajčetić *et al.* (2018)	Identifies key requirements of public transport users using HOQ to improve the service's quality
	Cudney, Elrod and Uppalanchi (2012)	Society members requirements analysis to improve membership benefits
	Kamvysi *et al.* (2014)	Academic course design according to students' requirements
Software	Chen *et al.* (2017)	Manufacturing apps with HOQ
Fashion Industry	Kiill Santos, Paulo de Souza and José Borges (2019)	Application of HOQ for the development of new clothing material
Energy Industry	Tang and Dincer (2019)	Selection of energy investment policies for emerging markets using HOQ with Fuzzy Sets

However, besides being currently mostly used in the design of products, it is also applied to select among options as a decision-making tool. The possibility of correlating needs to engineering characteristics allows for a varied set of applications. As an assessment tool, HOQ has been used mostly in technology selection (Ramírez, Cisternas and Kraslawski, 2017; Yang *et al.*, 2015) and in logistics. In the latter, it ranges from selecting suppliers (Rajesh and Malliga, 2013) to choose from a set of possible third-party service providers (Ho *et al.*, 2012).

In the case of technology assessment, Ramírez, Cisternas and Kraslawski (2017) use HOQ to select a water pretreatment technology and explains that the input to be considered as CAs were characteristics prominently cited as important in the relevant literature, once there was no customer to be surveyed.

On the other hand, the approach used by Ho *et al.* (2012) and Rajesh and Malliga (2013) for selecting a third-party service provider takes into consideration the requirements of the hiring company as CAs. The latter uses ECs from the relevant literature, differently from what Ramírez, Cisternas and Kraslawski (2017) have done, while the former sets ECs given by the customer. The result allowed an overview of the performance of each of the possible providers in each pair of CA-EC and then a direct comparison among themselves in the overall score. In their approach, however, some of the ECs are not assessed with measurable units and others that could be, are not either. This goes against the main principles of QFD, especially when regarding the setting of targets for the ECs, influencing directly the overall scores, which will later be presented.

Though, according to Erdil and Arani (2018), QFD is still extensively used in new product design while only a fraction of companies use its potential for product quality improvement without necessarily developing a new one. For this purpose, it is suggested the use of complaints and suggested points of improvements from customers to serve as the CAs in the HOQ.

These examples show how the QFD and HOQ methodology can be both easily adapted and incorrectly used. The flexibility for selecting sources for CAs and ECs is useful for exploring different approaches and applications.

3.3.2 Walking Through the Rooms of the House of Quality

The QFD starts with a product planning step, 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, provided by the QFD team. When joined together, all these links allow a comparison of the product against its benchmarks in the perspective of the customers and of the engineers. The former compares to the different competitor products regarding the CAs, while the latter compares to the ECs and gives an overall technical score. 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 QFD team. Figure 8 shows each of those rooms of the HOQ.

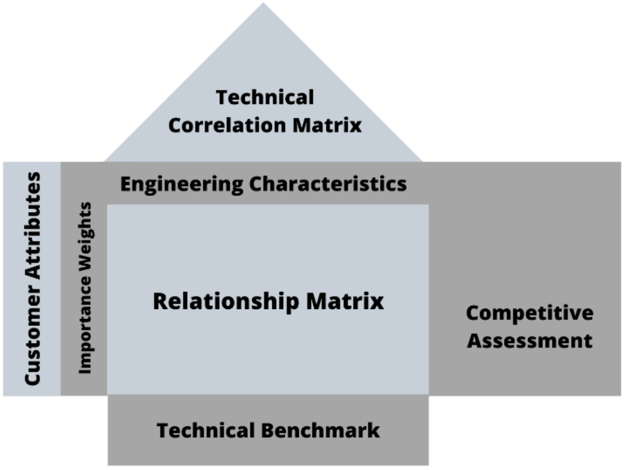


Figure 8 The House of Quality Rooms

3.3.2.1 The Customer Attributes Room

This is the most important part of the HOQ and also known as the voice of the customer (VoC), once from this section all the main points to be addressed will be used and generate the remaining steps of QFD. The customers will provide the aspects they think the product must have, customer attributes, and rate them according to their perception of importance.

This is achieved with interviews, focus groups, surveys, feedbacks and other common ways in marketing to obtain information. According to Griffin and Hauser (1991), customers identify between 200 – 400 customer needs that will later become CAs.

Hauser and Clausing (1988) suggest the schematization in a hierarchical way going further in the specificity of the CAs in three levels. The primary level is where the strategic CAs are, that will be used to set the overall objective of the QFD team. Then, these CAs need to be further analyzed and customers are required to clarify some of the terms they use to give origin to the secondary level, that describes how they see the results of the primary CAs. The tertiary level is detailed descriptions of how the customer perceives the secondary levels, giving engineers a path to follow and identify possible solutions to satisfy the secondary needs.

After the identification of all the CAs, the following step is to ask the interviewees to set their absolute importance of each CA. When created, this part used ordinal scales for simplicity, that can be of 1 to 3, 1 to 5, 1 to 9, or even 1 to 10 points. Although it is known that ordinal scales do not give weights, and they cannot be assigned as direct importance. They should be defined as a proportion of how much of one criterion is worth how much of the other criterion (Keeney, 1992), or in other words, a ratio scale. There are methods that will later be discussed that can solve this problem.

Another method to gather information on CAs and obtain their weights is the integration of Kano's model into the HOQ. It assesses their satisfaction in the case determined CA is implemented in the product and the dissatisfaction in case it is not. The CAs are then labeled according to Kano's categories and have their impact on satisfaction and dissatisfaction added as CA weights in the HOQ (Matzler and Hinterhuber, 1998; Sireli, Kauffmann and Ozan, 2007; Tan and Shen, 2000). Those categories were originally divided into three (Matzler and Hinterhuber, 1998), but additional divisions that some authors have b een using in the literature complement and improve the analysis of customer needs. They are:

- Must-be attributes (M): these are basic functions of the product. They are assumed to be in the product, and if they are not, dissatisfaction increases. Increasing such characteristics does not increase satisfaction significantly.
- One-dimensional attributes (O): these are directly related to the satisfaction of the customers. The higher the fulfillment, the higher the satisfaction. On the other hand, if they are not present, dissatisfaction increases.
- Attractive attributes (A): customers do not expect their fulfillment, but if they exist, they greatly increase satisfaction. There is no dissatisfaction in case they are not accomplished.
- Indifferent attributes (I): customers are indifferent to their fulfillment, either for satisfaction or dissatisfaction.
- Reverse attributes (R): as the name says, they have the opposite effect. If they are met, customers get dissatisfied, but if they are not fulfilled, customers get satisfied.
- Questionable attributes (Q): these are attributes to which the survey was incorrectly answered or written, or if the given reply did not make sense to the topic.

It is indeed a helpful tool to use with the HOQ for structuring data collection and as van de Poel (2007) says, it can be used to overcome two major issues in the HOQ he points out: customer demands cannot always be represented by linear additive value function, and the inconsistency in aggregating individual demands into a collective demand. However, it lacks more in-depth research on quantitative applications to the HOQ (Ji *et al.*, 2014; Poel, van de, 2007; Sireli, Kauffmann and Ozan, 2007).

3.3.2.2 The Competitive Assessment Room

This room of the HOQ represents the perspective customers have of different competitors' products, based on actual experiences and comparison on each CA. This provides a benchmark with competitors on each attribute the customer believes is important. To obtain such input, the customers are required to rate each competitor for each attribute.

Based on those ratings, it is also possible to set strategic goals for each CA, that is, what values the company's product should be getting after the new design. This is important to define because it gives an objective for that specific attribute and a focus for the QFD team.

It is in this step that sales points are assigned. According to Chan and Wu (2002) sale points provide information about how well the company can meet a customer need or the possibility of being in an advantageous selling position in this CA. They are usually 1, 1.25 or 1.5 for no sale point, moderate sale point and strong sale point respectively.

With this information, the QFD team is then able to calculate the absolute strategic weight of that CA for the design according to equation 1:

$$AW = (SG - CP) \times RW \times SP, \qquad (1)$$

where:

AW – absolute strategic weight of the CA;

SG – The intended rating by the QFD team for that CA after new design, or the Strategic Goal;

CP – The actual rating given by the customer for that CA, or the Current Points;

RW – The relative weight of the CA;

SP – The sale point assigned for that CA.

The overall result originates values to be analyzed by the QFD team when defining efforts for the design, where higher values mean that there is room for improvements (far from the intended objective), while small values represent a good market positioning for that CA (Chan and Wu, 2005). However, for better representation and to avoid large values, a weighted average of the calculated final importance is performed to give a strategic relative weight for the CA, as demonstrated below in equation 2:

$$w_i = \frac{AW_i}{\sum_{i=1}^{n} AW_i} \qquad (2)$$

where:

w_i – Strategic relative weight of CA *i;*

AW_i – absolute strategic weight of CA *i;*

n – number of CAs.

3.3.2.3 The Engineering Characteristics Room

After the voice of the customer is concluded, the QFD team comes into the scene with the responsibility of translating the CAs into Engineering Characteristics (EC) in more technical and measurable terms. As Hauser and Clausing (1988) emphasize, the team must be made of people from different backgrounds, including marketing and logistics.

According to Ficalora and Cohen (2009), a good EC comes from a cause-and-effect diagram or a tree diagram, proving by cause and effect analysis that it is the root cause of a specific CA. The QFD team must then identify measuring units for each EC that are as clear and objective as possible. Then, it is important to indicate the direction each EC must go, in order to satisfy the customer. They can be (Hauser and Clausing, 1988):

1. The More, the Better (↑): this means that the EC is unilateral, and its optimal value tends to infinity, having a lower boundary. An example would be miles per gallon of a car. It should be indicated with an upwards arrow;

2. The Less, the Better (↓): this means that the EC is unilateral, and its optimal value tends to zero, having an upper boundary. An example would be the number of defects identified in a product under a certain period. It should be indicated with a downwards arrow;
3. Target is Best (○): this means that the EC is bilateral, and its optimal value tends to a target value, having upper and lower boundaries. An example would be a freezer temperature for a specific product. It should be indicated with a circle or the target value;

3.3.2.4 The Technical Correlation Matrix

The technical correlation matrix, also known as the roof of the House of Quality (HOQ), is where all the ECs are correlated together to assess their influences on each other. As illustrated by Hauser and Clausing (1988) in their car door example, if an engineering characteristic is needed to satisfy a CA, for example the window motor, other features must as well be improved to assure the product has the desired functionality. However, there are negative collateral effects, and in this case, would be the increase of the door weight leading to an effect on the CA "stay open on hill".

This matrix gives a clear vision for engineers of all the implications a change in the design of a component will have on the others and spread out to a deeper thought of the consequences and the overall effort needed. According to Ficalora and Cohen (2009) when there is a negative effect of an EC on other, there is the possibility of a technological bottleneck that requires a breakthrough to be solved that otherwise may have gone unnoticed.

Another weak point of the HOQ is the underuse of the correlation between ECs to assess the final results (Chan and Wu, 2002).

3.3.2.5 The Technical Benchmark Room

As for each CA, a benchmark is undertaken to assess the performance of each competitor compared to the company's product in the view of the customers. Each EC also goes through a similar process.

Each EC is assessed in comparison to the same competitors, but this time under a technical point of view. The QFD team is responsible for making such comparisons, often requiring buying the competitor products to have access to sensitive information, normally confidential (Chan and Wu, 2002).

After this process, similarly to the customer benchmark, a target technical performance level, and if applicable an acceptable minimum, must be set by the QFD team for each EC. The minimum value is important because the targets might not be reached, and thus the minimum serves as veto for the design. The targets are the performance levels the team believes are required to accomplish the customer's expectations against the competition. Usually, ECs with higher relative importance and/or low performance compared to competitors should get higher targets, because they have higher impact on customers (Chan and Wu, 2002).

3.3.2.6 The Relationship Matrix

As the core of the HOQ, the relation matrix relates each CA to each EC by giving an arbitrarily relation value weight. This means how strongly a determined CA is fulfilled by each EC and allows the QFD team to set target values for each EC to satisfy a customer need. Such weights are often given with the use different arbitrary scales of 1 to 9, with distinct numbers defining weak, moderate and strong relationship. This is done for positive relations most of the cases, with 0 corresponding to "no relationship" (Bouchereau and Rowlands, 2005). Then, an overall EC weight is calculated based on the relation it has to each CA and multiplying by the CA weight, with a simple additive weighting (Ficalora and Cohen, 2009) as in equation 3.

$$ECW_j = \sum_{i=1}^{n} w_i \times R_{ij}, \quad (3)$$

where:

ECW_j – Weight of the EC *j;*

w_i – The strategic relative weight of the CA *i*, previously calculated;

R_{ij} – The relation weight between the CA *i* and the EC *j;*

n – the number of CAs.

Other authors propose different numerical approaches to obtain the overall importance, like Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) and Operational Competitiveness Rating (OCRA) (Chan and Wu, 1998). Another problem with this matrix is the uncertainty of the customers' judgements when providing importance weights, which implies in mistaken EC overall importance. It is proposed what is called a Robust QFD (Kim, Kim and Min, 2007) to mitigate such issues, using uncertainty modelling and solving with linear programming, simulation, or optimization to obtain the EC importance.

Also, Chan and Wu (2002) propose the use of a relative importance for an EC, simply dividing the importance of one specific EC by the sum of all ECs importance values, as well as setting a difficulty coefficient of achieving the target that was defined after evaluating the performance of competitors' products in every EC. This coefficient is a probability of success and is later used to compute the final importance of the EC.

The steps in this room are:

1. Correlate each CA with each EC;
2. Calculate the importance of each EC;
3. Compute the relative importance of each EC;
4. Set a probability coefficient for target achievability;
5. Compute the final importance of the EC as equation 4 shows.

$$FI = [(T - CP) \times RW \times TP] \div PF\ , \qquad (4)$$

where:

T – Target points

CP – Current points

FI – Final importance of the EC;

RW – Relative weight of the EC;

TP – Technical points, assigned similarly to the sales points for a CA;

PF – Probability factor.

It is worth noting that the PF can, instead of being a subjective probability, be a coefficient that represents the effort, or difficulty, needed to implement the referred EC. If using a probability factor in the same HOQ scales, it is lower for aggressive targets and higher for conservative ones, while if using an effort value, it should be the opposite. Additionally, it is important to compare using the obtained points, or "apples-to-apples", not the technical results. This is to avoid comparing a technical measurement of two different ECs, one in meters and the other in seconds, for example (Ficalora and Cohen, 2009).

3.3.3 Analysing HOQ results

Upon completion of the steps described so far, the House of Quality (HOQ) should be filled out and be able to provide valuable insights to the design team on how and what to prioritize on their new product development process. Yang *et al.* (2003) suggest to the analysis of the HOQ identifying the following:

- The blank and weak columns – they mean that a particular EC has a weak or no relation to a CA, and thus must be reviewed.
- Blank or weak rows – a CA is not being addressed or is partially addressed by an EC.
- Conflicts – technical competitive assessment that conflicts with customer benchmark. Identified when the technical benchmark suggests that the product is better than the competition, but customers do not see it that way. It can also be when technical benchmark indicates that the product is worse than the competition, but customers consider it better.
- Critical Points – situation where the technical benchmark and the competitive assessment are worse than the competition and there is a moderate or strong relationship between them.
- Significance – ECs that relate to many CAs, or that may be mandatory for safety, regulatory or internal company requirements.
- "Eye-opener" Opportunities – ECs where the company and competitors are doing poorly – the QFD and design teams should be able to develop those characteristics to increase the sales points.
- Benchmarking – the QFD team should be able to identify ECs where the competition is better and try to use their solutions incorporating to their own product.

- Deployment – the most relevant ECs, if not all, should be taken to the next house of QFD (Parts Characteristics).

When selecting ECs to allocate development time and effort, the team should look for those that have the higher relative weight, since this result comes from the higher importance ratings given by the customers to each CA. In this case, by working more on those characteristics the most important CAs will be taken care of (Sharma and Rawani, 2006). It is also important to consider, however, all the points mentioned above. If there are points of conflict or critical points, the team should reserve some effort to address them.

The team should also connect the information provided in each room, in an attempt to understand how the correlations of the ECs among themselves impact on the development, how to take advantage of poor competitors performance and where to improve the most to satisfy the customer at a greater level than the competition.

3.3.4 The HOQ Benefits and Points of Improvement

The HOQ has been widely used throughout several industries as shown, and the reason for that is because it is seen indeed as a tool that brings many benefits in time, cost reduction and customer satisfaction. Some of those benefits are enlisted below:

- It increases customer satisfaction by giving customers what they want (Hauser and Clausing, 1988; Vonderembse, Fossen, van and Raghunathan, 1997; Yang *et al.*, 2003)
- Reduces cost and development time (also referred to lead time). Some examples suggest a reduction of cost of around 60%, while the lead time reduction normally has only a moderate difference, depending on the experience of the participants and reaching up to 50% (Bouchereau and Rowlands, 2000; Cristiano, Liker and White, 2001; Hauser and Clausing, 1988; Yang *et al.*, 2003).
- Avoids design failures and decreases the need for redesign peaks before the launch of the product (Yang *et al.*, 2003).
- Can be used as a tool for knowledge transfer, since the information of the HOQ and its related documentation are a good source of information for the next team or product, especially in products that share the same customer base (and demands) (Vonderembse, Fossen, van and Raghunathan, 1997; Yang *et al.*, 2003).
- Improvement in teamwork and cross-functional communication. Many of the benefits provided by QFD application is only seen in the long term, and often intangible (Bouchereau and Rowlands, 2000; Miguel, 2003)

Besides all the known benefits in implementing QFD, it also brings some drawbacks in its use for large projects and teams as pointed by Bouchereau and Rowlands (2000) and confirmed with an extensive study by Miguel (2003), that can discourage managers from using QFD. Since strong support from managers is one of the key success factors for correct and efficient implementation of QFD according to Cristiano, Liker and White (2001), such discouragement may lead to partial or inefficient use of the tool. The drawbacks are presented below:

- Ambiguity and vagueness in the CAs;
- Need to input and analyze large amounts of subjective data, leading to large matrices;
- Manual input of data becomes time-consuming;
- QFD analyses often stop at the HOQ;
- Imprecision in setting targets;
- Strength of the relationships between CAs and ECs is imprecise;
- QFD is a qualitative method.

Some of these issues are already subject of improvement in the current literature, especially the ones that refer to the subjectivity, vagueness and qualitative aspect of QFD and the HOQ.

This leads to pointing out one of the major pitfalls of the current quantitative adaptations of the HOQ, which is the use of ordinal scales for evaluating alternatives, that only gives a priority ranking disregarding the “distances” between them. While many authors propose conversions to a cardinal scale from the ordinal scales normally used, this can also be dangerous, being a simple switching to other values (Franceschini and Rossetto, 1995).

For the matters appointed as drawbacks, a wide variety of methods were integrated into the HOQ use and presented in the next section.

3.3.5 Numerical Approaches

As previously mentioned, QFD and its houses suffer with the vagueness and subjectivity of the importance ratings assigned by the customers to each CA, by the engineers in the correlation between CA and EC, when setting sale points and probability factor. Additionally, customers tend to evaluate all CAs with the same importance in the provided absolute scales tending to the highest scores assuming they are all important independently of the scales used. Thus, finding ways to differentiate them is important (Bhattacharya, Sarkar and Mukherjee, 2005).

To overcome this difficulty, many authors propose several different numerical methods of assessing the real perceived importance of the CAs by the customers. The use of Analytical Hierarchy Process (AHP) is proposed to assess the relations of CAs and ECs based on pairwise judgements (Bhattacharya, Sarkar and Mukherjee, 2005; Chuang, 2001; Partovi, 1999). Other authors suggest the use of fuzzy sets theory to assess this same relation, by translating the meaning of linguistic terms into numbers, in order to diminish the uncertainties and fuzziness in the answers provided by customer judgements (Bottani and Rizzi, 2006; Chan, Kao and Wu, 1999; Chen and Weng, 2006; Chien and Tsai, 2000).

But despite fuzzy sets requiring less work from the interviewees, it is based on absolute and subjective importance ratings. It still does not solve the scale problem associated with the HOQ when determining correlations and weights. On the other hand, AHP offers a more stable set of judgements. However, critics of the HOQ with AHP bring around some important considerations on the integrated methodologies, as the lack of consistency of the judgements pointed out by Bana e Costa and Vansnick (2008), the use of ratio scales that are not as meaningful as interval scales (Belton and Stewart, 2002; Burke, Kloeber and Deckro, 2002) and the higher cost and time required to perform the judgements and complex computation involved (Sivasamy *et al.*, 2016; Wang, Xie and Goh, 1998).

Additionally, there are other methods to deal with missing or incomplete information, such as the one proposed by Franceschini and Rossetto (2002), that developed an algorithm to avoid using human judgements to obtain relationships between CAs and ECs, called Interactive Design Characteristic Ranking (IDCR), and Chin *et al.* (2009) that used evidential reasoning for assessing customer's judgements and their beliefs.

3.4 Decision Support Methods

As presented so far during the explanation of the HOQ methodology, there some common mistakes that occur when applying such framework and most of them are in the methodology itself. They have been addressed in different ways solving partially, as in the case of AHP, or just masking the problem with the use of fuzzy sets. This section presents Multicriteria Decision Analysis (MCDA) approaches that may be applied with HOQ in a proper way.

3.4.1 Multiple Criteria Decision Analysis

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 (see, e.g., (Figueira, Greco and Ehrogott, 2005). From now on 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).

As the human brain can only process a limited set of information simultaneously, mathematical models were developed to deal with situations where this limit is surpassed. MCDA models are not aimed to provide the "right" answer, they serve the purpose of guiding the decision-makers and manage the subjectivity of the decisions integrating value judgement with objective quantitative measurement. It comes particularly helpful in situations of conflicting criteria and stakeholders' opinions. MCDA models have been widely used in problems considered as "Range of Available Alternatives", where there is the need to select from a large number of choices the one that best suits the needs of the main stakeholder.

This selection process, as well for the other types of problems, have in common the construction of value measurement functions for each criterion as a starting point in the mathematical analysis. They provide means of assessing, and quantifying, the value of performances on that criterion according to the preferences of the decision-maker. Although, in order to leave the simple preference ranking behind, it is needed to categorize the criteria according to their "weight", which should take into account the preference ranges on the criteria (e.g., between the worst possible performance and the best). In the end, the value of the a given alternative may be obtained by the additive model, which is shown in equation 5 (Belton and Stewart, 2002).

$$V(a) = \sum_{i=1}^{n} w_i v_i(a), \text{ with } \sum_{i=1}^{n} = 1 \text{ and } w_i > 0, \forall i, \quad (5)$$

where:

$V(a)$ is the overall value of the alternative a;

w_i is the weight of criterion *i*;

$v_i(a)$ is the value score of the alternative a on criterion *i.*

However, the additive model above presented may only be applied if the criteria are mutually preferentially independent (Dyer and Sarin, 1979).

It is also important to mention at this point that the criteria value scales are interval scales, when they have an arbitrary zero. On opposition to others most commonly used in the HOQ (ordinal and ratio scales), adding new alternatives will not alter the preference order either the magnitude in preference between alternatives. In ratio scales, for example, adding one new alternative will significantly change the overall result, as the ratio between alternatives has changed possibly affecting their order of preference. The incorrect use of scales in the HOQ has been criticized by Burke, Kloeber and Deckro (2002), where they demonstrate the results using different measurements and conclude that from ratio, ordinal and interval scales, the latter presents the most meaningful scores for each Enginering Characteristic (EC). They suggest that the value function should be an interval scale while having weights in ratio scales.

Their conclusions bring a significant alert to QFD users, specifically the House of Quality for identification of customer needs and selection of design alternatives, as a study undertaken by Renzi, Leali and di Angelo (2017) showed that amongst the most common tools used as decision support in the automotive industry was QFD with MCDA models. They divided the problems into the following groups: automotive design problem related to uncertainty; related to product requirements; to customer needs; to design alternative selection; material selection; and process selection. In all of these categories, QFD had a considerable representation as the preferred tool for aiding decision with AHP coming soon after, but they not always came alone. The literature they analyzed often combined both and in other cases with different methodologies, with Fuzzy sets and TOPSIS being the most common aside from AHP and QFD (combined or not). It is worth noting that the authors do not specify which house of the QFD was used in each category, but it is possible to assume that it was often referred to the House of Quality.

3.4.2 MACBETH

Measuring Attractiveness by a Category-Based Evaluation Technique (MACBETH) is a 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, de Corte 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. Each one of these categories has a number associated with the creation of the scale, being 1 “very weak” and 6 “extreme”. It starts by asking the DM to rank the alternatives in order of decreasing attractiveness and then to pairwise compare them using the semantic scale, being able to choose one or more categories when there is hesitation in the process. In this method, each entry given by the DM is subject to a consistency analysis of the software M-MACBETH, developed for consultants and facilitators to quickly apply the methodology. The software will indicate an inconsistent judgement, if any is detected, and what needs to be changed to resolve the inconsistency.

In this process, MACBETH brings the advantage of not needing to complete the $n(n\text{-}1)/2$ judgements of the matrix, where n is the number of elements of the matrix, as the other methodologies do. In cases where no judgement is selected, it assumes a combination of all categories into a “positive” one, reducing the need of DM answers to a minimum of n-1. It is advisable to perform more comparisons to obtain a more precise value scale and have more consistency checks.

An interval scale is then generated with the use of linear programming respecting the set of judgements inserted into M-MACBETH (Bana e Costa and Vansnick, 1994; Bana e Costa, de Corte and Vansnick, 2012). In the end, the decision-maker is asked to validate the proposed scale and to adjust it if needed.

To weigh the criteria a similar procedure as before is applied, but this time using $n + 1$ fictitious alternatives for n criteria. Each fictitious alternative has an upper reference performance in one criterion (e.g. the “best” performance) and lower reference performances in the other criteria (e.g. the “worst” performances), with no repetitions, and there is a fictitious alternative with lower reference performances in all the criteria.

3.4.3 PROBE

Portfolio Robustness Evaluation (PROBE) is a decision support system (DSS) that integrates MCDA and portfolio decision analysis to obtain the efficient and convex-efficient portfolios of projects (the ones which cumulative values serve as the frontier in a Pareto graph) within a cost range (Lourenço, Morton and Bana e Costa, 2012).

PROBE uses optimization to identify efficient portfolios of projects, i.e. the portfolios that provide the highest possible (benefit) value for its cost. On the other hand, it also allows for a benefit-to-effort approach as used by Bana e Costa *et al.* (2014). In this approach, the selection of a portfolio of projects is made considering the benefit value provided and the effort needed to implement the selected projects.

The software tool allows users to structure the benefit criteria of the projects in a value tree to which at the bottom-level criteria it will always ask for input regarding the “best guess” in cost and benefit so that it is able to calculate the benefit value of each project. If the tree has more than one criterion, their respective weights must be input.

This tool shows a graph with the efficient portfolios and their position related to cost and benefit. With PROBE is also possible to set synergies between projects, cost of not selecting projects and levels of uncertainty, among other constraints. PROBE has also been used in combination with M-MACBETH for selecting project portfolios, with criteria weights and project benefit scores coming from the M-MACBETH tool (Bana e Costa *et al.*, 2014).

3.5 Conclusions on Engineering Design Practices

An extensive review of the House of Quality (HOQ) use in the industry and literature was presented throughout this chapter and the wide range of its applications.

The benefits of HOQ were highlighted as well as the major drawbacks and issues associated with it. It was possible to identify certain commonalities in the attempts to solve such issues, as the fact that they are mostly MCDA methodologies to assess the multiple criteria involved in a design process as well as the fact that they do not erase the subjectivity of decision (what was expected as humans provide the inputs, and therefore subjective).

The different methodologies rely on different scales, with the interval scale being considered as the most reliable for generating performance value scales and ratio scales for the weights of the Customer Attributes (CA). The AHP, TOPSIS and Fuzzy Sets methodologies were briefly explained and identified as being the most used in combination to the HOQ. Their benefits and issues were highlighted, being the AHP considered to have inconsistent judgements and extensive need for pairwise comparisons from the decision-makers, and Fuzzy Sets not solving the scale problem. MACBETH was then presented as an alternative to the previous methods.

Lastly PROBE was introduced, to be used combined with the other methodologies to help in the selection of solutions through a trade-off that can be either benefit-to-cost or benefit-to-effort.

4 The Application of HOQ at FST Lisboa's Design Phase

4.1 Introduction

Upon reviewing the main aspects that affect the work developed by the FST Lisboa team on the different phases of development of the electric prototype, it is possible to conclude that a special focus should be given to properly structure the entire design and, consequently, the development processes that remain.

As the team only has one chance to get the car right for that season, the design phase should be given specific attention by using its tools to design it right at the first time and therefore mitigating the issues that can arise from that as discussed in section 2.3.4 and later presented in Figure 3 in the beginning of Chapter 3. The early stages of design (Identify and Characterize) are more impactful and cost less to make changes than during production, for example. Thus, the first tool that could be used in early stages is the Quality Function Deployment, and specifically the House of Quality. These aspects that affect FST Lisboa's work can be seen below in a relation between the greatest benefits of the HOQ, referred in section 3.3.4, to the team's design problems and possible benefits:

- Increased customer satisfaction – may be represented as an increase in performance;
- Reduced development time – the issues in design, manufacturing and testing can be attenuated, by doing better planning that would decrease the delayed days and therefore increase testing kilometers. This may lead to improved reliability and better performance;
- Transfer of knowledge – by having a thorough HOQ the next teams may be able to understand certain decisions, have an overview of the team at that point and continue the work from data previously collected. This can solve one of the main problems FST Lisboa has, which is the transfer of knowledge from one team to another due to the lack of proper documentation and high turnover rates of team members;
- Improved Communication – the HOQ requires that different fields of knowledge work together to find solutions that are in the capabilities of each department. Therefore, a correct application in FST Lisboa would lead to reduced redesigns in later stages and also in a lower probability of interferences between different subassemblies of the car (normally found during assembly of the parts).

Those issues are some of the main purposes for the creation of the House of Quality in the 1960s, and being applied still today in the automotive industry, as shown by Renzi, Leali and di Angelo (2017), solving the exact same issues FST Lisboa has (although in a smaller scale). However, as presented by Burke, Kloeber and Deckro (2002), Franceschini and Rossetto (1995) and Sivasamy *et al.* (2016), the HOQ has some drawbacks that must be assessed such as the use of scales that are not meaningful and the complexity in implementing the advanced models.

The objective of this work is to introduce FST Lisboa to House of Quality in an attempt to guide the team in better planning of the design concepts, structure implementation and organization of the design phase. This aims to reduce redesign at later stages and delays that may compromise the overall season goals for the team while addressing the presented drawbacks of the methodology.

This chapter will explain how to integrate MACBETH into the HOQ, the selection of the QFD team, the step-by-step application in overall terms and how PROBE can be effective in the selection of Engineering Characteristics (EC) to be implemented in the new vehicle. The remaining part of the chapter is divided into five sections. Section 4.2 explains how the selection of the QFD team will be, section 4.3 explains the methodology to integrate MACBETH into each room of the HOQ, section 4.4 goes through the process of generating an effort coefficient for each EC, section 4.5 proposes the integration of the Roof into the analysis and section 4.6 presents conclusions about the selected methodology.

4.2 Selecting the QFD Team

Before starting any work with the House of Quality, it is needed to define who is going to participate as the QFD team for setting the ECs and technical benchmark and who are the customers for the product. This particular case has some peculiarities, serving more internal customers, that is, entities within the organization (Yang *et al.*, 2003), that would also be the QFD team.

As presented in section 2.3.5, the team is divided into eight different departments under the supervision of each head of department and two chief engineers. To undergo this study, the customers and the QFD team will be the same, as they decide both the car objectives, or CAs, and the design approach, that is how to meet those objectives being represented in HOQ by the ECs. They will be:

- Team Leader – will represent the less technical aspects of the decision-making, such as strategic goals for the team and car, the difficulty of obtaining funding and internal affairs;
- Mechanical Chief Engineer – represents all the mechanical departments and their integration in the vehicle;
- Electrical Chief Engineer – represents all the electronic and software departments, how they connect with each other and with the mechanical assemblies;
- Project Manager – will be representing less technical aspects, such as time, intercommunication among departments and potential conflicts of interests.

As suggested by Hauser and Clausing (1988) the QFD team must be as diverse as possible, and considering the high number of technical personnel, balancing in half for less technical and a half for more technical members can be considered enough for this study.

4.3 Integrating MACBETH into the House of Quality

The first step before implementing the HOQ into the team, it is important to address the main problem it has been reported to have, like the use of non-meaningful scales and the long and complex steps in the application of advanced models. To address both problems the MACBETH approach is considered to be adequate, as it requires fewer judgements from the decision-makers when compared to AHP or

Fuzzy Sets and because it generates interval scales, considered by Burke, Kloeber and Deckro (2002) as meaningful and recommended for HOQ. It is also capable of generating criteria weights, solving another problem of HOQ that is the incorrect use of weights by considering ordinal scales as cardinal scales, which they are not, as they only give an order of preference.

Therefore, MACBETH will be applied in defining the weights for each CA and their respective value scales for assessing the performance of each alternative and benchmarking against competitors. It will later be implemented in defining value scales for each EC and their technical competitive assessment. Finally, MACBETH, using the software M-MACBETH, will play a major role in determining the Relationship Matrix between each CA and EC and among ECs, in the Technical Correlation Matrix (The Roof).

Additionally, for every meeting with the QFD team where they will be required to answer the difference of attractiveness in the M-MACBETH software, they will be asked to privately answer them to not generate an informational cascade and social influence (Bikhchandani, Hirshleifer and Welch, 1992; Wood, 2000), a concept that states that the decision of one person affects in the decision of the next up to a point where the last one making a decision has almost no own thinking and will decide following the decisions of the ones that came before. Then, they will be asked to reveal their answers and discuss the results to generate a consensus about what to answer.

4.3.1 MACBETH in the Customer Attributes

The customer must be interviewed in order to obtain the Customer Attributes. In this case, due to time constraints and previous activities of the team members in defining the objectives for the 2019/20 season, the CAs will be extracted from the team's documentation. The objectives defined by the team come from performance analysis from the previous car, feedback from alumni and competition judges. The facilitator will interview the customer upon the previously set objectives in order to understand their origin, relevance to the study and filter them to avoid repetitive CAs.

Once that is done, the facilitator will build along with the customer a decision tree in MACBETH with every CA being a criterion in a similar approach to what Bana e Costa, de Corte and Vansnick (2012) did. Then, for every CA the customer will be asked to define a range of performance levels and set "Neutral" and "Good" levels, either qualitative or quantitative.

The next step is to generate a value scale for each CA, and that is done using the judgement matrix of M-MACBETH where the customer will answer giving judgements of difference of attractiveness in the semantic scale of "very weak", "weak", "moderate", strong", "very strong" and "extreme" (Bana e Costa, Corte, de and Vansnick, 2012).

With the value scale it becomes possible to assess competitors' cars. The customer will be asked to provide four competitor FS teams and to provide their performances for each CA, that when put into M-MACBETH as options, will provide their value scores. These scores will allow the team to assess their position against the competitors and also help in setting the strategic goals, as presented in section 3.3.2.2.

4.3.2 MACBETH in the Roof

The HOQ Roof, or the Technical Correlation Matrix, also suffers from the incorrect use of scales, which may lead to incorrect judgements and design choices. MACBETH weighing will be used to provide a measure of the correlation between each two correlated ECs, which can be interpreted as the strength of the effect of one EC into another. The following steps are needed:

1. Ask the QFD team to indicate where there is a positive correlation, no correlation and where there is a negative one;
2. Then, the pairs of negatively or positively correlated ECs are inputted into the M-MACBETH software tool;
3. Finally, the QFD team is asked to rate the strength of correlation between each two correlated ECs.

Then M-MACBETH will generate a proposal of correlation measure for each pair of ECs, which would vary between -1 (strongest negative impact) and 0 (no impact) for the negative correlations, and between 0 (no impact) and 1 (strongest positive impact) for the positive ones.

4.3.3 The Relationship Matrix with MACBETH

The Relationship Matrix is where the CAs are related to the ECs to assess how each engineering characteristic satisfies a determined customer attribute. In its original version, Hauser and Clausing (1988) suggest that these correlations should be done using a 1 to 9 scale, what was later proved by Burke, Kloeber and Deckro (2002), Franceschini and Rossetto (1995) and Sivasamy *et al.* (2016) to generate incorrect judgements and possibly unwise design choices.

The software tool M-MACBETH will also be used to assess these correlations. This implementation requires the following steps:

1. The QFD team will be asked to indicate where there is a relationship between CAs and ECs in the matrix, with no relation pairs of CA-EC being left blank in the matrix;
2. Each CA will be inputted into M-MACBETH as a criterion node and each EC as an option;
3. The QFD team will be asked to rank the ECs for each CA criterion node, using the semantic scale of MACBETH. In case two ECs get an equal judgement, they must be asked if one is stronger than the other, if not, it will be assumed indifference between the two;
4. After being ranked, the QFD team must answer questions to fill in the judgement matrix of M-MACBETH, assessing the differences of attractiveness between two consecutive ECs with pairwise comparisons. It is worth noting that it is only required to fill the upper diagonal of the matrix, however the more judgements, the more accurate the comparison becomes.

Once these steps are complete, M-MACBETH will return the weights each EC has in the CA being evaluated as a ratio scale. Such weight is considered to be the relationship CA-EC.

4.3.4 Technical Benchmark for MACBETH Results

Similarly to what is performed in the customer attributes fields with a customer benchmark against the competition, the same is undertaken with the Engineering Characteristics (EC), as presented in section 3.3.2.5. Here, the QFD team will be asked to define performance levels for each EC.

The ECs will be input into M-MACBETH as criteria, to later provide judgements in the matrix. This will allow M-MACBETH to generate a value scale that will be used to assess the performance of the competitors in a determined EC according to the scale that was created.

From these results, the technical target performance level can be set and the final score of importance for that EC can be calculated using the equation 4 presented in section 3.3.2.6.

4.4 The Effort Coefficient Using MACBETH

Some authors propose the use of a probability factor for achieving a technical performance target, as Chan and Wu (2002), while others propose an effort coefficient (Ficalora and Cohen, 2009). While the former benefits more the use of aggressive targets, the latter tends to give priority to low-effort options (Chan and Wu, 2002). When considering equation 4, if the *pf* factor is considered to be probability, the lower the value the higher will be the final importance of the EC (therefore being benefiting an aggressive and improbable target). On the other hand, if it is effort, the higher the value the lower will be the importance of the EC (benefiting lower efforts).

In this case, as costs and probabilities are difficult to assess due to the lack of information and control from the team, an effort coefficient will be used to select the efficient portfolio of ECs using PROBE in a benefit-to-effort basis. This coefficient will be obtained through an approach similar to the one by Bana e Costa *et al.* (2014) using MACBETH, with pairwise comparisons from the team regarding the effort required to implement design alternatives.

The QFD team will be asked to identify the characteristics that directly affect the effort needed to develop each possible design alternative in the car development, and to pairwise compare these solutions taking into account the difference of efforts needed to implement them.

4.5 Integrating the Roof in the Analysis

As pointed out by Chan and Wu (2002), the roof is underused in the analysis of the HOQ results. Ficalora and Cohen (2009) suggest that when there is a negative correlation, a breakthrough needs to be done to solve the problem. However, this is not enough, once the intent of all the advanced models is to make the analysis as direct and quantitative as possible. With scattered and subjective information spread across the HOQ matrices, it becomes difficult to get to a conclusion, even having well-defined scores. Additionally, it is not always that the highest-scoring ECs should be picked, as Yang *et al.* (2003)

propose, the team should also look for the results from other rooms such as competitive assessment. So, the question remains: what can be done with the scores?

To solve this problem, the use of PROBE is suggested. Inputting into the software tool all the ECs as they were projects in a portfolio, so they can also be correlated using synergies. As PROBE allows for options to be positively or negatively correlated (i.e. to have a negative or a positive synergy), it is possible to apply this feature to the ECs (which can also be positively or negatively correlated). PROBE can also be used to identify efficient design solutions according to their benefit (their scores) and their cost/effort (the effort coefficient in the HOQ).

4.6 Conclusions on the Proposed HOQ Application for FST Lisboa

The House of Quality has many issues that must be assessed in its implementation and has been subject of many studies. It is believed that the proposed methodology can address them at the same time that helps a novice team of students to use one of the most important tools in designing for quality and that is used by actual motor companies.

The MACBETH methodology is capable of addressing the main issues associated with the HOQ and does not require too much time from the decision-makers when comparing to other models that use AHP and Fuzzy Sets integrated, and do not have the burden associated to these methods.

Additionally, a new way of using the roof of the HOQ in assessing the results and selecting ECs for development is proposed using PROBE, bringing tools from other fields of knowledge to improve the use of HOQ.

It is believed that both combined can lead to significant improvement on managements and on the track for FST Lisboa

5 Implementing the HOQ

5.1 Introduction

In this chapter, the implementation of the proposed methodology will be presented, highlighting the step-by-step application of MACBETH and M-MACBETH software integrated with the House of Quality (HOQ) in the team. 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.

During the study, several meetings (that will be called sessions from now on) were held with the team to implement the HOQ integrated with MACBETH in FST Lisboa team. The entire process is described in the following sections. Section 5.2 explains how the Customer Attributes (CA) were obtained from the team's objectives, how their weights and value scales were created using the M-MACBETH software tool and the assessment of the competitive benchmark. Section 5.3 goes through the process of translating the CAs into Engineering Characteristics (EC) and creating their value scales.

Section 5.4 refers to the application of the MACBETH methodology in the relationship matrix and section 5.5 elaborates on the development of the correlations between ECs to build the roof using MACBETH. Section 5.6 addresses the competition, introducing the competitor cars and performing the technical and strategic benchmarks and identifying the technical and strategic goals. Section 5.7 presents the calculation of the importance of the ECs while section 5.8 closes the chapter with conclusions.

5.2 Obtaining CAs, Their Weights and Value Scales

The process for obtaining the Customer Attributes for a project this big and with no external customers differ from the standard procedures. Due to time constraints from the team, it was only possible to start this study at the end of the design phase of the FST 10e. The leaders of each department had already compiled what they believed were the season's goals for the car and team, based on the performance of the FST 09e (2018/19 season), feedback from alumni on the developments of the previous year and from competition judges, which advise on technical and managerial solutions.

This is the first step in obtaining the Voice of the Customer (VoC), that is, the Customer Attributes that will later be translated into Engineering Characteristics (EC). In the first session, the team, represented by the QFD team as described in section 4.2, presented the list of objectives shown in Figure 9.

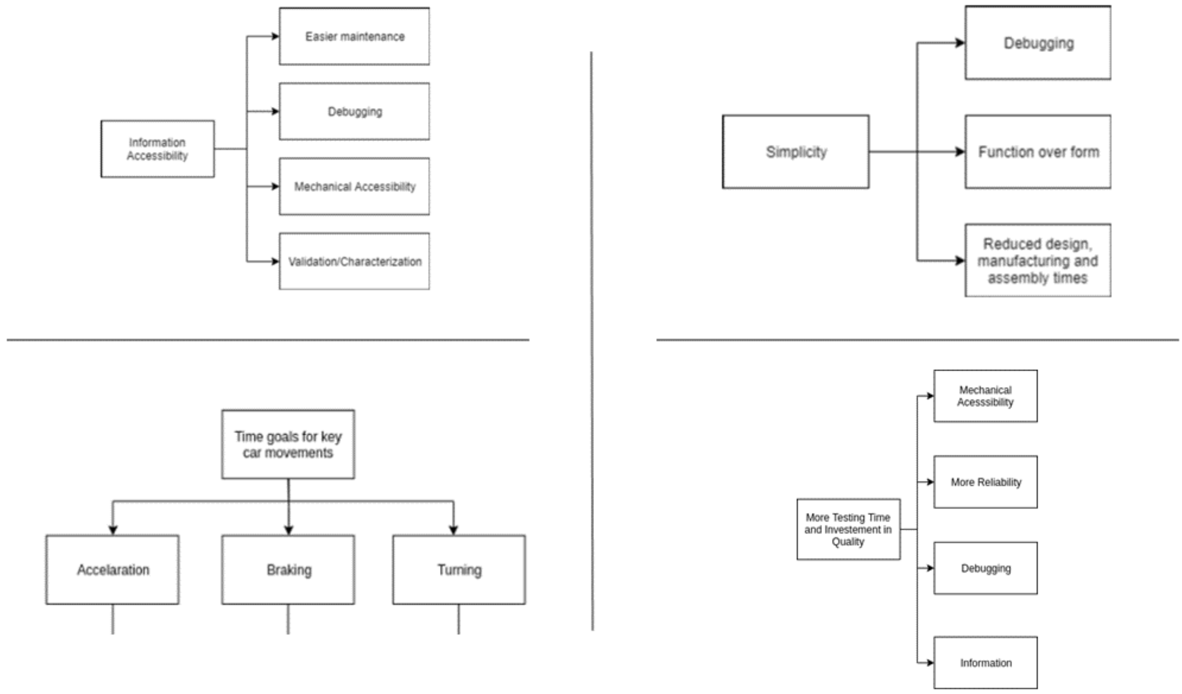


Figure 9 FST 10e requirements proposed by the team

The first challenge in this study was to "translate" their set of requirements for the car in actual CAs. This is because many of the items presented overlap themselves, are not specific enough to be used or may even represent design philosophies more than requirements. One example is "Debugging", as this requirement is present in the three main items with different implicit meanings. From those items, the facilitator and the group tried to understand the origin of each of those objectives and how they affected the overall project to better fit them with the methodology and be as meaningful and impactful as possible for the team.

After the analysis and discussion held with the team, the season objectives were reorganized and have become the CAs in Table 2. They were grouped into three primary level attributes: More Testing and Quality, Performance, and Simplicity, which gave origin to other secondary level attributes. It is worth noting that as it is an internal customer, some CAs can be directly related to the use of the car and also with its development, maintenance, operations and transportation to competitions. They can have qualitative or quantitative descriptors of performance, that were jointly defined with the team during the session, as seen in Table 3.

.

Table 2 Customer attributes hierarchy

Primary Level Attributes	Secondary Level Attributes
More Testing and Quality	Mechanical Accessibility
	Reliability
Performance	Good Acceleration Time
	Fast and Safe Breaking
	Good Turning Abilities
	Access to Information
Simplicity	Reduced Design, Manufacturing and Assembly Time

Table 3 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 6)
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 7)
Reduced Design, Manufacturing and Assembly Time	RDMA	The number of weeks of the development lifecycle, from design to first ride

5.2.1 Obtaining Customer Attributes' Weights Using MACBETH

To start using MACBETH the first thing that was done was the setup of the CAs in the M-MACBETH software, inserting the primary level CAs in the decision tree as non-criteria nodes, while the secondary level CAs were defined as criteria nodes and placed below their respective primary level attribute.

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 (assuming the FST Lisboa's perspective), 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 it would be neutral. The performance levels defined for each CA can be found in Table 4.

Table 4 "Neutral" and "Good" Levels of CAs

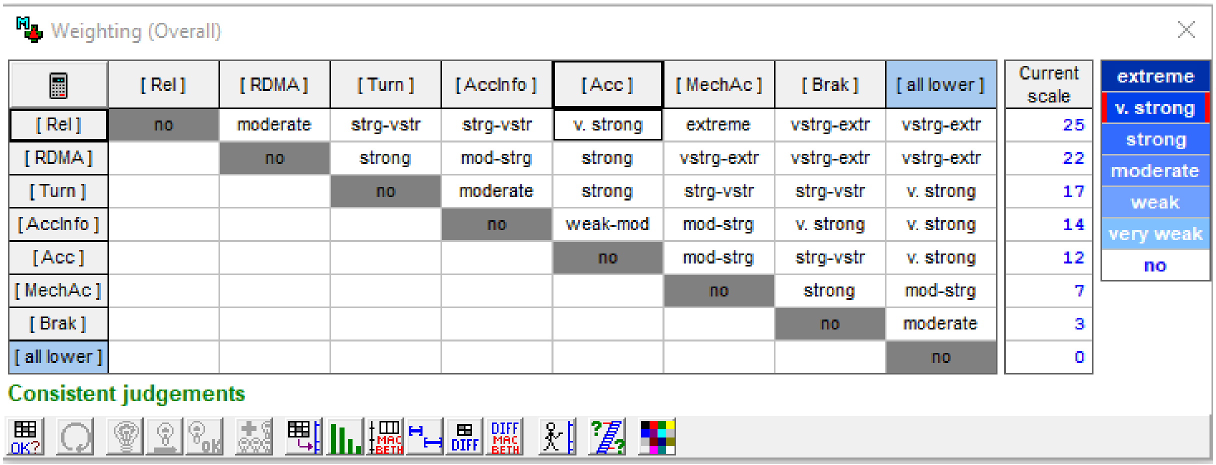
Customer Attribute	"Neutral" Level	"Good" Level
Mechanical Accessibility	Mounting easiness like FST 09e	Mounting easiness higher than FST 09e
Access to Information	Everything like FST 09e	All access over telemetry + all mechanical parts status
Reliability	64.1 %	82 %
Good Acceleration Time	3.8 seconds	3.5 seconds
Fast and Safe Braking	2 G	2.5 G
Good Turning Abilities	1.5 G	2 G
RDMA	39 weeks	36 weeks

With the CAs defined, the next step is to assign them importance weights. Originally this process used incorrect scales and methodology as already explained in Chapter 3. In this case, the secondary level attributes were chosen to be used in the HOQ and therefore were weighted using MACBETH methodology in the M-MACBETH software.

This process started with the facilitator 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". The steps are as follows:

1. The team was asked to order the CAs in the judgement matrix according to their preference following the MACBETH semantic scale of "very weak", "weak", "moderate", "strong", "very strong" and "extreme". If any two CAs had similar importance, the facilitator asked them if one could have more importance than the other, if not, they were considered indifferent;
2. In the judgement matrix of M-MACBETH the facilitator started asking the question: "imagine that there is one alternative that has a Neutral performance in all attributes, what is the difference in attractiveness if this improved to the "Good" level for "Fast and Safe Breaking"?;
3. Each member wrote down their answers using the MACBETH semantic scale to avoid informational cascades (see section 4.3). If they were not convergent the team was asked to deliberate and reach to a consensus on an answer to give and be inserted into the M-MACBETH matrix. In the case of "Fast and Safe Braking" the team replied "Moderate";
4. This process is repeated to all CAs;
5. Then, the next step is to do pairwise comparisons of CAs between themselves. The facilitator asked "what is the difference in attractiveness in improving from 'Neutral' to 'Good' in 'Fast and Safe Braking' compared to improving from 'Neutral' to 'Good' in 'Mechanical Accessibility'?

The process continued until the matrix was completed and the team kept answering individually and then discussing to reach a consensus. In the end, a judgement consistency check was done. Some judgements were not consistent, and the team had to alter their input following the suggestions of M-MACBETH software on where to change and to what direction. The facilitator assured that the team was changing the judgements to demonstrate the actual team's perception and not only because the software was telling them to change. The results obtained are shown in Figure 10.



Weighting (Overall)

	[Rel]	[RDMA]	[Turn]	[AccInfo]	[Acc]	[MechAc]	[Brak]	[all lower]	Current scale
[Rel]	no	moderate	strg-vstr	strg-vstr	v. strong	extreme	vstrg-extr	vstrg-extr	25
[RDMA]		no	strong	mod-strg	strong	vstrg-extr	vstrg-extr	vstrg-extr	22
[Turn]			no	moderate	strong	strg-vstr	strg-vstr	v. strong	17
[AccInfo]				no	weak-mod	mod-strg	v. strong	v. strong	14
[Acc]					no	mod-strg	strg-vstr	v. strong	12
[MechAc]						no	strong	mod-strg	7
[Brak]							no	moderate	3
[all lower]								no	0

Figure 10 CAs M-MACBETH weighting matrix

With a complete matrix and consistent judgements, it was possible to obtain the weights on a ratio scale of 0 to 100 for each CA, as shown at the right column in Figure 10. The team had the weights shown in a histogram for easier visualization (Figure 11) and was inquired if they agreed with the results. The resulting weights were unanimously accepted, and these are the weights to be used in the HOQ.

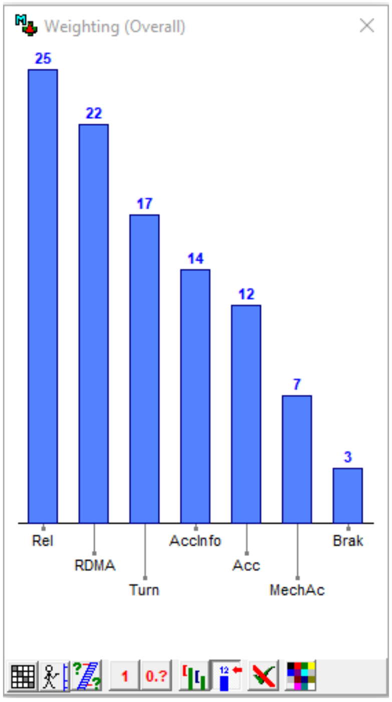


Figure 11 CA weights histogram

5.2.2 Implementing MACBETH in the Competitive Assessment Room

To better understand the position of FST Lisboa's car against its main competitors, it is essential to know how they compare among each other in each CA. This will allow the team to identify its potential and points of possible improvement considering the customer perspective (that in this case is the team itself).

To quantitatively obtain this perspective, it is necessary to create a value function for each CA using MACBETH. This way, knowing the performance of a competitor in a determined CA will allow its ranking with the others for that CA by returning scores for the performance of each car, including the team's own car. This will later be useful in determining the sale points and the relative strategic weight of the CA in a modified approach of the one presented in section 3.3.2.2).

The creation of value functions would require defining fixed scores for the two reference performance levels, "Neutral" and "Good", previously defined, to which were assigned 0 and 100 value units, respectively. In order 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 quantitative CA. To ease the judgments of the team, these quantitative levels had to be equidistant. 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 5, while the qualitative CAs "Mechanical Accessibility" and " Access to Information" are shown in Table 6 and Table 7, respectively.

Table 5 Quantitative CAs and the performance levels used to create value functions

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 6 Mechanical Accessibility performance levels used to create value function

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 7 Access to Information performance levels used to create value function

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+09Mech
Wired access to some variables more than FST 09e + more mechanical parts status than FST 09e	Wired09e+09eMech
Everything like FST 09e = "Neutral"	As09e
Less than FST 09e	Less09e

This process of creating the value scales started with the facilitator asking the team to rank 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 the previously defined performance levels in each CA. For example, for "Good Turning Abilities" the team was asked "what is the difference of attractiveness between a car that has a maximum lateral G-force of 1.25 Gs and a car that reaches 1.5 Gs when turning?" Each participant privately replied in a paper and was asked to show their answers. They were asked to discuss their reasons for the answer and reach a consensus, that was agreed to be "weak to moderate" according to the semantic scale of MACBETH. This was repeated for each pair of performance levels in this CA with a judgement consistency check at the end. 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. The team was asked to verify if it represented their evaluation of the performance levels, and if not, to adjust the scale directly in the graph. If it was still not representative, they would be asked to review the judgements matrix and change their judgements. This was repeated for every CA.

The judgement matrix and value scale for "Good Turning Abilities" can be seen in Figure 12, while the other matrices and scales can be found in Appendix A.

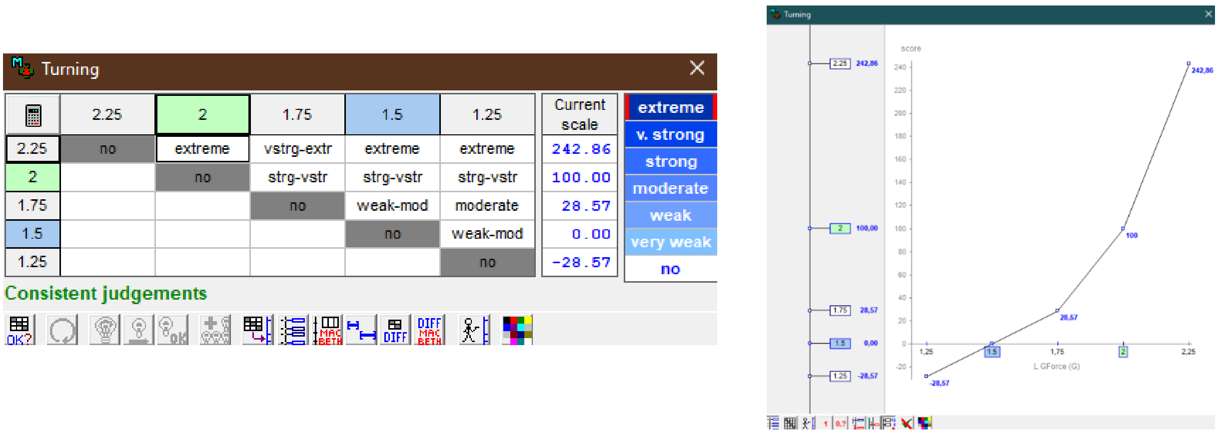


Figure 12 "Good Turning Abilities" judgements matrix and value scale

In some cases, the number of inconsistencies led the facilitator to question the importance of that CA or performance level to the team's objectives. For the attribute “Reliability” the metrics had to be changed because as the study progressed and several inconsistencies arose, the team realized that they were not very significant. After careful consideration, the team finally concluded that the current metric was adequate (days of the car on repair during testing), and the judgement process had to be restarted.

5.3 Translating the Voice of the Customer into Engineering Characteristics

A crucial step in the application of the House of Quality (HOQ) is the translation of the CA into Engineering Characteristics (EC), that is, technical aspects of the project that fulfill the attributes of the customer. This process can be done using a diverse set of frameworks and tools, always with the direct involvement of the QFD team.

In this study, the challenge was to obtain ECs that were both specific, so the team could have precise guidance, and not too general, otherwise it would not be of any use in the design process of the car. The process for obtaining FST Lisboa’s ECs followed a Value Focused Thinking approach (Keeney, 1992) having as starting points the Customer Attributes.

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. For example, for the CA “Good Acceleration Time” the team answered “weight” for the first question and “more torque” for the second. After some more brainstorming, the team concluded that controllers and drag also influenced the acceleration time of the car. Then, they were asked those same questions for the answers they provided, for example, “what influences the drag of the car?”. The answers were “better wing design” and “a working Drag Reduction System (DRS)”. They were then inquired again “how can we get a better wing design?” And the reply was “with more Computational Fluid Dynamics (CFD) studies”. 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 of influence. This gave origin to the map shown in Figure 13. Detailed images of the map can be found in Appendix B.

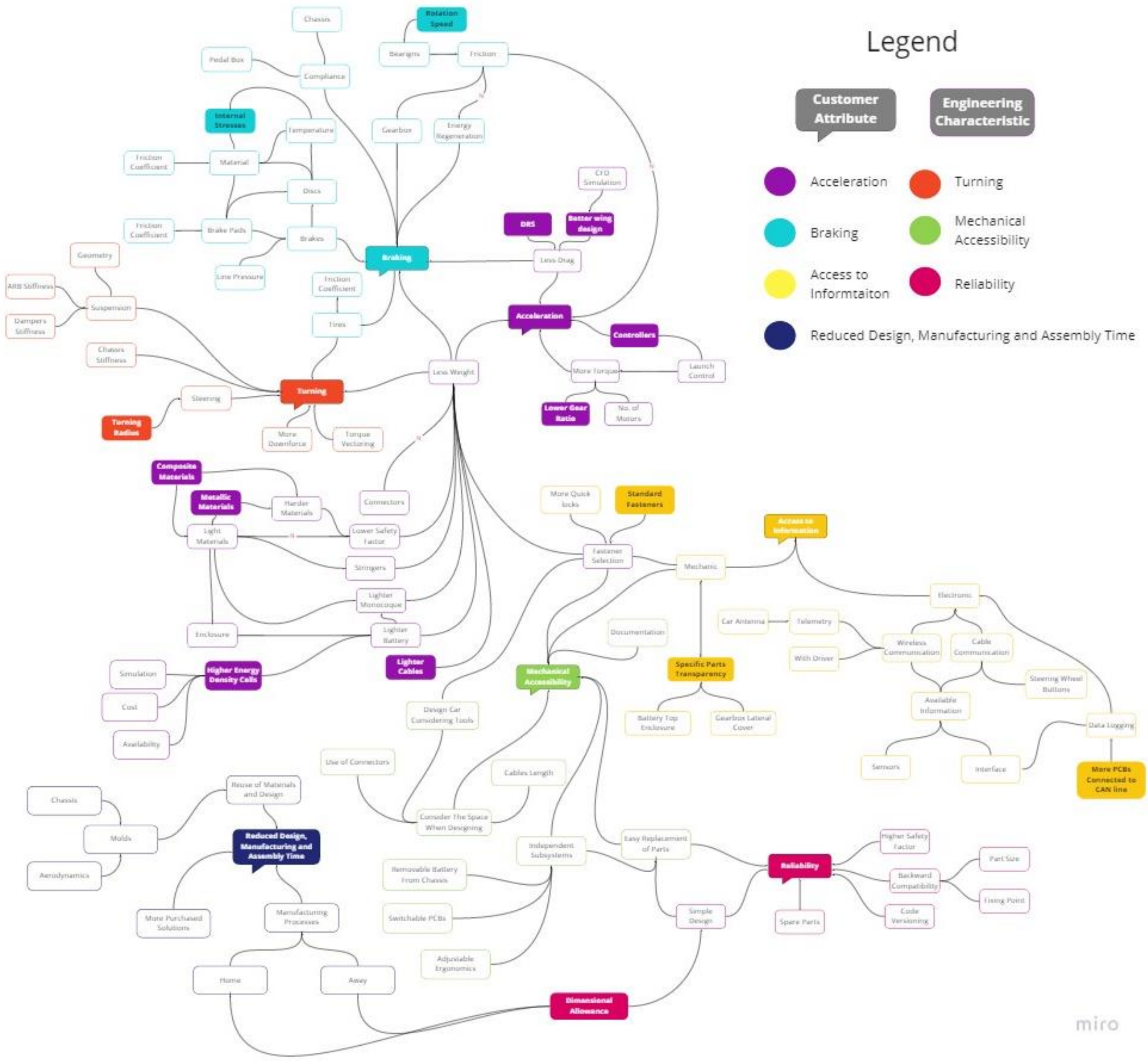


Figure 13 The FST 10e causal map of requirements

From the six CAs identified by the team, it was possible to find 15 ECs that met the requirement presented at the beginning of this chapter and that were also measurable, to meet the quantitative HOQ guidelines. Each one of them and their measurement units can be found in Table 8.

Table 8 Engineering Characteristics and measurement units

Engineering Characteristic	Measurement Unit	Engineering Characteristic	Measurement Unit
Rotation speed of bearings	rpm	**Internal Steel Strength on Brake Discs**	MPa
Battery Cells' Energy Density	Wh/kg	**Controllers**	No. Of controller types
Total Weight of Composite Materials	kg	**Gear Ratio**	Ratio between outer ring and planets

(continues)

Table 8 Engineering Characteristics and measurement units (continued)

Engineering Characteristic	Measurement Unit	Engineering Characteristic	Measurement Unit
Total Weight of Metallic Materials	kg	**Total Weight of the Cables**	kg
Turning Radius	meters	**PCBs Connected to CAN Line**	% of Connected PCBs Features
Dimensional Allowance	% deviation from designed target	**Transparency of Specific Parts**	Combinations of Parts
DRS that significantly reduces drag	% of drag reduction	**Better Wing Design**	Cl/cd (lift/drag) coefficient
Use of More Standard Fasteners	No. of Tools		

5.3.1 Technical Benchmark Using MACBETH

To compare the team's car with the competition in a quantitative way, it was needed to create a value function for each EC, in a similar process to the one undertaken for the CAs. This allows for scoring of the compared competitor in the created scale, making the process of benchmarking more reliable and numerically correct.

For each EC, the team was asked to provide performance levels and to set one to be the "Neutral" and other to be the "Good" level. According to the HOQ methodology, the ECs should be measurable, preferably in a quantitative way. In this study, all ECs are measurable, however, some of them have qualitative performance levels in the M-MACBETH software such as "Transparency of Specific Parts", "Controllers" and "Gear Ratio". Each one has a specific reason, even though they could be considered as quantitative performance levels at some point.

In the EC "Transparency of Specific Parts", the team suggested that there would be many possible combinations of parts that could be transparent, therefore determining performance levels for each combination would be daunting. The facilitator decided to approach the problem with an adapted version of the "determinants technique" proposed by Bana e Costa *et al.* (2002). Following this approach, the team was asked to indicate what parts could be transparent, and then stating:

1. Which ones are Determinants (D) – parts that if are not transparent the score would be negative;
2. Which ones are Important (I) – parts that are important to be considered, but the absence of one of them would not make the option to score negatively;
3. Which ones are Secondary (S) – parts that would be nice to be transparent, but do not have much impact and can be left out.

Differently than in the technique proposed by Bana e Costa et. al (2002), in this case, the alternatives were binary (either they were implemented or not). This way, it was not required to state how different negative or positive performances would affect the result. If one part was already selected to be transparent, then it was a positive improvement. However, if some important were selected and one determinant was not, then it is already worse than the current state, thus negative,

With this information, the facilitator created with the team quantitative performance levels that capture the possible combinations of transparent parts according to the number of Determinants, Important and Secondary parts that are in the design option. In this case, the team did not consider any of the parts as being secondary, mostly due to the small number of parts that could be both beneficial and allowed to be transparent. The performance levels for this EC are shown in Table 9.

Table 9 Transparency of Specific Parts Performance Levels

EC	Performance Levels	Short Name
Transparency of Specific Parts	All Determinants and All Important	ADAI
	All Determinants and the Majority of Important	ADMI
	All Determinants and Some Important	ADSI = “Good”
	All Determinant and No Important	ADNI = “Neutral”
	No Determinant and All Important	NDAI
	No Determinant and Some Important	NDSI

For the EC “Controllers” the levels were defined as combinations of types of controllers implemented in the car. According to the team, different orders of implementations would not make sense, therefore the use of the determinants technique was not needed. The performance levels of the EC “Controllers” can be seen in Table 10.

Table 10 Controllers Descriptor of Performance

“Controllers” Performance Levels	Short Name
Steering Proportional + Deratings and Safety + Traction Control with no Feedback + Traction Control with Feedback + Yaw Rate Controller + Launch Control	CTRL1
Steering Proportional + Deratings and Safety + Traction Control with no Feedback + Traction Control with Feedback + Yaw Rate Controller	CTRL2 = “Good”
Steering Proportional + Deratings and Safety + Traction Control with no Feedback + Traction Control with Feedback	CTRL3
Steering Proportional + Deratings and Safety + Traction Control with no Feedback	CTRL4
Steering Proportional + Deratings and Safety	CTRL5 = “Neutral”
Steering Proportional	CTRL6
No Controller	NO

On the other hand, the ECs “Gear Ratio” was defined as having binary measurements. As the gear ratio of a gearbox is, in this case, the reduction factor of the rotation coming from the motor to the wheels, it has a target design value obtained from preliminary studies. That means that either the team reaches the goal by manufacturing a gearbox that has this value of reduction (what often happens), or not (that may happen due to manufacturing problems). As there is no “one-size-fits-all” value, each team has its own target, only differentiating on the capabilities of actually reaching it. It was kept for the analysis because it has significant importance for some CAs, and therefore was worth the attention during design. Its performance levels can be seen in Table 11. The performance levels for the remaining ECs are linear quantitative levels and are shown in Table 12.

Table 11 Gear Ratio Descriptor of Performance

Gear Ratio Performance Levels	On Target = "Good"
	Off Target = "Neutral"

Table 12 Quantitative ECs Performance Levels needed for creating the value functions

Battery Cells' Energy Density	**Rotation speed of bearings**	**Internal Steel Strength on Brake Discs**	**Total Weight of Composite Materials**
210	6800	320	50
200 = "Good"	6300 = "Good"	280 = "Good"	60 = "Good"
190	5800	240	70
180 = "Neutral"	5300 = "Neutral"	200 = "Neutral"	80 = "Neutral"
170	4800	160	90
Total Weight of Metallic Materials	**Total Weight of the Cables**	**PCBs Connected to CAN Line**	**Dimensional Allowance**
80	6	100	0.0025
90 = "Good"	8 = "Good"	95 = "Good"	0.05 = "Good"
100	10	85	0.075
110 = "Neutral"	12 = "Neutral"	75 = "Neutral"	0.1 = "Neutral
120	14	65	0.125
DRS that significantly reduces drag	**Better Wing Design**	**Use of More Standard Fasteners**	**Turning Radius**
35	4.1	1	7.5
30 = "Good"	3.5 = "Good"	20 = "Good"	8 = "Good"
25	2.9	40	8.5
20 = "Neutral"	2.3 = "Neutral"	60 = "Neutral"	9 = "Neutral"
15	1.7	80	9.5

With the performance levels set, the following step was to create a value function for each one of the ECs, similarly to what was undertaken in section 5.2.2 for the Customer Attributes' value functions, asking for pairwise judgements of difference in attractiveness between every two levels of performance. As it happens with the Customer Attributes the "Neutral" reference performance will have a value score of 0, and the "Good" reference level a score of 100. Note that the assignment of zero value units to the "Neutral" performance level (which is a performance that is neither positive nor negative on the corresponding EC) is the definition of a "true" zero value on the value scale, which is a requirement to apply a meaningful portfolio analysis (Clemen and Smith, 2009), as it will be done in this dissertation.

5.4 The Relationship Matrix Using MACBETH

The central point of the HOQ, however, is the relationship matrix. In this part, all the CAs, what the customer wants from the product, are related to engineering characteristics of the design that may satisfy them.

In the original model, this process used ordinal scales to rate the intensity of the relation of each CA to an EC, which is not adequate, as it was previously explained. With the use of MACBETH and the M-MACBETH software, it is possible to relate them in a quantitative way, based on the judgements of difference of attractiveness, that in this case is the difference in intensity of relation.

The steps undertaken to achieve this were as follows:

1. Each CA was inserted into M-MACBETH software as criteria nodes, and their basis of comparison was "the options +2 references", while each EC was inserted as an option;
2. The reference levels were selected so that the upper reference was 1 (perfect relation) and the lower reference was 0 (no relation);
3. For each CA the team was asked to order the options (ECs) according to the intensity of relation with the CA using the MACBETH semantic scale of "very weak", "weak", "moderate", "strong", "very strong", "extreme" and "no" (no relation and value of 0) filling the right-most column (no relation). When two or more ECs had the same semantic level, the team was asked if any of them had a stronger relation to the CA being analyzed. They were then ordered according to the answers given;
4. Then, the team was asked to pairwise compare consecutive ECs regarding the difference in relation intensity using the MACBETH's semantic scale filling the first line and the diagonal above the main diagonal of the matrix similarly to Bana e Costa *et al.* (2014) approach. In this step the team was asked to consider the improvement from "Neutral" to "Good" of the two ECs being compared as a basis.

This process once more made use of private answers to avoid informational cascades. The obtained matrices for every CA can be found in Appendix C, and the House of Quality with the relationship matrix filled can be seen in Figure 14 below.

Customer Attributes	CA Weigths	Battery Cells' Energy Density	Total Weight of Composite Materials	Total Weight of Metallic Materials	Turning Radius	Controllers	Gear Ratio	Total Weight of the Cables	Dimensional Allowance	PCBs Connected to CAN Line	Transparency of Specific Parts	DRS that significantly reduces drag	Better Wing Design	Internal Steel Strength on Brake Disc	Rotation Speed of Bearings	Use of More Standard Fasteners
		Wh/kg	kg	kg	m	No. Of controller types	Ratio between outer ring and planets	Kg	% deviation from designed target	% of Connected PCBs Features	Combination of Parts	% of drag reduction	Coefficient of lift/drag	MPa	rpm	No. of Tools
		↑	↓	↓	9m	↑	15:21	↓	↓	↑	↑	↑	↑	↓	↑	↓
Good Acceleration Time	0,12	0,84	0,78	0,45		0,73	0,89	0,03	0,08			0,38	0,62		0,51	
Good Turning Abilities	0,17	0,15	0,34	0,32	0,78	0,98		0,02	0,43				0,88	0,24		
Safe and Fast Braking	0,03	0,09	0,34	0,23		0,05	0,87	0,02	0,13			0,75	0,36	0,98	0,40	
Reliability	0,25	0,61	0,75	0,64		0,25		0,11	0,50	0,07			0,04	0,89	0,36	
Mechanical Accessibility	0,07		0,35	0,07			0,12	0,16	0,30		0,80		0,67			0,95
Access to Information	0,14		0,02	0,04			0,12		0,14	0,93	0,95		0,46			0,30
Reduced Design, Manufacturing and Assembly Time	0,22		0,07				0,18		0,75	0,11	0,68		0,35			0,89

Figure 14 HOQ Relationship Matrix

5.5 Correlating ECs in the Roof Using MACBETH

The Roof of the HOQ is the section of the framework that allows design teams to understand how each EC correlates with the others. This can be powerful if used correctly, allowing for a sounder selection of design trade-offs. The MACBETH methodology applied to this part of the HOQ provides each correlation with a value that is obtained with a similar approach of the one described for the relationship matrix in section 5.4. The steps in this part were:

1. The team was asked to indicate what EC-EC pairs had a positive and a negative correlation;
    a. For the positive correlations the upper reference was set to 1 (extreme positive correlation) and the lower reference to 0 (no correlation);
    b. For the negative correlations the upper reference was set to 0 (no correlation) and the lower reference to -1 (perfectly symmetric correlation);
2. The team was then asked to assign an intensity to the correlation using the MACBETH semantic scale. This allowed ordering the positive and negative correlations filling the right-most column of the matrix. When two or more correlations had equal intensities, the facilitator asked if one was stronger than the other. If they were not, they were assumed indifferent.
    a. For the positive correlations the team was asked what the difference in intensity of "no correlation" to "extreme positive correlation" was;
    b. For the negative correlations the team was asked what the difference in intensity from the "perfectly symmetric correlation" to "no correlation" was;
3. Lastly, pairwise comparisons between correlations in the diagonal above the main diagonal of the matrix were undertaken.
    a. The team was asked questions similar to "what is the difference in the intensity of the correlation between 'Controllers-PCBs Connected to CAN Line' and 'Battery Cells' Energy Density-Total Weight of Composite Materials'?". The same question could be translated to a simple "how much more correlated are 'Controllers-PCBs Connected to CAN Line' than 'Battery Cells' Energy Density-Total Weight of Composite Materials'?"

The last point of this process is particularly difficult to translate into familiar words and terms that make the team easily understand what they are being asked. During this part, the team often asked to be remembered of the question and to correct previous answers.

The correlation matrix (roof) can be seen in Figure 15, and the judgement matrix can be found in Appendix D. This process allowed for correct identification of the values of correlation between each pair of ECs, with the positive ones represented in green and the negative in red.

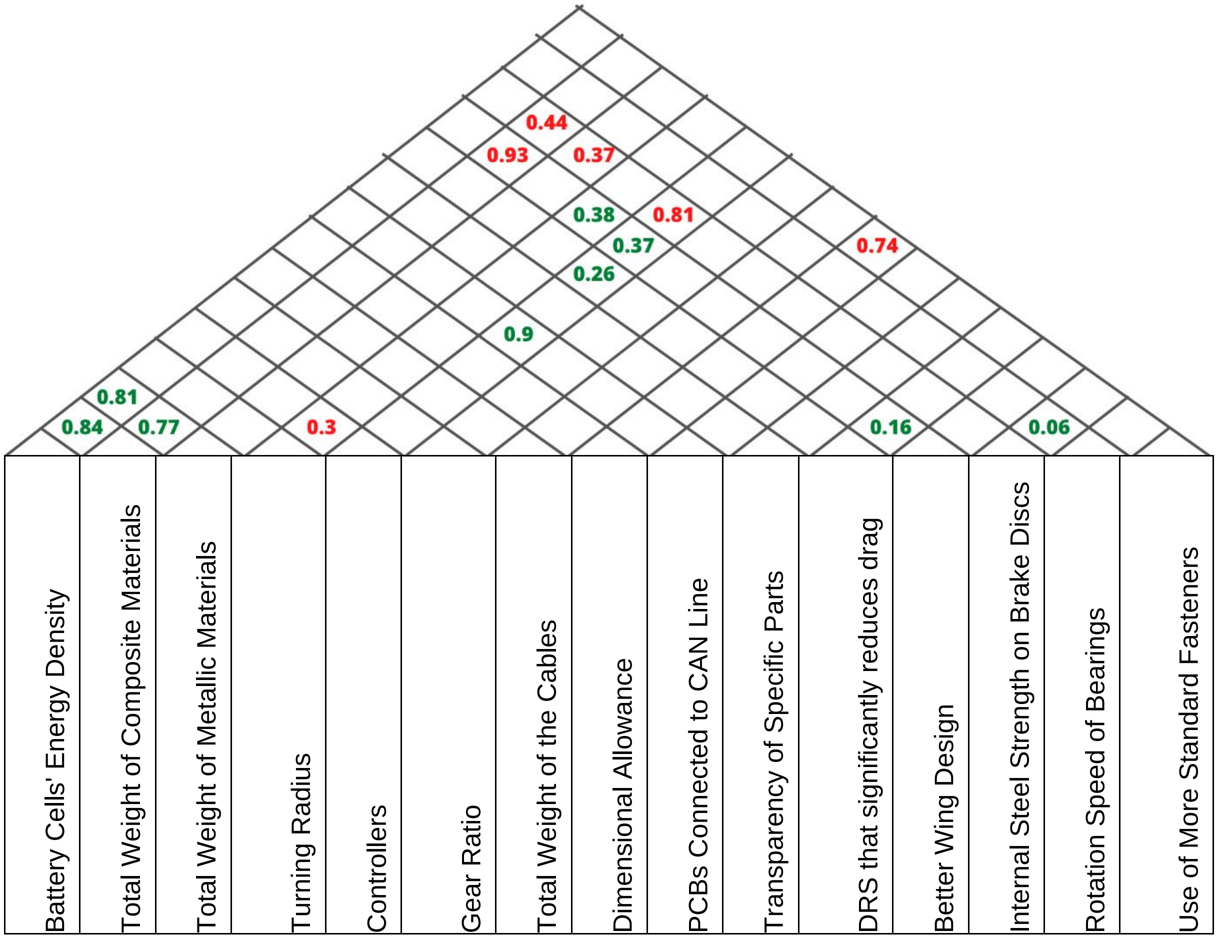


Figure 15 The Roof

5.6 Benchmarking Competition with MACBETH

Upon completing the steps presented in section 5.2.2 it becomes possible to do a benchmark of the competitors' cars against the FST 09e inserting their performances for each CA and EC into M-MACBETH software. The program automatically returns scores for each competitor following the value scale created.

The team was asked to provide a list of competitors, that could be diverse. They selected four teams, of which three are at a similar level, and one is better. The performance of the other prototypes for each CA was obtained in two different ways: online search and asking the teams. As FS is an open space for knowledge exchange, this was the best way of obtaining answers. The selected teams (and their 2018/19 cars) were UPC ecoRacing (ecoRX 2019), Aristurtle (Thetis), WHZ Racing Team (FP13.19e) and Superior Engineering (SE18) shown in Figure 16, Figure 17, Figure 18, Figure 19, respectively. From the obtained answers, the performance of each competitor car could be inserted in the software returning their scores for each CA as shown in Figure 20, while the ECs table is in Appendix E.

Figure 16 UPC EcoRacing's EcoRX 2019. Photo by UPC EcoRacing

Figure 17 Aristurtle's Thetis. Photo by Aristurtle

Figure 18 WHZ Racing Team's FP13.19e. Photo by WHZ Racing Team

Figure 19 Superior Engineering's SE18. Photo by Formula Student Germany

Table of scores

Options	Overall	MechAc	Rel	Acc	Brak	Turn	AccInfo	RDMA
[Good All Over]	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
WHZ	89.13	0.00	-83.52	37.77	0.00	385.72	34.77	159.25
UPC	64.55	100.00	12.26	26.00	100.00	11.43	34.77	188.88
Arist	55.46	0.00	87.23	-10.81	-75.00	42.86	56.52	100.00
SupEng	9.57	-133.33	116.98	-11.85	-30.00	28.57	12.77	-66.66
[Neutral All Over]	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weights :		0.0700	0.2500	0.1200	0.0300	0.1700	0.1400	0.2200

Figure 20 Competitors' Scores for CAs

The scores themselves are already of good use comparing where each competitor excels, but to fully understand what the best design choices and trade-offs are, the HOQ must be completed. The next step was to define strategic and technical goals.

5.6.1 Strategic and Technical Goals

The strategic and technical goals allow the team to have little guidance on what to do with the results from the HOQ and how to compare its car to the others on each Customer Attribute (CA) and Engineering Characteristic (EC). There are many options for these objectives, always considering the obtained scores (in this case from M-MACBETH) and the related competitors. They are set according to the team strategy and capabilities, with the possibility to differ in each CA, EC and for each competing car. Some examples are:

- Get to the "Good" level –When A scores lower than B, which is also below the "Good" level;
- Keep the "Good" level – When A scores lower than B, but it is at the "Good" level;
- Worsen to the "Good" level – When A scores higher than B and is above the "Good" level;
- Equalize the competitor – When B is above the "Good" level, and A is below or at the "Good" level;
- Surpass competitor in X% - When A and B are below or at the "Good" level and A scores lower than B.

In this study, the team was asked to provide strategic goals that met their requirements, and they considered important for the design.

5.6.1.1 Customer Attributes Strategic Goals

The team has defined its Customer Attributes' strategic goals for the season observing the following:

- The score should never decrease in any CA;
- The minimum score is the "Good" level (100 points);
- If the best competitor is above the "Good" level, the team must surpass in 15% the difference between the "Neutral" and the "Good" levels of the CA.

Following the defined criteria for the strategic goals, they can be calculated according to equation 6, slightly adapted from Coelho (2017).

$$sg_i = \begin{cases} max[100, v_i(FST\ 09e)], & if\ max[v_i(X), v_i(FST\ 09e)] < 100 \\ max\ [v_i(FST\ 09e), [0{,}15 \times [v(good) - v(neutral)] + max\ \{v_i(X)\}]], & otherwise \end{cases} \quad (6)$$

Where sg_i is the strategic goal of CA *i*, $v_i(X)$ is the score of the competitor X in the CA *i*, with X = {FP13.19e, SE18, EcoRX 2019, Thetis}. The strategic goals can be seen in Table 13 below.

Table 13 Scores and Strategic Goals

Customer Attribute	FST 09e Score	EcoRX 2019 Score	SE18 Score	FP13.19e Score	Strategic Goal
Good Acceleration Time	0	26	-11.85	37.77	100
Good Turning Abilities	0	11.43	28.57	385.72	400.72
Safe and Fast Braking	0	100	-30	0	115
Reliability	0	12.26	116.98	-83.52	131.98
Mechanical Accessibility	0	100	-133.33	0	115
Access to Information	0	34.77	12.77	34.77	100

(continues)

Table 13 CA Scores and Strategic Goals (continued)

Customer Attribute	FST 09e Score	EcoRX 2019 Score	SE18 Score	FP13.19e Score	Strategic Goal
Reduced Design, Manufacturing and Assembly Time	0	188.88	-66.66	159.25	203.88

5.6.1.2 Engineering Characteristics Technical Goals

Similarly to what was done for the Customer Attributes (CA) in the previous section, it was also needed to define objectives for the engineering characteristics (EC). For this, the FST 09e's score had first to be compared to the best performing competitor as equation 7 below demonstrates:

$$\Delta T_j = v_j(FST\ 09e) - max\{v_j(X)\} \qquad (7)$$

Being ΔT_j the FST 09e benchmark in EC *j* and $v_j(X)$ the competitor X score in the EC *j,* with X = {FP13.19e, SE18, EcoRX 2019, Thetis}.

The obtained results allowed for a better understanding of the positioning of FST Lisboa's car against the other teams, meaning that if $\Delta T_j < 0$ the FST 09e was worse than the best competitor in the EC *j* (the lower the worst), if $\Delta T_j = 0$ it is equal and if $\Delta T_j > 0$ it is better (the greater, the better).

Then, objectives were defined starting from this analysis, similarly to what was previously done in section 5.6.1.1. They were:

- The minimum score is 100 points;
- When $v_j(FST\ 09e) < max\{v_j(X)\}$ and $max\{v_j(X)\} \geq 100$, the technical goal score must surpass the $max\{v_j(X)\}$ in 15% the difference between the "Neutral" and the "Good" levels of the *jth* EC.

Equation 8 defines the technical goals (tg_j) for the *jth* EC.

$$tg_j = \begin{cases} max[100, v_j(FST\ 09e)], & if\ max[v_j(X), v_j(FST\ 09e)] < 100 \\ max\ [v_j(FST\ 09e), [0{,}15 \times [v(good) - v(neutral)] + max\ \{v_j(X)\}]], & otherwise \end{cases} \qquad (8)$$

The scores, benchmark and technical goals are shown in Table 14.

Table 14 EC Scores, Benchmark and Technical Goals

	Cars Scores						
Engineering Characteristics	**FST 09e**	**EcoRX 2019**	**SE 18**	**FP13. 19e**	**Thetis**	**Bench-mark**	**Technical Goal**
Battery Cells' Energy Density	0	115	100	50	-50	-115	130
Total Weight of Composite Materials	0	357.13	14.29	288.56	442.84	-442.84	457.84

(continues)

Table 14 EC Scores, Benchmark and Technical Goals (continued)

	Cars Scores						
Engineering Characteristics	**FST 09e**	**EcoRX 2019**	**SE 18**	**FP13. 19e**	**Thetis**	**Bench-mark**	**Technical Goal**
Total Weight of Metallic Materials	0	33.33	474.99	225	100	-474.99	489.99
Turning Radius	0	100	-80	100	100	-100	115
Controllers	0	133.33	-50	133.33	50	-133.33	148.33
Gear Ratio	0	100	100	100	100	-100	115
Total Weight of the Cables	0	200	100	0	33.33	-200.01	215.01
Dimensional Allowance	0	0	-200	100	-200	-100	115
PCBs Connected to CAN Line	0	114.29	71.43	114.29	42.86	-114.29	129.29
Transparency of Specific Parts	0	-175	300	0	-175	-300	315
DRS that significantly reduces drag	0	64	-160	-160	-160	-64	100
Better Wing Design	0	16.67	-11.25	14.17	87.5	-87.5	100
Internal Steel Strength on Brake Discs	0	-97.51	-53.58	57.15	328.56	-328.56	343.56
Rotation Speed of Bearings	0	1370	170	1470	3470	-3470	3485
Use of More Standard Fasteners	0	76.33	97.63	88.16	142.11	-142.11	157.11
Total Weight of Metallic Materials	0	33.33	474.99	225	100	-474.99	489.99
Turning Radius	0	100	-80	100	100	-100	115
Controllers	0	133.33	-50	133.33	50	-133.33	148.33
Gear Ratio	0	100	100	100	100	-100	115
Total Weight of the Cables	0	200	100	0	33.33	-200.01	215.01

5.6.2 Sale Points

The Sale Points, as already explained in section 3.3.2.2, is a benchmark of the competition in a customer's perspective. It provides insights on how well the company's product, or in this case the FST 09e, is performing against competitors for each of their attributes to be used as a sale point. In the traditional application of the HOQ, the sale points are chosen based on the "feeling" the company has that that CA is a selling point or not. In this study, this is applied following the approach suggested by Coelho (2017) as described in equation 9.

$$SP_i = W_i \times [v(a) - v(b)], \quad (9)$$

where:

SP – Sale points of the *ith* CA;

W – The weight of the *ith* CA, obtained with M-MACBETH software tool;

v(a) – the score in the *ith* CA for the product *a*, with *a* being the company's own product;

v(b) – the score in the *ith* CA for product *b*, with *b* being the best performing competitor.

If SP < 0, it means that the competition is better in the view of the customer for that particular attribute (the lower the value, the worst is the perception). If SP > 0, the company's product is seen in advantage and the attribute should be used to promote the product (the greater the value, the better the product is considered against the competition), while if SP = 0 both products are equally good or the CA is not relevant for the customer. After all the weights and scores for each competitor were calculated, it was possible to obtain the sale points for the FST 09e, which are shown in Table 15.

Table 15 Sale Points of the FST 09e in each CA

Customer Attribute	CA Weight	FST 09e Score	Best Competitor Score	Sale Point
Good Acceleration Time	0.12	0	37.77	-4.532
Good Turning Abilities	0.17	0	385.72	-65.572
Safe and Fast Braking	0.03	0	100	-3.000
Reliability	0.25	0	116.98	-29.245
Mechanical Accessibility	0.07	0	100	-7.000
Access to Information	0.14	0	56.52	-7.913
Reduced Design, Manufacturing and Assembly Time	0.22	0	188.88	-41.554

The results obtained by multiplying the weight of the CA with the difference of the FST 09e's scores to the best competitor shows that FST Lisboa should not use any of these attributes as a marketing differential. In every case, the team's car is below the competition regarding the "client" perspective.

5.6.3 Deviations

After calculating all the scores for both the competition and the FST 09e, establishing strategic goals and sale points, it is important to compare the results by assessing the difference between the FST 09e and the strategic goal. Thus, it was defined (Coelho, 2017):

- Unweighted Deviation – allowing to assess the scoring difference between the FST 09e and the strategic goal for that CA (equation 10);
- Weighted Deviation – allowing to assess the scoring difference of the FST 09e and the strategic goal for a CA and also compare to the other attributes according to their weight (equation 11).

$$\Delta E_i = v(A_i) - SG_i \qquad (10)$$

$$\Delta E_i^* = [v(A_i) - SG_i] \times w_i \qquad (11)$$

Being $v(A_i)$ the score of the FST 09e in the *ith* CA, the SG_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. Table 16 provides the obtained scores with and without deviations.

Table 16 CA Deviations

Customer Attribute	CA Weight	FST 09e Score	Strategic Goal	ΔE_i	ΔE_i^*
Good Acceleration Time	0.12	0	100	-100	-12.000
Good Turning Abilities	0.17	0	400.72	-400.72	-68.122
Safe and Fast Braking	0.03	0	115	-115	-3.450
Reliability	0.25	0	131.98	-131.98	-32.995
Mechanical Accessibility	0.07	0	115	-115	-8.050
Access to Information	0.14	0	100	-100	-14.000
Reduced Design, Manufacturing and Assembly Time	0,22	0	203.88	-203.88	-44.854

5.7 The Importance of the Engineering Characteristics

The importance of the ECs will be the most important 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^*.

With this approach, the EC scores consider not only the weights of each CA given by the client (the team) but also how they compare to the competition. The higher the difference from the best-performing competitor above 100 points in score, and the higher the weight for the CA, more importance the related EC gets (or in other words, the greater the benefit of improving it). It is worth recalling that this is a different approach than the one presented in section 3.3.2.6, otherwise the result of the several multiplications would origin an extravagant number with redundancies.

The EC importance can also be represented in an unweighted and weighted manner, as proposed by Coelho (2017) obtained through the equations 12 and 13.

$$ECI_j = \sum_{i=1}^{n} R_{i,j} \times |\Delta E_i^*| \quad (12)$$

$$rECI_j = \frac{\sum_{i=1}^{n} R_{i,j} \times |\Delta E_i^*|}{\sum_{j=1}^{m} \sum_{i=1}^{n} R_{i,j} \times |\Delta E_i^*|} \times 100 \quad (13)$$

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 17.

Table 17 EC Importance and Weighted Importance

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%

(continues)

Table 17 EC Importance and Weighted Importance (continued)

Engineering Characteristic	ECI	rECI
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%

It is worth mentioning that this is the strategic technical importance, as it is not calculated using the CA weight, but its strategic final importance based on the benchmark and strategic goals. The House of Quality was then completed, and its final full version can be seen in page 73.

5.8 Welcome Home – Chapter Conclusions

In this chapter, the steps to build a House of Quality integrated with the MACBETH methodology were presented. The approach started with the selection of the CAs from the team's documentation, selection of the ECs from those attributes and went on to create value scales for each one of them and weights for the CAs. The value scales were used to perform a competitive assessment against real data from other Formula Student teams. A correlation matrix, also known as the roof, was created using the same methodology. The relationship matrix was developed assigning a relationship weight for each pair of CA-EC, which was later used to define the EC importance. A technical benchmark was also done using the value scales and used to set up the technical goals. It is worth noting that this approach herein applied provides meaningful results, which does not happen with the traditional usage of the HOQ, correcting the common issues within this framework. However, it takes longer than the traditional HOQ to be completed.

Following the steps proposed by Yang et al. (2003), as explained in section 3.3.3, the HOQ is analyzed. First, it is needed to check for blank and weak columns to see if all the ECs are related to a CA. Indeed, that are a few weak relations between EC and CAs, but if removing them, no column would be unaddressed and would still have at least one strong link. For example, the EC "PCBs Connected to CAN Line" is related to three different CAs, in two of them the links are 0.07 and 0.11, while for "Access to Information" it is 0.93 in a maximum of 1. In the case of "Turning Radius", this EC is only related to "Good Turning Abilities", but with a relation of 0.78, meaning it is relevant. This way, every EC is strongly related to at least one CA.

Then, looking at blank or weak rows to assess if a CA is not being addressed or is partially addressed by an EC. In this case, the row with the fewer number of ECs related is the CA "Reduced Design, Manufacturing and Assembly Time", counting 7 relations out of 13 ECs with at least three of them being over 0.5. This means that every CA is well addressed by the ECs defined.

The next step is to look for conflicts. In this HOQ, there is no conflict, as the FST 09e has a negative benchmark performance in both the technical benchmark and the competitive assessment. Looking at a specific case, for example, "Safe and Fast Braking" (the CA the FST 09e is best performing against the competition), the ECs with stronger relationships are "DRS That Significantly Reduces Drag" and "Internal Steel Strength in Brake Discs". In "DRS That Significantly Reduces Drag", the FST 09e performs better than all except the EcoRX2019, which is the best performing in "Safe and Fast Braking". On the other hand, for "Internal Steel Strength in Brake Discs", the FST 09e performs better than all but Thetis and FP13.19e, with the former being worse and the latter being equal in "Safe and Fast Braking". Overall, there are no conflicts. On the other hand, the entire design is a critical point, as it is not the best performing in any CA and any EC, having negative benchmark compared to the four selected competitor teams.

Then, it is suggested to look for the significance of ECs, the ones that relate to many CAs, or that may be mandatory for safety, regulatory or internal company requirements. "Total Weight of Composite Materials", "Total Weight of Metallic Materials", "Gear Ratio", "Dimensional Allowance" and "Better Wing Design" are the ECs with the most relationships to CAs. At the same time "Controllers", "Transparency of Specific Parts", "Internal Steel Strength on Brake Discs" and "Use of More Standard Fasteners" are the ECs with the highest relationship weights, having all at least one with a relationship weight higher than 0.95 out of one. Not surprisingly, they were all the ECs with the highest calculated weights. The next step was to look for "Eye-opener" Opportunities. They are ECs where the team and competitors are doing poorly. Looking at the scores of each competitor car in the ECs, it is worth noting that only two have a functioning Drag Reduction System (DRS). As this ECs is correlated to all the CA, it is worth calling attention to its development, potentially leading to better results. The EcoRX2019 is the car that performed consistently better than the FST 09e in all Customer Attributes and is the only one besides the FST 09e to have a DRS and that works better.

Benchmarking the competition also has the purpose of understanding where they excel so that the team could incorporate a few features. In the current benchmark, an enormous difference appears in the EC "Rotation Speed of Bearings" with three teams scoring over 1000. It is an alert for FST Lisboa, especially when the closest competitor is scoring 170. It means that the team is far behind the competition in this EC. In broad terms, it is possible to say that the FST 09e is around an average performer. For the CA "Good Acceleration Time" the team performs better than two competitors and worse than other two. For "Good Turning Abilities" it is by far the worst-performing car in the comparison, while for "Safe and Fast Braking" it is better than Thetis and SE18, equal to FP13.19e and worse than EcoRX2019.

Let alone, the results obtained so far would be enough to perform an analysis of the design to be prioritized, but that exercise would not guarantee the most efficient selection of improvement measures for the car. The intent of this study is precisely to diminish the time and manage the complexity of the analysis, proposing a design strategy to be followed, and therefore it goes one step further towards this purpose

6 One Step Further – The Efficient Selection of ECs

6.1 Introduction

Following the guidelines proposed by Yang *et al.* (2003), the process of selecting Engineering Characteristics (EC) to be improved requires a comprehensive analysis of the information provided in each room of the House of Quality. One has to analyze the EC scores, then check with which ones it correlates with, maybe look for the CAs performing poorly, all based on sole judgements from the design team with no structured approach.

This study intends to allow this process to be wholly defined and provide an efficient selection of ECs, thus allowing the team to spend more time on design solutions that could provide more benefit within the effort the team is willing to put. To identify efficient portfolios of improvement measures the PROBE software tool was used, using the EC scores as benefit scores and the efforts needed to implement the improvements as costs. Additionally, the roof was integrated into the portfolio analysis developed with PROBE through the use of synergies between ECs. The following sections of this chapter explain how this process occurred.

Section 6.2 explains how the portfolio options were defined and how the process of transforming continuous EC performances into discrete alternatives. Section 6.3 describes how M-MACBETH software was used to obtain a measure of the effort needed to implement each portfolio option. Section 6.4 goes through the implementation of the benefits and efforts of each alternative into PROBE software. Section 6.5 explains how constraints were set in PROBE. Section 6.6 presents the efficient frontier of projects portfolios that were obtained in PROBE. In section 6.7, the roof is integrated into the analysis using synergies between ECs, while section 6.8 presents the efficient portfolio of options considering synergies between ECs.

6.2 Defining Portfolio Options

This approach's challenge was to define the options a portfolio may have in PROBE, as there are many ECs and each one with several different performance levels (some quantitative and other qualitative) affecting the benefits and costs.

The dilemma was on how to measure the increments from one performance level to the other without having an infinite number of combinations of ECs performances and still being coherent. As most of the ECs have quantitative and continuous descriptors of performances, it was decided that the best approach for this would be to discretize the possibilities offered, by creating a finite set of plausible scenarios of performance (SP) for each EC. This set should follow a standard, that could be evaluated on benefit and cost (or effort) for each EC. Then, another question arose: what is this standard and how to know what is the performance we would like to place as an option for each EC? To solve this problem, it was needed to get back to the fundamentals of engineering design.

As already explained in section 3.2, engineering design is all about trade-offs following different strategies. The SPs were developed using a Strategy Generation Table, slightly adapted from the one indicated by Howard (1988). In his example, the decision-makers first define the scenarios of performance for each "EC", and later define the strategies connecting the options they believed would fit into a company objective. In this study, the team had first to set the design strategies. The facilitator suggested it to be an expanded and modified version of the two strategies proposed byOtto and Antonsson (1991), where they suggest the use of a "Conservative Strategy" and an "Aggressive Strategy" in their modelling. The Aggressive Strategy is the one that improves, even more, the characteristics that have higher preference, because the overall benefit they generate is greater than the toll for not improving the low performing characteristics. On the other hand, the Conservative Strategy is the one that focuses on improving the ones with lower preference. As the selection of what to improve and not to improve is undertaken by the PROBE software tool, these names intend to guide the team to select performance options. Table 18 presents the strategies used in this study.

Table 18 Trade-off Strategies

Trade-Off Strategy	Performance Levels
Aggressive Strategy	The dream performance, almost a stretch
Mid-Aggressive Strategy	Performance with a good attractiveness increment. Could correspond to the "Good" reference level
Mid-Conservative Strategy	Performance with a moderate increment in attractiveness
Conservative Strategy	Keep all in "Neutral" (let the car stay unchanged)

The following step was to define the SPs for each EC following the proposed strategies. For each EC, it is worth noting, there was no need for having performance scenarios for each trade-off strategy if it did not make sense. The team was free to define anything from one to four different performance scenarios for each engineering characteristic. The resulting options are shown in Figure 21.

	Battery Cells' Energy Density	Total Weight of Composite Materials	Total Weight of Metallic Materials	Turning Radius	Controllers	Gear Ratio	Total Weight of the Cables	Dimensional Allowance	PCBs Connected to CAN Line	Transparency of Specific Parts	DRS that significantly reduces drag	Better Wing Design	Internal Steel Strength on Brake Discs	Rotation Speed of Bearings	Use of More Standard Fasteners
Units	Wh/kg	kg	kg	m	No. Of controller types	Ratio between outer ring and planets	Kg	% deviation from designed target	% of Connected PCBs Features	Combination of Parts	% of drag reduction	Coefficient of lift/drag	MPa	rpm	No. of Tools
Aggressive Strategy	220	40	75	8	CTRL1		5	0,005	100	ADAI	40	5	300	8000	20
Mid-Aggressive Strategy	195	50	90		CTRL2		8,5	0,02		ADMI	35	3,5	270	7000	40
Mid-Conservative Strategy	185	60	100		CTRL4		10	0,05		ADSI	25	2,8	230	6000	55
Conservative Strategy	180	80	110	9	CTRL5	On Target	12	0,1	75	ADNI	20	2,3	200	5300	60

Figure 21 Performance Options for Each EC

As it was already known that some ECs were correlated to others from the creation of the Roof of the HOQ (see section 5.5), there was a concern that some performance options of one EC could be incompatible with performance options of other EC. However, the team said that there were no incompatibilities among the different SPs, meaning that every combination was possible.

6.3 The Effort of the Scenarios of Performance

It is impossible to analyze how efficient an allocation of resources is without knowing the cost of implementing the improvements. Therefore, it was needed to assess the cost of each scenario of performance. The challenge here was that it was tough for FST Lisboa to precisely estimate a cost in monetary terms, 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. It would be possible to estimate monetary values, but they would be very unreliable and could jeopardize the study leading to incorrect conclusions.

However, the effort needed to implement an improvement on the car was very present in the team's minds and could provide a more reliable source for the “cost”. Because of that, 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”. This criterion was said to have three main contributors to be considered: man-hours, money and management. Man-hours consider the time and number of members needed to implement something (looking for sponsors, workshop work, etc.); money is the amount required to invest (better solutions cost more, but often it is not known the actual number); and management is the managing effort of this work (turns creation, selection of members, implications to other developments, etc.).

The process to assess the efforts required was similar to the previous one and followed the approach proposed by Bana e Costa *et al.* (2014), which was used to obtain a measure of the “doability” of programs of actions (in that case a lower “doability” implies a high implementation “effort” and vice-versa).

1. Define the Scenarios Efforts basis of comparison;
    a. The upper reference is 100 (extreme effort);
    b. The lower reference is 0 (no effort).
2. Insert every scenario of performance as an option;
3. Ask the team to rank all of the scenarios of performance by decreasing effort;
    a. This was done asking questions similar to “what is the difference in the effort needed between ‘no effort’ and the effort to implement the scenario of performance ‘Composites 40’?”. The team, in this case, replied “extreme” filling up the right-most column of the judgement matrix;

b. The process was repeated to all the scenarios of performance, and in case two or more of them had similar judgements the team was asked to say if any of them required more effort than the other to be ordered accordingly. If they had no difference, they were considered indifferent.

4. Ask the team to fill the first row of the matrix by questioning the difference in the effort needed to implement a scenario of performance against the “extreme effort”;
5. Ask the team to pairwise compare two consecutive scenarios of performance with questions similar to “what is the difference in effort needed to implement the scenario of performance ‘Composites 40’ against ‘Fasteners 20’?”. In this case, the team replied “very weak to weak” difference in the effort needed.

After completing this matrix, the effort of each scenario of performance was obtained and validated by the team (the full matrix can be found in Appendix F). The resulting measures of effort are shown in Figure 22 and Figure 23.

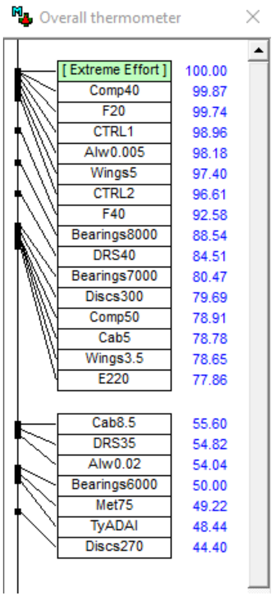


Figure 22 Scenarios of Performance Efforts - Extract 1

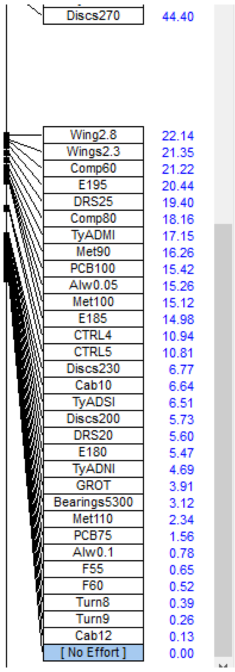


Figure 23 Scenarios of Performance Efforts - Extract 2

6.4 Defining PROBE Projects

PROBE considers the benefits and the costs of projects to identify efficient portfolios using optimization. On the contrary to the benefit-to-cost, this approach does not exclude non-convex efficient portfolios and aims to maximize the benefit for the budget available. The benefit-to-cost approach only suggests convex-efficient portfolios, which might neglect other more costly efficient portfolios that provide more benefit for the budget available.

To reach to the different portfolios, PROBE needs a set of benefit criteria to be defined, with each criterion having its weight and each project having a score in each of these criteria and a cost. Then, each project will have an overall benefit value score computed by applying the additive model (or by the hierarchical additive model, if there are several criteria levels).

The results that were obtained using the HOQ matrix and the M-MACBETH software tool must be inputted on PROBE. For this purpose, a root criterion called "EC Benefit" was created on PROBE and below it, a criterion node for each Engineering Characteristic (EC), as it is shown in Figure 24. The weight of each EC criteria was the relative weight calculated in the HOQ matrix using the results presented in Table 17. This way, the benefit of every scenario of performance for each EC was directly linked to the previous steps of this study and to the relevance of each EC to the fulfillment of the Customer Attributes (CA).

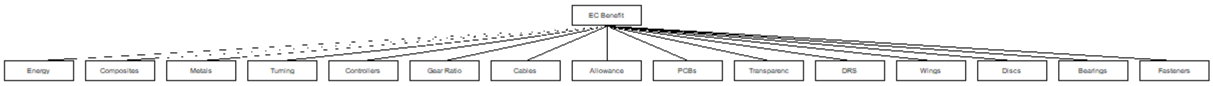


Figure 24 PROBE's Benefit Value Tree

The next step was to insert into the software every scenario option as a project, their benefit score on each EC (criterion) and also its effort (cost). The benefit score of each scenario option came from the M-MACBETH software tool, to which was inserted the trade-off strategies as options. Figure 25 shows the table of performances in M-MACBETH for each scenario of performance (SP) and Figure 26 shows the corresponding table of scores.

Table of performances

Options	Energy	Composite	Metals	Turning	CTRL	GR	WCables	Allowance	CAN	Transparency	DRS	Wings	Discs	Bearings	Fasteners
Aggressive	220	40	75	8	CTRL1	?	5	0.005	100	ADAI	40	5	300	8000	20
Mid-Agg	195	50	90	?	CTRL2	?	8.5	0.02	?	ADMI	35	3.5	270	7000	40
Mid-Con	185	60	100	?	CTRL4	?	10	0.05	?	ADSI	25	2.8	230	6000	55
Conservative	180	80	110	9	CTRL5	Target	12	0.1	75	ADNI	20	2.3	200	5300	60

Figure 25 M-MACBETH Table of Performances for Each Strategy

Table of scores

Options	Overall	Energy	Composite	Metals	Turning	CTRL	GR	WCables	Allowance	CAN	Transparency	DRS	Wings	Discs	Bearings	Fasteners
Aggressive	?	200,00	271,42	225,00	100,00	133,33	?	200,01	145,00	114,29	300,00	260,00	412,50	114,29	270,00	100,00
Mid-Agg	?	75,00	185,71	100,00	?	100,00	?	83,33	130,00	?	200,00	180,00	100,00	85,72	170,00	52,65
Mid-Con	?	25,00	100,00	33,33	?	50,00	?	33,33	100,00	?	100,00	40,00	41,67	32,15	70,00	13,16
Conservative	?	0,00	0,00	0,00	0,00	0,00	100,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
[all upper]	?	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00	100,00
[all lower]	?	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00

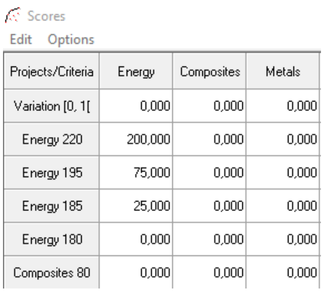
Figure 26 M-MACBETH Table of Scores for Each Scenario of Performance

These scores were inserted as benefits into PROBE in their respective EC criteria. For example, the scores of the SP of Battery Cells' Energy Density (Energy) were input as the benefits for the criterion Energy in PROBE as in Figure 27 .

As already explained in the previous section, the cost, on the other hand, was defined as the effort needed to implement each one of these SPs. The effort values obtained using M-MACBETH were inserted into PROBE costs in the respective scenarios of performance, as in Figure 28. The efforts (costs) were rounded to integers to not cause computational issues on the optimization solver used by PROBE.

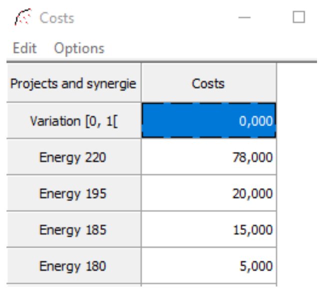
6.5 Defining Constraints

PROBE allows different configurations and constraints to be assigned to projects, for example, allows dividing them into groups. Then, it is possible to assign group constraints, such as the number of projects selected from a group is exactly, at most or at least a specific value (Lourenço, 2017).



Projects/Criteria	Energy	Composites	Metals
Variation [0, 1[	0,000	0,000	0,000
Energy 220	200,000	0,000	0,000
Energy 195	75,000	0,000	0,000
Energy 185	25,000	0,000	0,000
Energy 180	0,000	0,000	0,000
Composites 80	0,000	0,000	0,000

Figure 27 Battery Cells' Energy Density (Energy) Scenarios of Performance Scores in PROBE



Projects and synergie	Costs
Variation [0, 1[	0,000
Energy 220	78,000
Energy 195	20,000
Energy 185	15,000
Energy 180	5,000

Figure 28 Battery Cells' Energy Density (Energy) Scenarios of Performance Costs

In this case it was important to assign mutually exclusivity constraints to the selection of scenarios of performance (SP) so that the software did not select more than one from a determined EC (what would be impossible in real life, for example, having a car with both 40 kg and 80 kg in composites materials), neither less than one (it should be at least the Neutral level, leaving the design as is).

To address this, a group was created for each EC, assigning each group the respective SP and defining the constraint to be "exactly 1". This means that for every EC the software tool would select exactly one scenario of performance for a portfolio, as Figure 29 exemplifies.

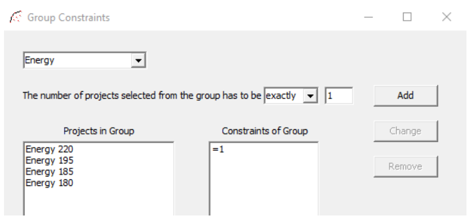


Figure 29 Group Constraint Example - Battery Cells' Energy Density (Energy)

6.6 The Efficient Frontier of SPs Portfolios

With all the SPs added as projects to PROBE, as well as their respective benefits, costs (in terms of effort) and group constraints, it was possible to obtain the efficient frontier of portfolios. PROBE identified

179 different efficient portfolios to an upper bound of cost equal to the sum of all costs, as shown in Figure 30.

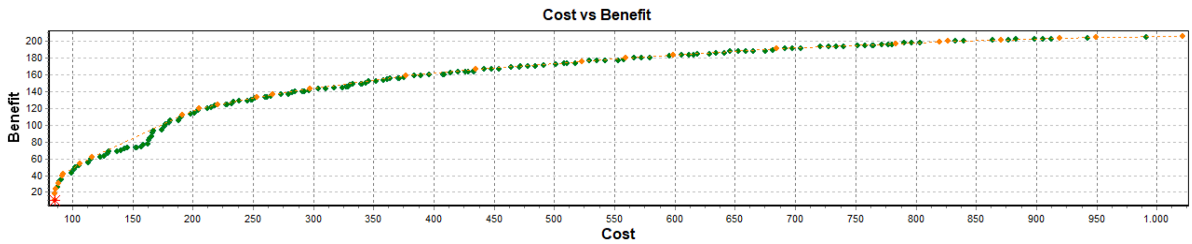


Figure 30 PROBE Efficient Frontier of Possible Portfolios

It is worth noting that in this case, the benefit of a portfolio is the sum of the benefits of all the selected scenarios of performance (SP) multiplied by their respective EC weights. The benefit of an SP on an EC represents the increment in the benefit it has upon the "Neutral" performance level on that EC (i.e. the "conservative strategy"), to which was assigned zero benefit value units. This means that any non "Neutral" scenario of performance represents an improvement in benefit to which is assigned a value score greater than zero. However, all the scenarios of performance, being "Neutral" or not, require some effort to be implemented; thus, there is no SP with zero effort.

Each of the dots in the graph of Figure 30 represents an efficient portfolio of SPs identified by PROBE, with efforts ranging from 85.43 to 1021.4 units of effort. It would be possible to exclude from consideration any portfolio that requires an effort higher than 100 (extreme effort) as this is the upper boundary of the effort scale for an SP, and because it would not be reasonable to consider a portfolio that required ten times an extreme effort. The suggested efficient portfolios are shown in Figure 31 and in Table 19, where OT means "On Target" and CE means Convex Efficient (a "1" in the CE column indicates a convex efficient portfolio).

It is worth noting that the SPs "60 tools" for "Use of More Standard Fasteners" and "Controllers 5 (CTRL5)" for "Controllers" are not included in none of the affordable portfolios, and the SP "9 meters" for "Turning Radius" is present in only one of these portfolios. Because these are the "Neutral" performances currently applied to the FST 09e, it means that the team is currently operating with an inefficient selection of SPs.

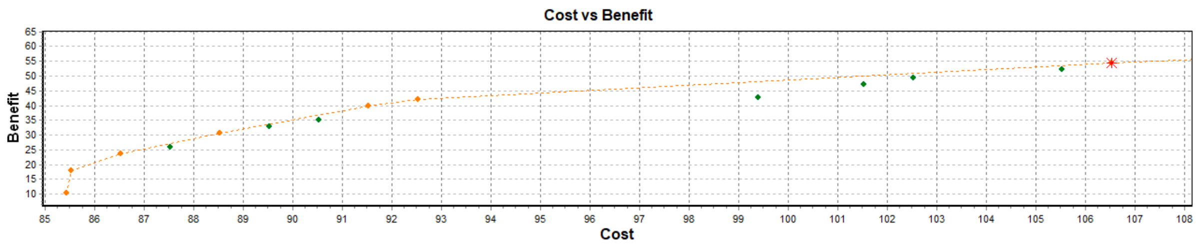


Figure 31 Suggested portfolios within possible boundaries of effort of the team

Table 19 Efficient Portfolios of SPs Without Synergies (each row corresponds to a portfolio)

CE	Cost (Effort)	Benefit	Battery Cells' Energy Density	Total Weight of Composite Materials	Total Weight of Metallic Materials	Turning Radius	Controllers	Gear Ratio	Total Weight of the Cables	Dimensional Allowance	PCBs Connected to CAN Line	Transparency of Specific Parts	DRS that significantly reduces drag	Better Wing Design	Internal Steel Strength on Brake Discs	Rotation Speed of Bearings	Use of More Standard Fasteners
1	85.4	10.411	180	80	110	9	CTRL4	OT	12	0.1	75	ADNI	20	2.3	200	5300	55
1	85.53	17.911	180	80	110	8	CTRL4	OT	12	0.1	75	ADNI	20	2.3	200	5300	55
1	86.53	23.661	180	80	110	8	CTRL4	OT	12	0.1	75	ADNI	20	2.8	200	5300	55
0	87.53	25.912	180	80	110	8	CTRL4	OT	12	0.1	75	ADNI	20	2.8	230	5300	55
1	88.53	30.761	180	80	110	8	CTRL4	OT	12	0.1	75	ADSI	20	2.8	200	5300	55
0	89.53	33.012	180	80	110	8	CTRL4	OT	12	0.1	75	ADSI	20	2.8	230	5300	55
0	90.53	35.12	180	60	110	8	CTRL4	OT	12	0.1	75	ADNI	20	2.8	230	5300	55
1	91.53	39.961	180	60	110	8	CTRL4	OT	12	0.1	75	ADSI	20	2.8	200	5300	55
1	92.53	42.212	180	60	110	8	CTRL4	OT	12	0.1	75	ADSI	20	2.8	230	5300	55
0	99.,4	42.545	180	60	110	8	CTRL4	OT	10	0.1	75	ADSI	20	2.8	230	5300	55
0	101.53	47.061	180	60	110	8	CTRL4	OT	12	0.1	75	ADMI	20	2.8	200	5300	55
0	102.53	49.312	180	60	110	8	CTRL4	OT	12	0.1	75	ADMI	20	2.8	230	5300	55
0	105.53	52.061	180	60	110	8	CTRL4	OT	12	0.05	75	ADSI	20	2.8	200	5300	55
1	106.53	54.312	180	60	110	8	CTRL4	OT	12	0.05	75	ADSI	20	2.8	230	5300	55

6.7 Creating Synergies Between ECs

The results so far obtained are useful, but they lack one critical part of the HOQ: the roof. It is known that some ECs are correlated to others, either positively or negatively, and this has not been considered in the previous portfolios. One of the features available in PROBE is the possibility to create synergies between two or more projects. Synergies allow that the joint benefit (and joint cost) of two or more projects to be different from the sum of the individual benefits (or costs) of these projects (Lourenço, Morton and Bana e Costa, 2012) Therefore, the joint benefit value of two (or more) projects may be worth more (or less) than the sum of the benefits of these projects, and the same may be considered for the costs (efforts).

In this study, the correlation matrix of the HOQ (the roof) was used to determine the joint benefits and efforts of correlated Engineering Characteristics (EC). This way, the software tool could identify efficient portfolios considering the different effects that the several combinations of ECs (and their SPs) would have.

The first thing to do was to understand how each scenario of performance of an engineering characteristic was correlated to another from other EC. In the roof of the HOQ (in section 5.5) the correlations between ECs were identified and then measured with M-MACBETH. However, the team pointed out that correlation between them was not always equal and bidirectional. To analyze this, the team was asked to develop, together with the facilitator, an Option Graph (Friend and Hickling, 2005). In this graph, each EC is represented as a rounded rectangle, within which the smaller circles represent its scenarios of performance. The team was asked to analyze pairs of performance scenarios of correlated ECs, to understand what the direction of the correlation was and if it had impact in effort, in benefit or both. Figure 32 shows the correlations between Battery Cells' Energy Density with Total Weight of Composite Materials and Battery Cells' Energy Density with Total Weight of Metallic Materials.

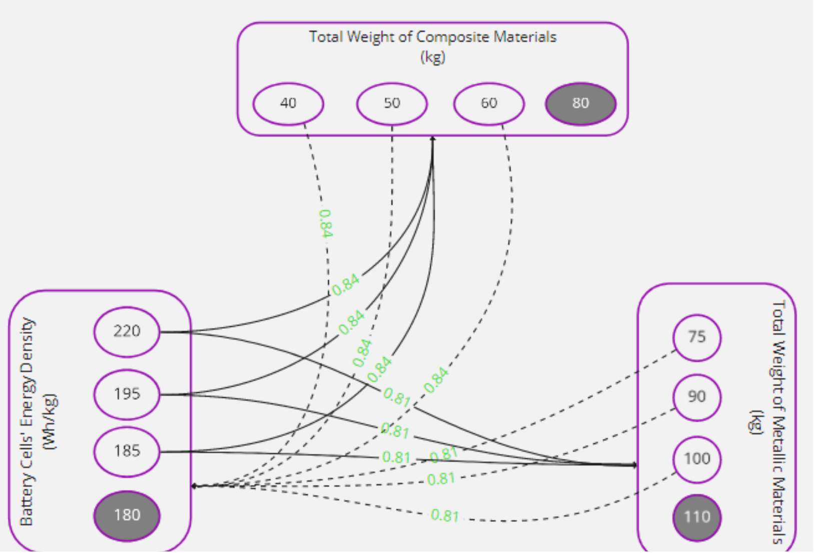


Figure 32 Correlations Between Battery Cells' Energy Density with Total Weight of Composite Materials, and Between Battery Cells' Energy Density with Total Weight of Metallic Materials

In Figure 32, the dashed lines relate to the benefit, the continuous lines relate to the effort, and the number is the correlation weight. Grey background circles refer to the "Neutral" performance level. It is also worth noting that there is a correlation between Total Weight of Composite Materials and Total Weight of Metallic Materials, but the analysis was done separately.

The process was to check pair by pair what were the effects on each other. For example, "what would happen to the weight of metals and composites if the energy density was kept as is?" In this case, it was said "nothing", it would not be any easier and no extra benefit would be gained. The same was valid for the metals and composites weights to the energy density. However, if the energy density was improved to any other level, it would become easier to reduce the weights in metals and composites or even to maintain the same weight, as less space would be required and therefore less material. On the other hand, reducing the weight of either metals or composites would have a gain in benefit to any level of energy density, as the car would be lighter and as a consequence could run more kilometers with the same battery. It would also mean that the battery could be smaller even keeping the same density, as less energy would be needed to run the 22 km of the longest event. The other correlations can be seen in Appendix G.

The following task was to express these correlations in numerical terms, so they could be used as synergies. What happens, numerically, to the benefits and efforts of each of those SPs? The weight of the correlation already existed, but it did not have any significant meaning alone, especially considering the differences between each pair of SPs. Thus, it was needed to calculate new benefit and effort scores to every SP that had a correlation, using the equations 14 and 15.

$$NB = (1 + c) \times Bs_{kj} \qquad (14)$$

$$NE = (1 - c) \times Ef_{kj} \qquad (15)$$

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*.

This way, when there was a positive correlation in benefit, the benefit value would increase according to the correlation weight. If there is a negative correlation, the benefit value would decrease. The higher the correlation, the higher the benefit gain (positive) or the benefit loss (negative). When regarding effort, if there is a high positive correlation, the effort value would decrease accordingly. If there were a negative correlation, the effort value would increase. It is worth noting that this only applies to benefit and effort values, and not in ECs performances.

Using these equations, every possible combination of SPs was analyzed and had their new benefit and effort values calculated. Always considering case by case, if the correlation was in effort, benefit or both and to which direction (one EC to another, both ways or just in individual SPs). Table 20 shows the example for the correlation exemplified above.

Table 20 New Benefit and New Effort for the Correlation Battery Cells' Energy Density (Energy) with Total Weight of Composite Materials (Composites)

Scenario of Performance 1	Scenario of Performance 2	Synergy	Benefit 1	Benefit 2	Effort 1	Effort 2	New Benefit 1	New Benefit 2	Combo Effort
Energy 220	Composites 40	0.84	200	271.42	77.86	99.87	368	271.42	94
Energy 195	Composites 50	0.84	75	185.71	20.44	78.91	138	185.71	33
Energy 185	Composites 60	0.84	25	100	14.98	21.22	46	100.00	18
Energy 220	Composites 50	0.84	200	185.71	77.86	78.91	368	185.71	90
Energy 195	Composites 40	0.84	75	271.42	20.44	99.87	138	271.42	36
Energy180	Composites 60	0.84	0	100	5.47	21.22	0	100.00	27
Energy 220	Composites 60	0.84	200	100	77.86	21.22	368	100.00	81
Energy 185	Composites 50	0.84	25	185.71	14.98	78.91	46	185.71	28
Energy180	Composites 40	0.84	0	271.42	5.47	99.87	0	271.42	105
Energy 195	Composites 60	0.84	75	100	20.44	21.22	138	100.00	24
Energy 185	Composites 40	0.84	25	271.42	14.98	99.87	46	271.42	31
Energy180	Composites 50	0.84	0	185.71	5.47	78.91	0	185.71	84
Energy 220	Composites 80	0.84	200	0	77.86	18.16	200	0	81
Energy 195	Composites 80	0.84	75	0	20.44	18.16	75	0	23
Energy 185	Composites 80	0.84	25	0	14.98	18.16	25	0	18

For every combination of two correlated SPs, a synergy was created in PROBE, that needed a benefit and a cost. The benefit of the synergy had to be divided into two, that is, the benefit obtained from the SP of one EC and the benefit obtained from the other SP of another EC. The input into PROBE synergies had to be the difference between the new and old values in their respective criteria to account for the weight of the EC to the overall objective that is to satisfy the Customer Attributes (CAs). On the other hand, the cost has a single entry, as there is no different weight to cost. This way, the cost (effort) input into PROBE is the difference between the new and old sums of both SP's efforts rounded to an integer. This sum depends on the type of correlation, and again, was analyzed case by case. As PROBE does not allow inserting null costs to projects, and a synergy is created there as it were a project, the synergies that had no effect on effort had their cost inputted as an insignificant amount of effort (precisely, 0.01). Figure 33 shows the respective combined costs, while Figure 34 shows the table filled for the first three combinations of Energy and Composites.

Costs

Edit Options

Projects and synergie	Costs
*Sy_E220-Cmp40	-84,000
*Sy_E195-Cmp50	-66,000
*Sy_E185-Cmp60	-18,000

Figure 33 Costs of the First Three Possible Combinations of Energy and Composites

Scores

Edit Options

Projects/Criteria	Energy	Composites
*Sy_E220-Cmp40	168,000	0,000
*Sy_E195-Cmp50	63,000	0,000
*Sy_E185-Cmp60	21,000	0,000

Figure 34 New Benefits of the First Three Combinations of SP for Energy and Composites

It is worth noting that the synergies in PROBE only take effect when the two SPs are selected to the portfolio. If the combination is not included in a portfolio, it has no effect on the outcome.

6.8 The Efficient Frontier of Portfolios with Synergies

Now that the synergies were created to consider the correlations between ECs, it was possible to obtain a new efficient frontier of portfolios. PROBE identified 138 efficient portfolios with different values of benefit and effort, which can be considered more realistic, as it now considers the impacts each EC has into another. Again, the portfolios spanned from 76.46 to 1071.45 units of effort. Figure 35 shows the graph of the efficient frontier of portfolios between 76 and 106 units of effort.

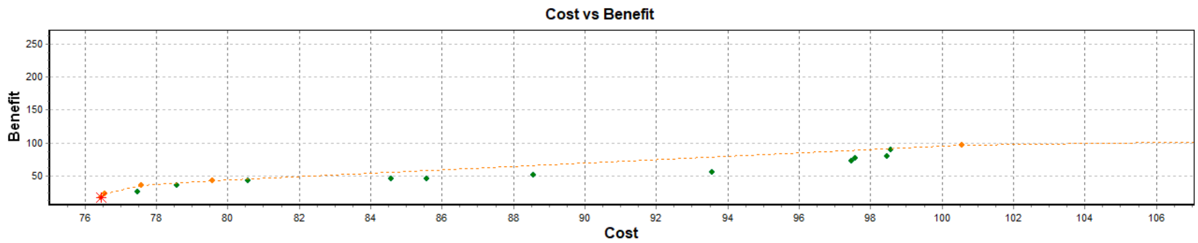


Figure 35 Efficient Frontier of Portfolios with Synergies

It is possible to see that the synergies have a positive result overall, as the total efforts were reduced, and some benefits increased.

Again, these results show that currently the FST Lisboa team is operating inefficiently. In section 6.6 it was presented that for portfolios without synergies, some neutral SP were not selected by PROBE, meaning that the team currently does not have an efficient selection of design solutions. One could argue that it was because of the lack of synergies, but this phenomenon was identified again with more “Neutral” SPs being left out of portfolios. “Battery Cells’ Energy Density” and “Number of PCBs Connected to CAN Line” did not have their “Neutral” SPs selected, in addition to “Controllers” and “Use of More Standard Fasteners” as previously identified. PROBE not including them in the efficient portfolios, not even in a portfolio comprised of only “Neutral” SPs (representing the conservative strategy), means that the FST 09e is not efficient.

7 Results Analysis of the New Car (FST 10e)

7.1 Introduction

The creation of the House of Quality is an improvement in the overview of the design process for FST Lisboa. It and can help understanding how the different departments of the team, namely Chassis, Suspension, Vehicle Dynamics, Aerodynamics (here represented by the Mechanical Chief Engineer), Electronics, Powertrain, Software (here represented by the Electronics Chief Engineer) and Management (represented by the Team Leader and the Project Manager) can work together and in which car specs. It can also provide a better view for the team about how the customer attributes (season goals) and engineering characteristics interact and benchmark against competitors.

All cars analyzed in this study were built in the academic year of 2018/19, so it is important to clarify that this study depicts the teams' situation and their cars performances and results in competitions, in that point in time. It is possible to assume that no team will decrease its performance in the next season, while the ones with poor performances may improve their cars. As there is no way of predicting these movements, because most of the teams have unstable performances throughout the years, the analysis will only consider the cars studied.

The approach comparing the 2018/19 season cars was chosen considering the FST 09e as the “Neutral” option in all performance levels. Thus, comparing this car to the others of the same year would help to understand the competitive positioning of FST Lisboa at that time and where the new car (the FST 10e) could benefit more of any improvements made upon the FST 09e.

This chapter analyses the results obtained. Section 7.2 provides an overview of the House of Quality (HOQ) analysis. Later in section 7.3, it expands the analysis to the portfolios identified by PROBE and how the team can select the most appropriate one for them.

7.2 Looking at the House of Quality

In section 5.8, the House of Quality (HOQ) was analyzed and some conclusions were reached. They were that every EC was related to at least one CA with a strong relation and that every CA was addressed by at least one EC, meaning that the CAs and ECs were defined correctly.

It is concluded that no conflicts were found between technical and competitive benchmark, but the entire design could be considered a critical point. Additionally, the ECs with the highest importances were the ones with the highest relations to the CAs, meaning they are significant to the study.

In terms of opportunities, it was identified that there is room for improvement in “DRS that significantly reduces drag” (eye-opener opportunity), because only one team performs better, while the others do not even have a DRS system. Also, the FST 09e is way behind the competition in “Rotation Speed of Bearing” and is also one of the worst-performing cars in “Good Turning Abilities”, meaning some significant improvements are needed in these Engineering Characteristics.

Overall, it was concluded that the FST 09e is an average performer among the set of competitors cars selected for the benchmark. Of course, there are over 700 teams in Formula Student and is not possible to conclude that it is an average among all of them, which in fact is quite the opposite. Over the past years, the FST Lisboa team has always been in the top 60 teams in the world.

7.3 The Suggested Portfolio of ECs for the FST 10e

After analyzing the HOQ, some general conclusions were reached, as presented in the step-by-step analysis following the literature's guidelines. However, despite having the technical goals for each EC and their respective relative weight, such values do not take into account the actual cost or effort to implement them.

Having effort values for each scenario of performance (SP) allowed undergoing a portfolio analysis based on the identification of efficient combinations of SPs considering their aggregated benefits and efforts. The effort values obtained in section 6.3 show that the SPs representing the technical goals calculated in the HOQ are practically unachievable for the team. In the example of the EC "DRS that significantly reduces drag" the technical goal has a score of 100. This can only be achieved by having a DRS with a 30% drag reduction, that has an effort value between 19.40 (25% of drag reduction) and 54.82 (35% of drag reduction) out of 100 units of effort. This would alone consume a significant amount of effort that could not be allocated to other, more essential features of the car.

Not surprisingly, in none of the efficient portfolios below an effort of 100, these SPs are selected. The same applies to other ECs. Some exceptions are"Turning Radius" (technical goal of 115), "Dimensional Allowance" (technical goal of 130), "PCBs Connected to CAN Line" (technical goal of 115), and "Gear Ratio" (technical goal of 115). "Turning Radius"'s technical goal is almost achieved with the SP "8 meters" in this EC, which represents the "Good" level and therefore having a score of 100 (equalizing the best competitors). The team had no intent in developing a car with a smaller turning radius, and thus no better-performing SP for this EC was assigned.

With this part aside, what would be the selected portfolio for the FST 10e, or at least, towards which SPs the team should try to assign more design efforts in order to have a better car? This depends on how much effort the team is willing to put into action. Currently, it is assigning a total effort of 76.46. To determine how much extra effort the team would be willing to make, they were asked: "what is the percentage increase in effort you think is feasible at the moment?". The team replied that they were willing to increase the effort by 5%, reaching an effort value of 80.283. Before selecting the affordable portfolio, the facilitator and the team analyzed portfolios with a similar effort looking at their increments in benefit/effort ratio. Figure 36 shows the values analyzed.

CE	Cost	Benefit	Inc B/C
0	77,470	25,077	2,920
1	77,570	35,361	102,845
0	78,580	35,789	0,423
1	79,570	42,461	6,740
0	80,580	42,889	0,423
0	84,570	45,361	0,620

Figure 36 List of Similar Portfolios and Their Values

The team effort limit was 80.283, but they were asked if an increment in the benefit/effort ratio of 0.423 would be worth breaking this limit to 80.58. The team said that 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 is 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 21.

Table 21 The Selected Portfolio of SPs for the FST 10e

Engineering 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

The selected portfolio differs from the current FST 09e in Battery Cells' Energy Density, Controllers, Turning Radius, PCBs Connected to CAN Line, Transparency of Specific Parts, Better Wing Design and Use of More Standard Fasteners. It is also possible to compare the new proposed FST 10e in the House of Quality against the FST 09e and the other competitors in Figure 37.

It is observed that the proposed FST 10e is not a top performer, but it gets closer to the competition in some ECs. Unfortunately, it is impossible to make this comparison in the Competitive Assessment room as the car does not exist yet, so acceleration times, manufacturing time, accessibility, turning, braking and reliability would be merely hypothetical.

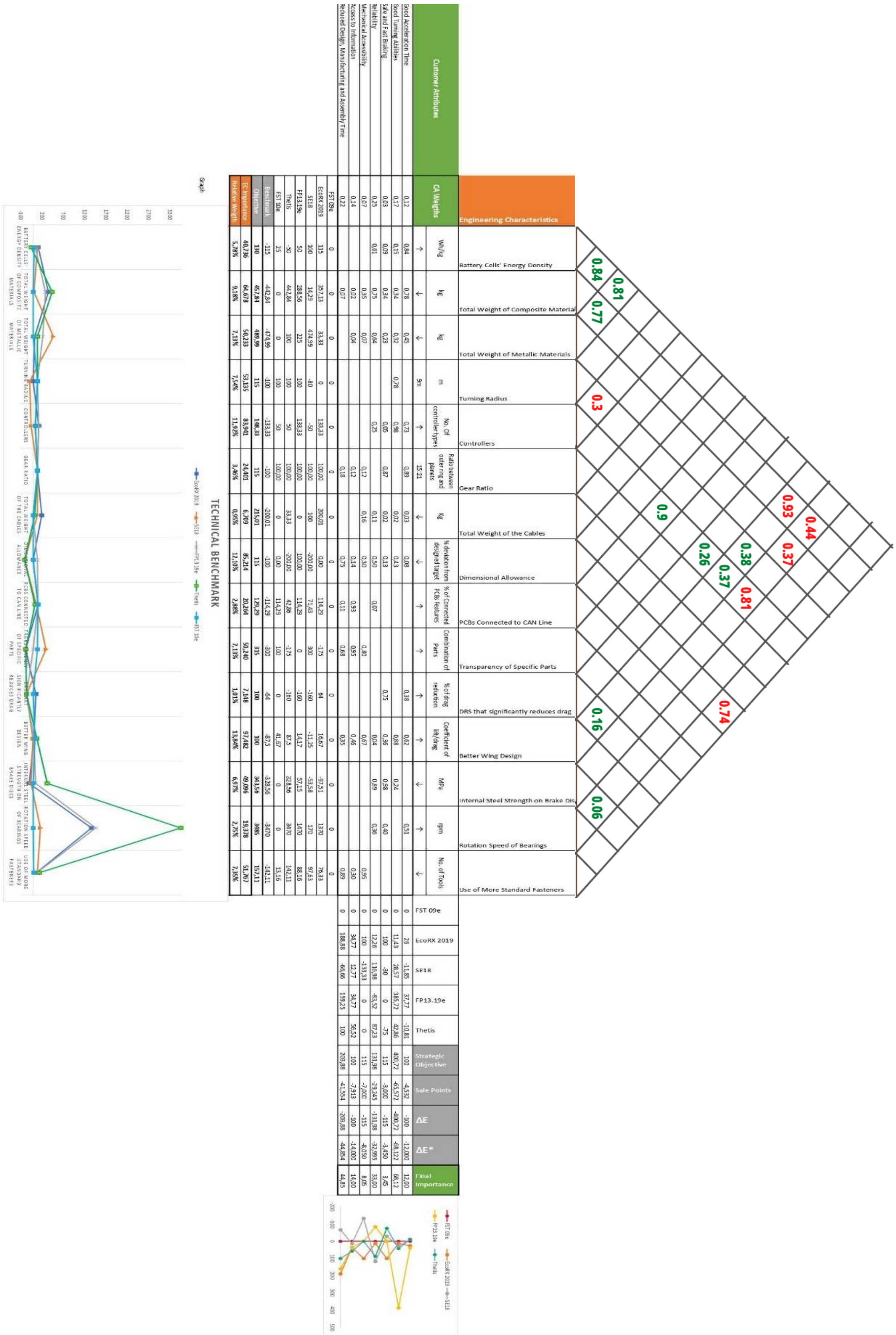


Figure 37 Full HOQ with FST 10e in the Technical Benchmark

8 Conclusions, Limitations and Future Study

8.1 Conclusions

In this study, the House of Quality framework was applied to the engineering design process of an electric formula student car jointly with Multicriteria Decision Analysis and resource allocation methodologies. Its main objective was to improve the design efforts of the FST Lisboa team as well as overcome the drawbacks of the HOQ framework. During the literature review, some issues of the HOQ arose, they were mainly:the use of direct weights as importance values for customer attributes, the use of ordinal scales as cardinal scales and an unstructured analysis of the HOQ and a complete disregard for the Roof.

Several studies tried to fill these gaps with Analytical Hierarchical Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Interactive Design Characteristic Ranking (IDCR), Operational Competitiveness Rating (OCRA) or Fuzzy Sets. In the literature, such methodologies were often used alone in the engineering design process or in combination with other tools, such as the HOQ. But they were unsuccessful in fixing the drawbacks of the HOQ. Taking as an example the most commonly used methods (AHP and Fuzzy Sets), AHP requires too many inputs from the decision-makers and can lead to inconsistent scales, while the Fuzzy Sets are based on the same judgements as of the traditional HOQ approaches, thus not removing the measurement scales mistakes.

According to Burke, Kloeber and Deckro (2002), the scales to be used in the HOQ should, if possible, be ratio scales in the weights and relationship matrix and interval scales for the column scores (EC strategic importance). This study used the MACBETH methodology and M-MACBETH software to overcome the fragilities found and create proper scales in the HOQ, using qualitative judgements of difference of attractiveness, having a consistent scale, which does not happen with AHP, for example.

The application of the HOQ integrated with MACBETH was done by the facilitator alongside four decision-makers of the FST Lisboa team, the Team Leader, Electrical Chief Engineer, Mechanical Chief Engineer and Project Manager representingtechnical and non-technical sides. The team performed a causal map with the facilitator to identify all the possible engineering characteristics behind the selected customer attributes. This process gave origin to 15 different ECs that had their performance levels defined by the team. They had interval scales created from input of the team in M-MACBETH through judgements of difference of attractiveness. The team's judgement replies were always private at first, and later discussed to generate consensus. This was an effort to avoid informational cascades in their judgements. This approach can be considered as successful. On several occasions, the members' replies were very different, and from the discussions, the team had new ideas or reconsiderations about their processes, metrics or objectives. This means that the team was forced to discuss topics for the first time, or with a different perspective, which is one of the objectives of the HOQ.

After all the scales were created, the roof has been filled out, and the relationship matrix completed, the team appointed four competitor teams to benchmark. The competitor teams helped provide the requested information on good will and had their performance values inserted into M-MACBETH to translate them into scores and be assessed in the HOQ. Such scores were used to calculate the final CA importance and then the technical benchmark and EC importance. It could be concluded that the FST 09e is an average performer, with some areas falling behind the competition. It was also identified that a big opportunity is in the development of better DRS systems. One worrying aspect is the EC “Rotation Speed of Bearings”, in which FST Lisboa is the worst-performer.

However, it was needed to complement the analysis and truly indicate the team where their efforts should go to be more efficient in the resource allocation. The HOQ does not allow for such analysis, so a complementary methodology was needed. The team used M-MACBETH to associate efforts to Scenarios of Performance (SP) that were defined for each EC. Those SPs were possible performance values for each EC, that were inserted into PROBE software tool to perform a portfolio analysis and suggest efficient portfolios of SPs to be built in the new car.

PROBE was also used to integrate the correlation matrix, the roof, into the analysis, tackling one of the weakest points of the HOQ. This way, the always neglected part of the HOQ could be numerically assessed and meaningfully used in the analysis. To do so, the team had to analyze every SP, pair by pair, to understand if the correlations of their respective ECs affected all or some SPs, if they were unidirectional or bidirectional, and if in terms of effort or benefit. The result of this analysis was put in PROBE as synergies, giving origin to several efficient portfolios of SPs to be built in the car. The team had to choose how much more effort they were willing to assign to the project, and then select an efficient portfolio to help them steer resources in that direction in the next car development.

The use of PROBE allowed for the team to have a structured and less time-consuming analysis process of the HOQ and the implications of one EC to another. Proposing design strategies as portfolios gave the team a clear and objective result out of the HOQ. Thus, managing the complexity of the analysis and presenting the team with a pre-defined set of efficient options to implement.

The combination of both the House of Quality, MACBETH and PROBE helped address some of the issues identified in the FST Lisboa team, as presented in section 2.4. Communication has been slightly improved, because now the team has in written form how the different characteristics of the car are correlated in the HOQ, which also serves as a structured and standard design document to be used for future reference. The team was required to consider different outcomes and implications of the design throughout the application of this study, and the team now has a formal and specific definition of targets and a suggested allocation of design efforts to meet them.

This study solved some of the main issues associated with the HOQ regarding scales, integrated the roof into the analysis and performed a quantitative assessment of the framework's results with PROBE. The team validated its results, that thought it to be very useful in the design process and that it has the capability to improve their decision-making process and solve recurrent issues in the team.

As far as we know, there is no other approach in the literature that incorporates the HOQ together with resource allocation as it is done in this dissertation.

8.2 Limitations

This study has some limitations, mostly due to team availability and externalities. They do not affect the results of the study, but if not in place, the study could have been more accurate or validated. The first one is that this study was meant to be conducted during early days of the design phase of the FST 10e, but due to time constraints, it lasted for longer and was not used in the development of that car. The study was conducted until the middle of the manufacturing phase. This can also be explained by the fact that the team was not familiar with MACBETH and the House of Quality, requiring more time to conclude the sessions with them and potentially having some inaccuracies.

The second is that the competition is analyzed at a fixed point in time. It is a "photograph" of the current year cars, not representing what the next year cars will be. This means that the benchmark is for the cars that competed in 2019 against FST Lisboa and the FST 09e. It can be misleading to compare 2019 cars to develop a new prototype that will compete against completely different vehicles one year later. It gives a broad understanding of the competition level, but it does not mean that they will remain in that level in the next season.

The third one is that the study lacks validation. Due to the COVID-19 pandemic, all competitions were suspended, and the team did not finish the FST 10e in 2020 until the delivery of this thesis. The original intent was to validate the FST 10e real specifications to the theoretical ones, as the study was not completed before the design freeze.

8.3 Future Study

The first thing to consider when considering the continuation of this study is ensuring that this knowledge stays within the team. It is one of the main concerns for every topic in all formula student teams, and therefore hard to ensure. Some proposals are developing a "self-service" form to fill-up judgements of the matrix in an asynchronous way.

Another relevant point for discussion is based on the fact that this study was conducted in a broad perspective of the entire development, aggregating the different departments and trade-offs that the team must undergo on a high level. However, to be more aligned with industry practices and get more accurate results, this process should be undertaken in two different levels: general and department level with the further deployment of QFD and the Parts Design House.

The effort should also be the aim of future studies, trying to reach a deeper understanding of how much effort is needed to increase team competitiveness. A suggested approach would be to understand the feasibility of extrapolating the technological frontier concept that exists in economics to this scope. The question is: how much effort is needed to push the technological frontier boundary of the team significantly?

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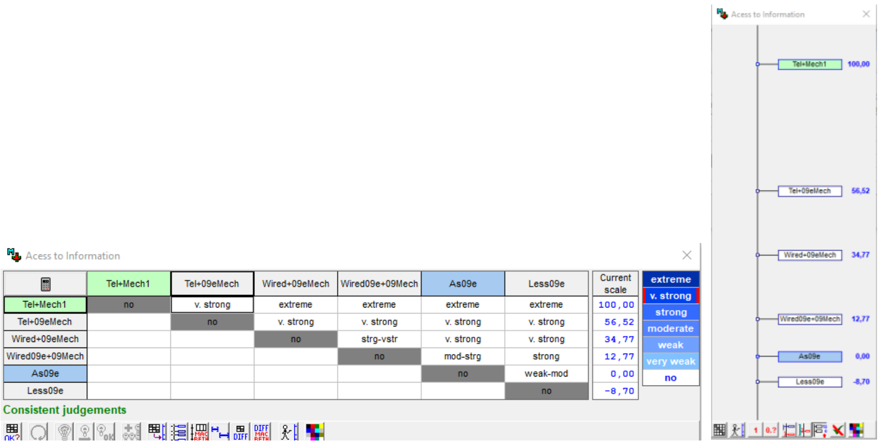
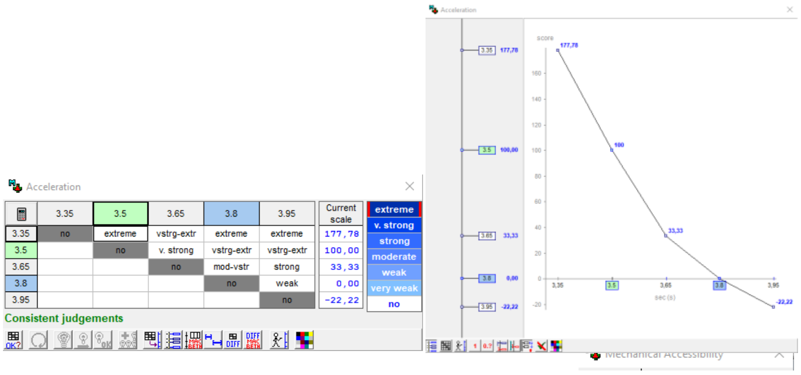
Appendix A

Customer Attributes Judgement Matrix and Value Scales



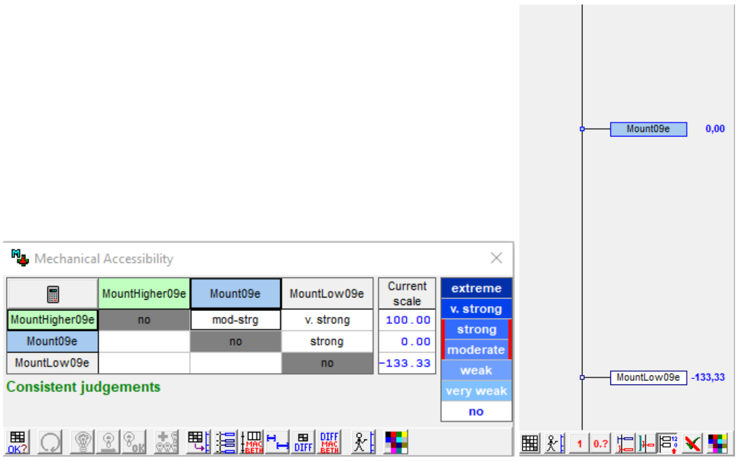
	Tel+Mech1	Tel+09eMech	Wired+09eMech	Wired09e+09Mech	As09e	Less09e	Current scale
Tel+Mech1	no	v. strong	extreme	extreme	extreme	extreme	100,00
Tel+09eMech		no	v. strong	v. strong	v. strong	extreme	56,52
Wired+09eMech			no	strg-vstr	v. strong	v. strong	34,77
Wired09e+09Mech				no	mod-strg	strong	12,77
As09e					no	weak-mod	0,00
Less09e						no	-8,70

Appendix A Figure 1 Judgement Matrix and Scale for the Customer Attribute "Access to Information"



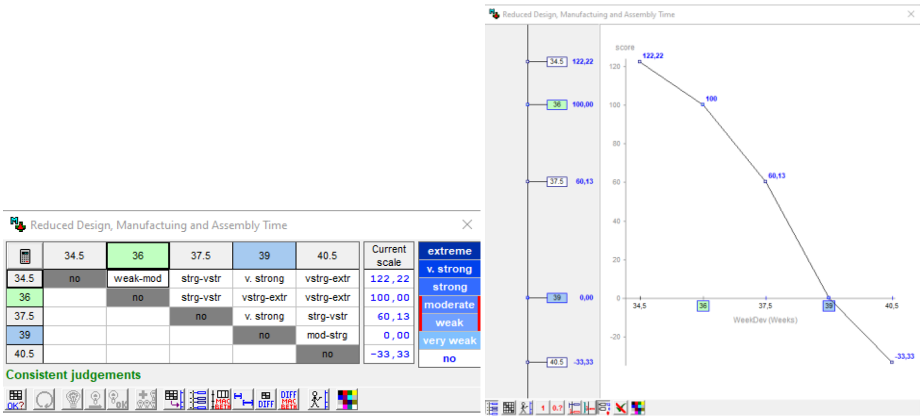
	3.35	3.5	3.65	3.8	3.95	Current scale
3.35	no	extreme	vstrg-extr	extreme	extreme	177,78
3.5		no	v. strong	vstrg-extr	vstrg-extr	100,00
3.65			no	mod-vstr	strong	33,33
3.8				no	weak	0,00
3.95					no	-22,22

Appendix A Figure 2 Judgement Matrix and Value Scale for the Customer Attribute "Good Acceleration Time"

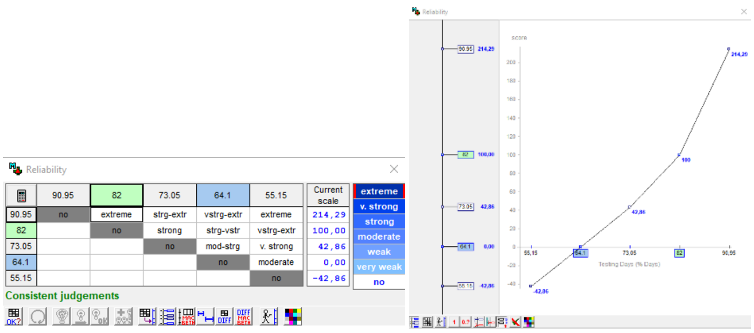


	MountHigher09e	Mount09e	MountLow09e	Current scale
MountHigher09e	no	mod-strg	v. strong	100.00
Mount09e		no	strong	0.00
MountLow09e			no	-133.33

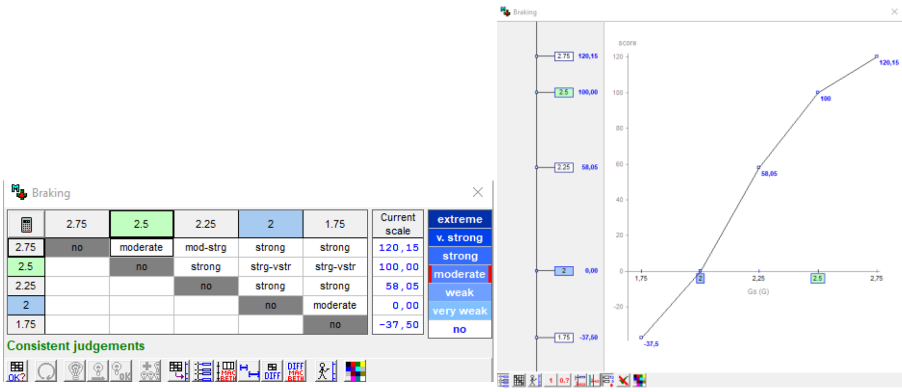
Appendix A Figure 3 Judgement Matrix and Value Scale for the Customer Attribute "Mechanical Accessibility"



Appendix A Figure 4 Judgement Matrix and Value Scale for the Customer Attribute "Reduced Design, Manufacturing and Assembly Time"



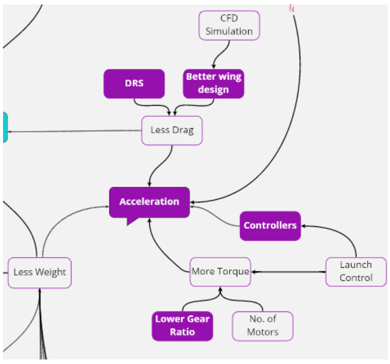
Appendix A Figure 5 Judgement Matrix and Value Scale for the Customer Attribute "Reliability"



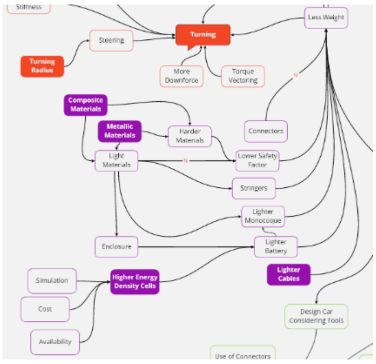
Appendix A Figure 6 Judgement Matrix and Value Scale for the Customer Attribute "Safe and Fast Braking"

Appendix B

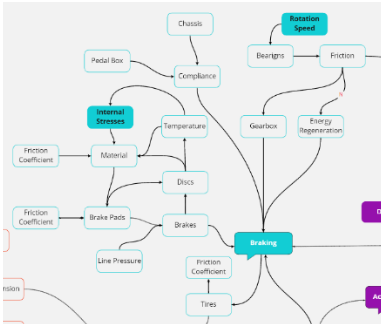
Causal Map Extracts of Each Customer Attribute



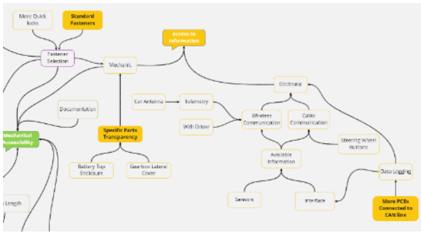
Appendix B Figure 1 "Good Acceleration Time" Causal Map – part 1 of 2



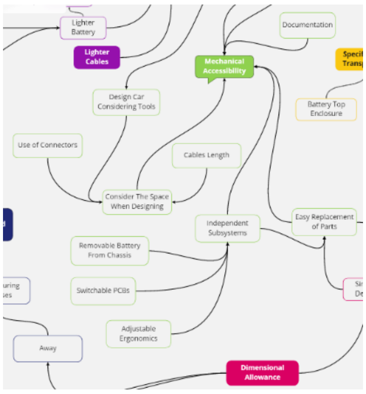
Appendix B Figure 2 "Good Acceleration Time" Causal Map – part 2 of 2



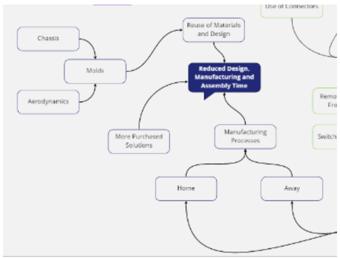
Appendix B Figure 3 "Safe and Fast Braking" Causal Map



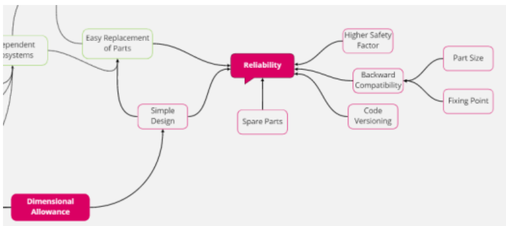
Appendix B Figure 4 "Access to Information" Causal Map



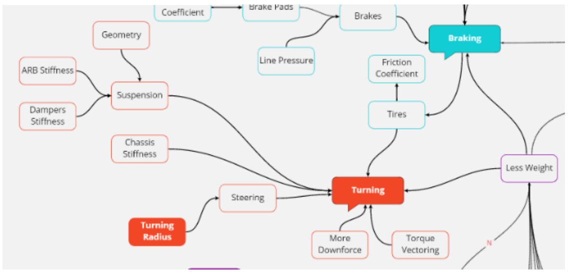
Appendix B Figure 5 "Mechanical Accessibility" Causal Map



Appendix B Figure 6 "Reduced Design, Manufacturing and Assembly Time" Causal Map



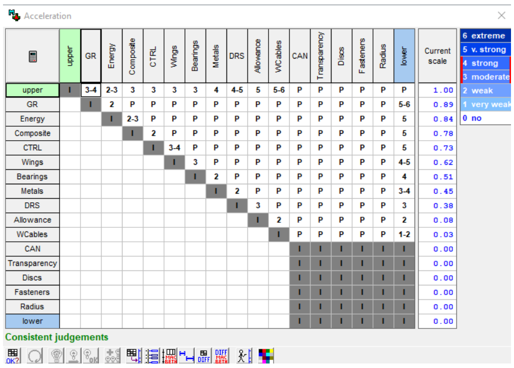
Appendix B Figure 7 "Reliability" Causal Map



Appendix B Figure 8 "Good Turing Abilities" Causal Map

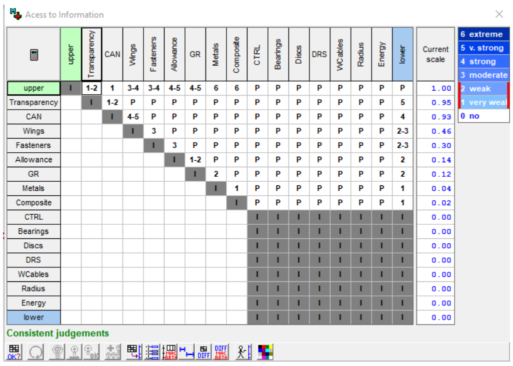
Appendix C

M-MACBETH Judgement Matrices of Each Customer Attribute for Building the Relationship Matrix



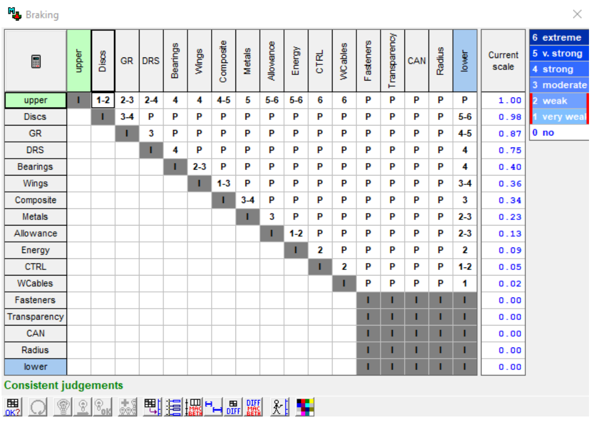
	upper	GR	Energy	Composite	CTRL	Wings	Bearings	Metals	DRS	Allowance	WCables	CAN	Transparency	Discs	Fasteners	Radius	lower	Current scale
upper	I	3-4	2-3	3	3	3	3	4	4-5	5	5-6	P	P	P	P	P	P	1.00
GR		I	2	P	P	P	P	P	P	P	P	P	P	P	P	P	5-6	0.89
Energy			I	2-3	P	P	P	P	P	P	P	P	P	P	P	P	5	0.84
Composite				I	2	P	P	P	P	P	P	P	P	P	P	P	5	0.78
CTRL					I	3-4	P	P	P	P	P	P	P	P	P	P	5	0.73
Wings						I	3	P	P	P	P	P	P	P	P	P	4-5	0.62
Bearings							I	2	P	P	P	P	P	P	P	P	4	0.51
Metals								I	2	P	P	P	P	P	P	P	3-4	0.45
DRS									I	3	P	P	P	P	P	P	3	0.38
Allowance										I	2	P	P	P	P	P	2	0.08
WCables											I	P	P	P	P	P	1-2	0.03
CAN												I	I	I	I	I	I	0.00
Transparency												I	I	I	I	I	I	0.00
Discs												I	I	I	I	I	I	0.00
Fasteners												I	I	I	I	I	I	0.00
Radius												I	I	I	I	I	I	0.00
lower												I	I	I	I	I	I	0.00

Appendix C Figure 1 Relationship Matrix Judgements for the Customer Attribute "Good Acceleration Time"



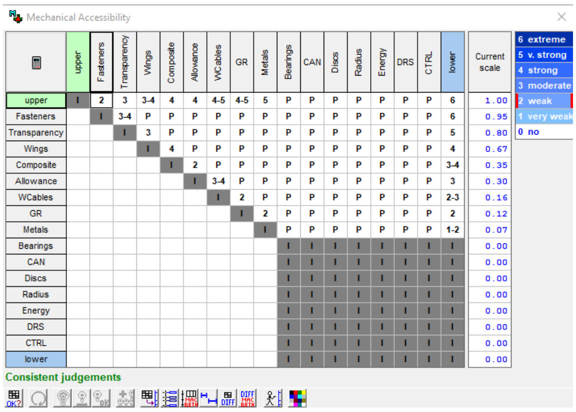
	upper	Transparency	CAN	Wings	Fasteners	Allowance	GR	Metals	Composite	CTRL	Bearings	Discs	DRS	WCables	Radius	Energy	lower	Current scale
upper	I	1-2	1	3-4	3-4	4-5	4-5	6	6	P	P	P	P	P	P	P	P	1.00
Transparency		I	1-2	P	P	P	P	P	P	P	P	P	P	P	P	P	5	0.95
CAN			I	4-5	P	P	P	P	P	P	P	P	P	P	P	P	4	0.93
Wings				I	3	P	P	P	P	P	P	P	P	P	P	P	2-3	0.46
Fasteners					I	3	P	P	P	P	P	P	P	P	P	P	2-3	0.30
Allowance						I	1-2	P	P	P	P	P	P	P	P	P	2	0.14
GR							I	2	P	P	P	P	P	P	P	P	2	0.12
Metals								I	1	P	P	P	P	P	P	P	1	0.04
Composite									I	P	P	P	P	P	P	P	1	0.02
CTRL										I	I	I	I	I	I	I	I	0.00
Bearings										I	I	I	I	I	I	I	I	0.00
Discs										I	I	I	I	I	I	I	I	0.00
DRS										I	I	I	I	I	I	I	I	0.00
WCables										I	I	I	I	I	I	I	I	0.00
Radius										I	I	I	I	I	I	I	I	0.00
Energy										I	I	I	I	I	I	I	I	0.00
lower										I	I	I	I	I	I	I	I	0.00

Appendix C Figure 2 Relationship Matrix Judgements for the Customer Attribute "Access to Information"



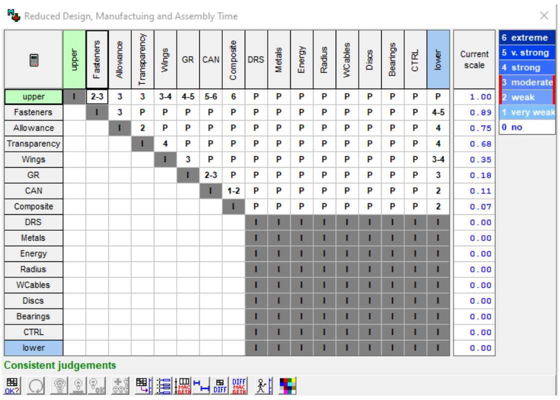
	upper	Discs	GR	DRS	Bearings	Wings	Composite	Metals	Allowance	Energy	CTRL	WCables	Fasteners	Transparency	CAN	Radius	lower	Current scale
upper	I	1-2	2-3	2-4	4	4	4-5	5	5-6	5-6	6	6	P	P	P	P	P	1.00
Discs		I	3-4	P	P	P	P	P	P	P	P	P	P	P	P	P	5-6	0.98
GR			I	3	P	P	P	P	P	P	P	P	P	P	P	P	4-5	0.87
DRS				I	4	P	P	P	P	P	P	P	P	P	P	P	4	0.75
Bearings					I	2-3	P	P	P	P	P	P	P	P	P	P	4	0.40
Wings						I	1-3	P	P	P	P	P	P	P	P	P	3-4	0.36
Composite							I	3-4	P	P	P	P	P	P	P	P	3	0.34
Metals								I	3	P	P	P	P	P	P	P	2-3	0.23
Allowance									I	1-2	P	P	P	P	P	P	2-3	0.13
Energy										I	2	P	P	P	P	P	2	0.09
CTRL											I	2	P	P	P	P	1-2	0.05
WCables												I	P	P	P	P	1	0.02
Fasteners													I	I	I	I	I	0.00
Transparency													I	I	I	I	I	0.00
CAN													I	I	I	I	I	0.00
Radius													I	I	I	I	I	0.00
lower													I	I	I	I	I	0.00

Appendix C Figure 3 Relationship Matrix Judgements for the Customer Attribute “Safe and Fast Braking"



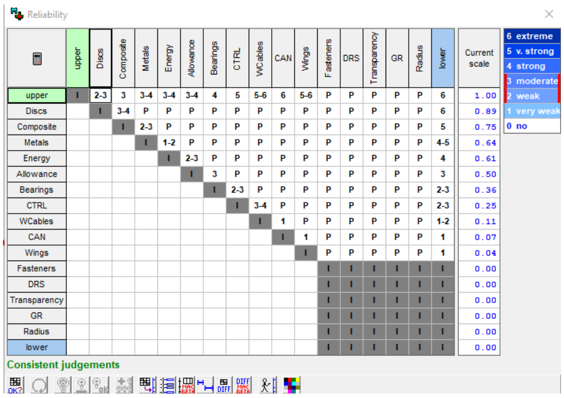
	upper	Fasteners	Transparency	Wings	Composite	Allowance	WCables	GR	Metals	Bearings	CAN	Discs	Radius	Energy	DRS	CTRL	lower	Current scale
upper	I	2	3	3-4	4	4	4-5	4-5	5	P	P	P	P	P	P	P	6	1.00
Fasteners		I	3-4	P	P	P	P	P	P	P	P	P	P	P	P	P	6	0.95
Transparency			I	3	P	P	P	P	P	P	P	P	P	P	P	P	5	0.80
Wings				I	4	P	P	P	P	P	P	P	P	P	P	P	4	0.67
Composite					I	2	P	P	P	P	P	P	P	P	P	P	3-4	0.35
Allowance						I	3-4	P	P	P	P	P	P	P	P	P	3	0.30
WCables							I	2	P	P	P	P	P	P	P	P	2-3	0.16
GR								I	2	P	P	P	P	P	P	P	2	0.12
Metals									I	P	P	P	P	P	P	P	1-2	0.07
Bearings										I	I	I	I	I	I	I	I	0.00
CAN										I	I	I	I	I	I	I	I	0.00
Discs										I	I	I	I	I	I	I	I	0.00
Radius										I	I	I	I	I	I	I	I	0.00
Energy										I	I	I	I	I	I	I	I	0.00
DRS										I	I	I	I	I	I	I	I	0.00
CTRL										I	I	I	I	I	I	I	I	0.00
lower										I	I	I	I	I	I	I	I	0.00

Appendix C Figure 4 Relationship Matrix Judgements for the Customer Attribute "Mechanical Accessibility"



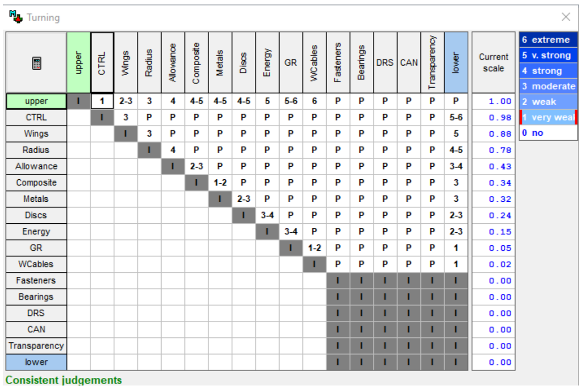
	upper	Fasteners	Allowance	Transparency	Wings	GR	CAN	Composite	DRS	Metals	Energy	Radius	WCables	Discs	Bearings	CTRL	lower	Current scale
upper	I	2-3	3	3	3-4	4-5	5-6	6	P	P	P	P	P	P	P	P	P	1.00
Fasteners		I	3	P	P	P	P	P	P	P	P	P	P	P	P	P	4-5	0.89
Allowance			I	2	P	P	P	P	P	P	P	P	P	P	P	P	4	0.75
Transparency				I	4	P	P	P	P	P	P	P	P	P	P	P	4	0.68
Wings					I	3	P	P	P	P	P	P	P	P	P	P	3-4	0.35
GR						I	2-3	P	P	P	P	P	P	P	P	P	3	0.18
CAN							I	1-2	P	P	P	P	P	P	P	P	2	0.11
Composite								I	P	P	P	P	P	P	P	P	2	0.07
DRS									I	I	I	I	I	I	I	I	I	0.00
Metals									I	I	I	I	I	I	I	I	I	0.00
Energy									I	I	I	I	I	I	I	I	I	0.00
Radius									I	I	I	I	I	I	I	I	I	0.00
WCables									I	I	I	I	I	I	I	I	I	0.00
Discs									I	I	I	I	I	I	I	I	I	0.00
Bearings									I	I	I	I	I	I	I	I	I	0.00
CTRL									I	I	I	I	I	I	I	I	I	0.00
lower									I	I	I	I	I	I	I	I	I	0.00

Appendix C Figure 5 Relationship Matrix Judgements for the Customer Attribute "Reduced Design and Manufacturing Time"



	upper	Discs	Composite	Metals	Energy	Allowance	Bearings	CTRL	WCables	CAN	Wings	Fasteners	DRS	Transparency	GR	Radius	lower	Current scale
upper	I	2-3	3	3-4	3-4	3-4	4	5	5-6	6	5-6	P	P	P	P	P	6	1.00
Discs		I	3-4	P	P	P	P	P	P	P	P	P	P	P	P	P	6	0.89
Composite			I	2-3	P	P	P	P	P	P	P	P	P	P	P	P	5	0.75
Metals				I	1-2	P	P	P	P	P	P	P	P	P	P	P	4-5	0.64
Energy					I	2-3	P	P	P	P	P	P	P	P	P	P	4	0.61
Allowance						I	3	P	P	P	P	P	P	P	P	P	3	0.50
Bearings							I	2-3	P	P	P	P	P	P	P	P	2-3	0.36
CTRL								I	3-4	P	P	P	P	P	P	P	2-3	0.25
WCables									I	1	P	P	P	P	P	P	1-2	0.11
CAN										I	1	P	P	P	P	P	1	0.07
Wings											I	P	P	P	P	P	1	0.04
Fasteners												I	I	I	I	I	I	0.00
DRS												I	I	I	I	I	I	0.00
Transparency												I	I	I	I	I	I	0.00
GR												I	I	I	I	I	I	0.00
Radius												I	I	I	I	I	I	0.00
lower												I	I	I	I	I	I	0.00

Appendix C Figure 6 Relationship Matrix Judgements for the Customer Attribute "Reliability"

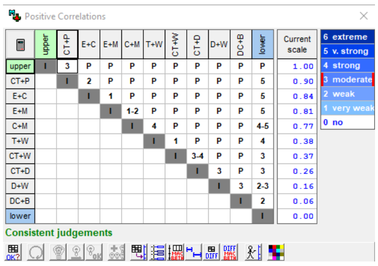


	upper	CTRL	Wings	Radius	Allowance	Composite	Metals	Discs	Energy	GR	WCables	Fasteners	Bearings	DRS	CAN	Transparency	lower	Current scale
upper	I	1	2-3	3	4	4-5	4-5	4-5	5	5-6	6	P	P	P	P	P	P	1.00
CTRL		I	3	P	P	P	P	P	P	P	P	P	P	P	P	P	5-6	0.98
Wings			I	3	P	P	P	P	P	P	P	P	P	P	P	P	5	0.88
Radius				I	4	P	P	P	P	P	P	P	P	P	P	P	4-5	0.78
Allowance					I	2-3	P	P	P	P	P	P	P	P	P	P	3-4	0.43
Composite						I	1-2	P	P	P	P	P	P	P	P	P	3	0.34
Metals							I	2-3	P	P	P	P	P	P	P	P	3	0.32
Discs								I	3-4	P	P	P	P	P	P	P	2-3	0.24
Energy									I	3-4	P	P	P	P	P	P	2-3	0.15
GR										I	1-2	P	P	P	P	P	1	0.05
WCables											I	P	P	P	P	P	1	0.02
Fasteners												I	I	I	I	I	I	0.00
Bearings												I	I	I	I	I	I	0.00
DRS												I	I	I	I	I	I	0.00
CAN												I	I	I	I	I	I	0.00
Transparency												I	I	I	I	I	I	0.00
lower												I	I	I	I	I	I	0.00

Appendix C Figure 7 Relationship Matrix Judgements for the Customer Attribute "Good Turning Abilities"

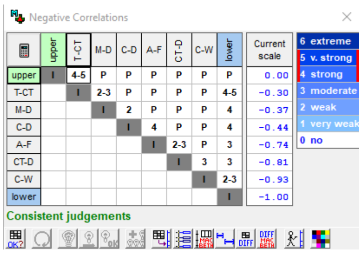
Appendix D

Judgement Matrices for Building the Correlation Matrix (the Roof)



	upper	CT+P	E+C	E+M	C+M	T+W	CT+W	CT+D	D+W	DC+B	lower	Current scale
upper	I	3	P	P	P	P	P	P	P	P	P	1.00
CT+P		I	2	P	P	P	P	P	P	P	5	0.90
E+C			I	1	P	P	P	P	P	P	5	0.84
E+M				I	1-2	P	P	P	P	P	5	0.81
C+M					I	4	P	P	P	P	4-5	0.77
T+W						I	1	P	P	P	4	0.38
CT+W							I	3-4	P	P	3	0.37
CT+D								I	3	P	3	0.26
D+W									I	3	2-3	0.16
DC+B										I	2	0.06
lower											I	0.00

Appendix D Figure 1 Poitive Correlations Judgement Matrix



	upper	T-CT	M-D	C-D	A-F	CT-D	C-W	lower	Current scale
upper	I	4-5	P	P	P	P	P	P	0.00
T-CT		I	2-3	P	P	P	P	4-5	−0.30
M-D			I	2	P	P	P	4	−0.37
C-D				I	4	P	P	4	−0.44
A-F					I	2-3	P	3	−0.74
CT-D						I	3	3	−0.81
C-W							I	2-3	−0.93
lower								I	−1.00

Appendix D Figure 2 Negative Correlations Judgement Matrix

Appendix E

Competitors Performance Scores in M-MACBETH for Every Engineering Characteristic

Table of scores

Options	Overall	Energy	Composite	Metals	Turning	CTRL	GR	WCables
WHZ	?	50.00	288.56	225.00	100.00	133.33	100.00	0.00
SupEng	?	100.00	14.29	474.99	-80.00	-50.00	100.00	100.00
EcoRacing	?	115.00	357.13	33.33	0.00	133.33	100.00	200.01
Arist	?	-50.00	442.84	100.00	100.00	50.00	100.00	33.33
[all upper]	?	100.00	100.00	100.00	100.00	100.00	100.00	100.00
[all lower]	?	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weights :		?	?	?	?	?	?	?

Appendix E Figure 1 M-MACBETH's Table of Scores of the Competition - part 1 of 2

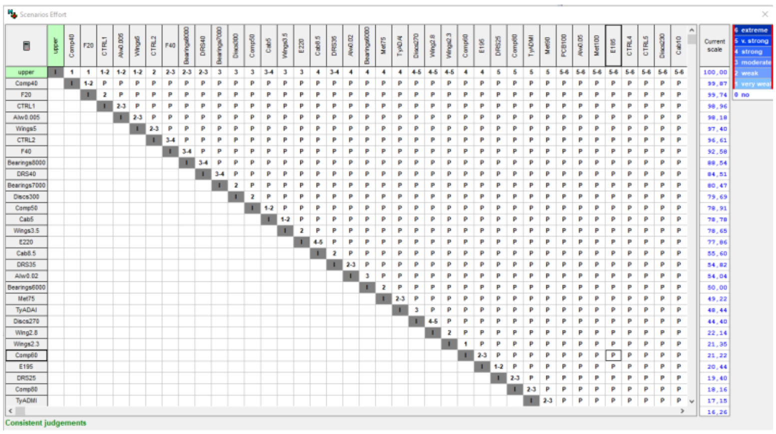
Table of scores

Options	Overall	Allowance	CAN	Transparency	DRS	Wings	Discs	Bearings	Fasteners
WHZ	?	100.00	114.29	0.00	-160.00	14.17	57.15	1470.00	88.16
SupEng	?	-200.00	71.43	300.00	-160.00	-11.25	-53.58	170.00	97.63
EcoRacing	?	0.00	114.29	-175.00	64.00	16.67	-97.51	1370.00	76.33
Arist	?	-200.00	42.86	-175.00	-160.00	87.50	328.56	3470.00	142.11
[all upper]	?	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
[all lower]	?	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Weights :		?	?	?	?	?	?	?	?

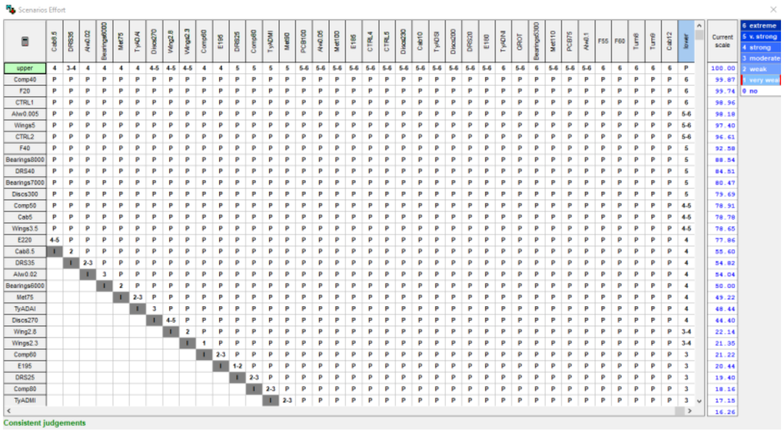
Appendix E Figure 2 M-MACBETH's Table of Scores of the Competition – part 2 of 2

Appendix F

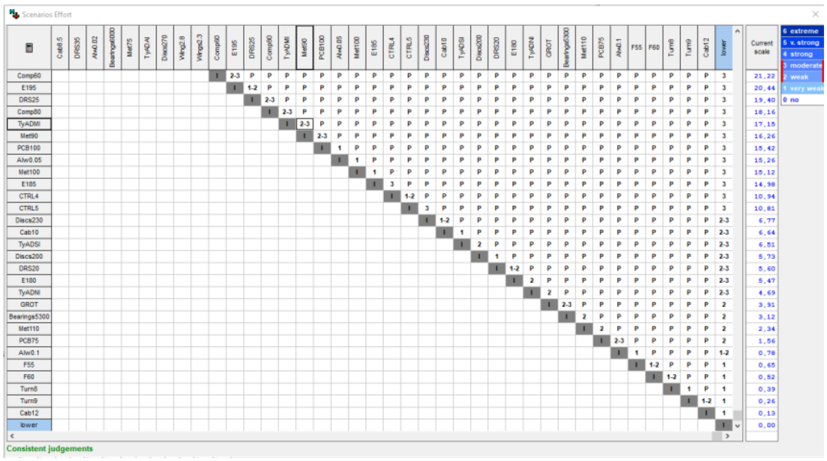
M-MACBETH Effort Judgement Matrix



Appendix F Figure 1 Scenarios of Performance Efforts Judgement Matrix – part 1 of 3



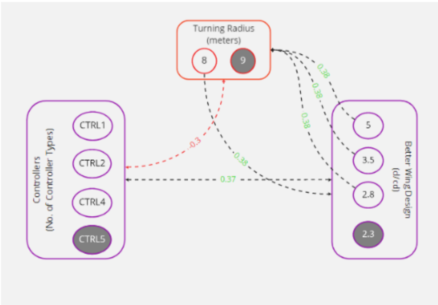
Appendix F Figure 2 Scenarios of Performance Efforts Judgement Matrix – part 2 of 3



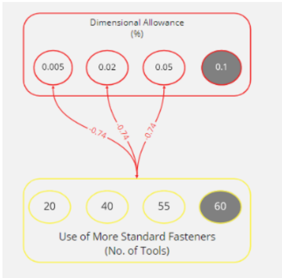
Appendix F Figure 3 Scenarios of Performance Efforts Judgement Matrix – part 3 of 3

Appendix G

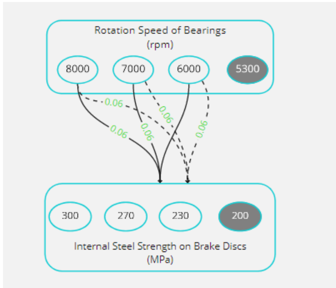
Correlations Between Engineering Characteristics - Option Graphs



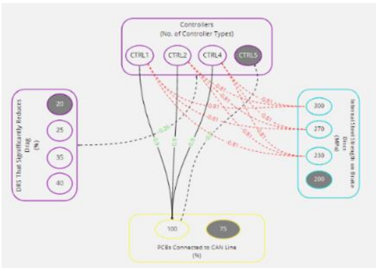
Appendix G Figure 1 Correlations Between “Controllers”, “Turning Radius” and “Better Wing Design”



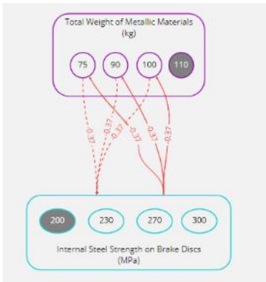
Appendix G Figure 2 Correlations Between “Dimensional Allowance” and “Use of More Standard Fasteners"



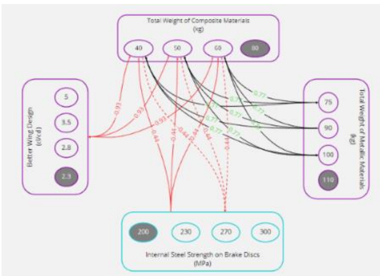
Appendix G Figure 3 Correlations Between "Rotation Speed of Bearings" and “Internal Steel Strength on Brake Discs



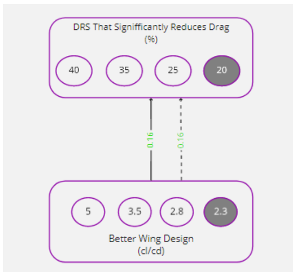
Appendix G Figure 4 Correlations Between "Controllers", “DRS That Significantly Reduces Drag”, “Internal Steel Strenght on Brake Discs” and “PCBs Connected to CAN Line”



Appendix G Figure 5 Correlation Between “Total Weight of Metallic Materials” and "Internal Steel Strength on Brake Discs"



Appendix G Figure 6 Correlations Between "Total Weight of Composite Materials", “Total Weight of Metallic Materials", “Better Wing Design" and Internal Steel Strength on Brake Discs"



Appendix G Figure 7 Correlation Between "DRS That Significantly Reduces Drag" and "Better Wing Design"