A PROBABILISTIC CONCEPTUAL DESIGN AND SIZING APPROACH FOR A HELICOPTER

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

SELİM SELVİ

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
AEROSPACE ENGINEERING

SEPTEMBER 2010

Approval of the thesis:

A PROBABILISTIC CONCEPTUAL DESIGN AND SIZING APPROACH FOR A HELICOPTER

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ABSTRACT

A PROBABILISTIC CONCEPTUAL DESIGN AND SIZING APPROACH FOR A HELICOPTER

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September 2010, 62 Pages

Due to its complex and multidisciplinary nature, the conceptual design phase of helicopters becomes critical in meeting customer satisfaction. Statistical (probabilistic) design methods can be employed to understand the design better and target a design with lower variability. In this thesis, a conceptual design and helicopter sizing methodology is developed and shown on a helicopter design for Turkey.

Keywords: Helicopter, Conceptual Design, QFD, OEC, RF-Method, Response Surface, Probabilistic Design, Sensitivity and Monte Carlo Analysis

ÖZ

BİR HELİKOPTER İÇİN PROBABİLİSTİK KAVRAMSAL TASARIM VE BOYUTLANDIRMA YAKLAŞIMI

Selvi, Selim
Yüksek Lisans, Havacılık ve Uzay Mühendisliği Bölümü
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Eylül 2010, 62 Sayfa

Helikopter tasarımının karmaşık ve çok-disiplinli doğası gereği, kavramsal tasarım sürecindeki boyutlandırma çalışmasının müşteri memnuniyeti için başarım seviyesi büyük önem taşır. Böyle karmaşık bir sistemin çok-disiplinli analizi yoğun çalışma ve uzun zaman gerektirir. Tasarım için gereken bu sürenin kısaltılması için istatistiksel (olasılıksal) tasarım metodları kullanılabilir. Bu tez çalışmasında, Türkiye ihtiyaçlarına uygun bir helikopterin kavramsal boyutlandırılması, çok-disiplinli ve olasılıksal bir tasarım yaklaşımı ile yapıldı.

Anahtar Kelimeler: Helikopter, Kavramsal Tasarım, QFD, OEC, RF-Metodu, Response Surface, Olasılıksal Tasarım, Hassasiyet ve Monte Carlo Analizi

To My Family,

ACKNOWLEDGMENT

I wish to express his gratitude to my supervisor Asst. Prof. Dr. İlkay YAVRUCUK for his guidance, advice, criticism, encouragements and insight throughout the research.

I also would like to address my deepest thanks to my family for their endless support during this study and throughout my life.

Finally, the assistance of anyone who has a contribution somehow is gratefully acknowledged.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbol	**Definition**	**Unit**
C	Specific Fuel Consumption	lb/hp/lb
W	Weight	lb
W_G	Gross Weight	lb
W_U	Useful Load	lb
Φ	Empty to Gross Weight Ratio	-
R	Main Rotor Radius	ft
V_c	Cruise Velocity	knot
P	Power	hp
ω	Angular velocity	rad/s
σ	Disk Loading	-
A_R	Range Parameter	-
A_T	Hover Parameter	-
K	Weight Correction Factor	-
L_F	Fuselage Length	ft
L_{T2M}	Distance Between Tail And Main Rotors	ft
R_{TR}	Tail Rotor Radius	ft
L_{Cl}	Clearance Length	ft
L_{TOTAL}	Total Length	ft

Abbreviation	**Definition**
RSE	Response Surface Equation
RF	Fuel Fraction
AHS	American Helicopter Society

BB	Box Behnken
OEC	Overall Evaluation Criteria
CCD	Central Composite Design
QFD	Quality Functional Deployment
HOT	Higher Order Terms
SFC	Specific Fuel Consumption
P/W	Power to Weight Ratio
MTBF	Mean Time Between Failure
MTTR	Mean Time to Repair
HOQ	House of Quality
TR	Tail Rotor
DS	Drive Shaft
LG	Landing Gear
FC	Flight Control
RPM	Revolution Per Minute

CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Modern aircraft design is a multidisciplinary design problem with many contradicting decisions to make. In the conceptual design phase, the designers have more freedom to make design changes and the most influential design choices are made in this phase. Yet, this is the design phase where the least about the problem is known. On the other hand, it is desired to obtain more and more information about the system at its early design phases. In this thesis, probability based design methods are employed to target customer satisfaction. Consequently, a conceptual helicopter design and sizing suitable for the Turkish market is used as a case study.

1.2 Literature Survey

In this section a literature survey on helicopter design is presented. The main concentration of this survey is on the conceptual design of rotary wing aircrafts, implementation of the concurrent engineering tools such as Quality Functional Deployment (QFD) and Overall Evaluation Criteria (OEC), and probabilistic design methods such as Response Surface Methodology and Monte Carlo Analysis.

The theoretical background on helicopter rotor hub design can be found in Ref. [1]. Specifically, the selection and sizing procedures of rotor hubs are given in detail in this reference. Similarly, the detailed information on the preliminary design of helicopters is illustrated in Ref. [10]. This handbook covers almost all aspects of helicopter preliminary design. It includes the methods for the selection of configurations (Chapter 3 of [10]).

Lecture notes of Schrage, D.P on Rotorcraft Systems Design [2] present analytical design methods which prevent the need for trial and error. In this reference, simultaneous solutions to both weight and aerodynamic performances of helicopters are presented. Thus, this paper is the main source to utilize the Fuel Fraction (RF) method and sizing of the helicopter.

In 2006, a short course on Response Surface Methodology was hold by Mavris, D. N. at Middle East Technical University (METU) in Ankara. Application of Response Surface Methodology on aircraft preliminary design was introduced in this course. References [4] and [5] belong to the course material and were quite helpful for the generation of the Response Surface Equations for the conceptual design. Also, the implementations of Design of Experiments and Response Surface Method (RSM) with JMP (a statistical design tool) are illustrated in these references.

A study on “System Synthesis In Preliminary Aircraft Design Using Statistical Methods” had been presented at the 20th Congress of the International Council of the Aeronautical Sciences DeLaurentis, D., Mavris, D. N. and Schrage, D.P. in 1996 [3]. In this study, an approach to conceptual and early preliminary aircraft design is documented. System synthesis is accomplished using statistical methods, such as Design of Experiments (DOE) and Response Surface Methodology (RSM). A systematical implementation of DOE, RSM and QFD tools on an air vehicle preliminary design work can be found in this paper.

Another study was carried out by Frits, A. P., Fleeman, E. L. and Mavris, D. N. named as “Use of a Conceptual Sizing Tool for Conceptual Design of Tactical Missiles” [6]. Together with Ref. [3], assistance of the methodology introduced in this paper played a significant role in implementation of statistical methods in this thesis.

In 2006 the Metucopter Design Team entered the American Helicopter Society’s helicopter graduate design competition. The design report [7] presents a helicopter design procedure with the use of concurrent engineering tools. This report was employed as a guide especially in construction of the QFD matrix and implementation of OEC.

A study was conducted by Vikhansky A., Kraft M. at 2003 regarding Monte Carlo Methods for Identification and Sensitivity Analysis of Coagulation Processes [8],. Although, the area of implementation is quite different, this paper led the way in application of Monte Carlo method for sensitivity analysis.

Ref. [11] presents the main construction and evaluation steps of Monte Carlo Analysis.

The thesis required the search for helicopters for a similar class. Thus a search was conducted to find similar helicopters and their specifications. The two helicopters of Eurocopter Company were selected as competitors and the specifications were found in companies' official site [9].

1.3 Motivation and Contributions of This Thesis

The motivation of this thesis is to accomplish a conceptual design and sizing approach of a civilian helicopter suitable for the Turkish Market and to provide a basis for a conceptual system design with the implementation of multidisciplinary and probabilistic design approaches in the conceptual sizing of a helicopter.

1.4 Thesis Outline

In Chapter 1, first the problem is introduced and then, a literature survey is provided. Chapter 2 gives the theoretical background on the multidisciplinary and probabilistic design methods employed in the conceptual sizing process.

Chapter 3 presents the conceptual design, analysis procedure and results.

Chapter 4 discusses the analysis results and presents the conclusions.

CHAPTER 2

THEORITICAL PRELIMINARIES

In this section, the theoretical background of the methods utilized in this thesis is presented. First, the Quality Functional Deployment (QFD) analysis method is introduced. This method enables the designer to relate the customer requirements to engineering parameters. Then, a method of helicopter configuration selection is explained. In that part, preliminaries for Fuel Fraction (RF) (for hover and forward flight) and Overall Evaluation Criteria (OEC) methods are given in details. Next, the methodology of the parameter sensitivity analysis is defined. Finally, some empirical formulas for conceptual helicopter sizing are illustrated. These equations are to be employed in the determination of the size of main helicopter components.

2.1 Quality Functional Deployment Analysis

In classical helicopter design some of the driving design parameters are disk loading, solidity, tip speed and empty weight,. Although those parameters are significant for all helicopters, the most important design variables may change according to customer needs, type of the helicopter or mission profile. In order to account for this fact and to find out the most important design variables a QFD method is employed in this thesis.

In this method, helicopter sizing, a large scale problem, is defined as one that possesses both high dimensionality and multi-objective attributes. The design of a complex vehicle such as helicopter requires analysis across multiple disciplines. Some of these disciplines might have competing objectives. As a result, the designer usually has control over many input variables and wants to track how each variable affects the responses to determine what trade-offs are needed to be made. When the number of design variables coming into play is increased, the dimensionality of the design space grows, and more sample design points are required to explore the entire region in all dimensions.

The QFD matrix is employed to discover the most important design drivers by relating the customer requirements to engineering parameters through the decision matrix ('whats' vs. 'hows'). This method also allows the designer to find out the real most important design variables regardless of what the traditional methods say.

In this method, each customer requirement is given a weighted importance level between 1 (least important) and 5 (most important). Then, for several sections of the helicopter design discipline (aerodynamics, structure, propulsion, control, life cycle cost), the main design drivers are determined. The matrix is filled with symbols (weak, moderate, high) to establish a relationship between the customer requirements and the design parameters. If there is no symbol in the box (empty box), it implies that no significant relationship is established between those.

Consequently, the significance order of design variables show up at the bottom of the QFD matrix. The weights (significances) are evaluated based on customer requirements and their relationship to design parameters. The variables related to most significant parameters then can be used in the formulation of the Overall Evaluation Criteria.

The detailed information about how the QFD matrices are constructed is given in Appendix A.

2.2 Selection of Helicopter Configuration

The feasible domain of helicopter configurations is defined by the requirements which stem from both aerodynamic and weight analyses. A unique relation between these analyses is the fuel weight ratio (R_F). The Fuel Fraction (RF) Method utilizes this relation to determine feasible helicopter configurations. An overall block diagram of the RF sizing procedure is shown in Figure 2.1.

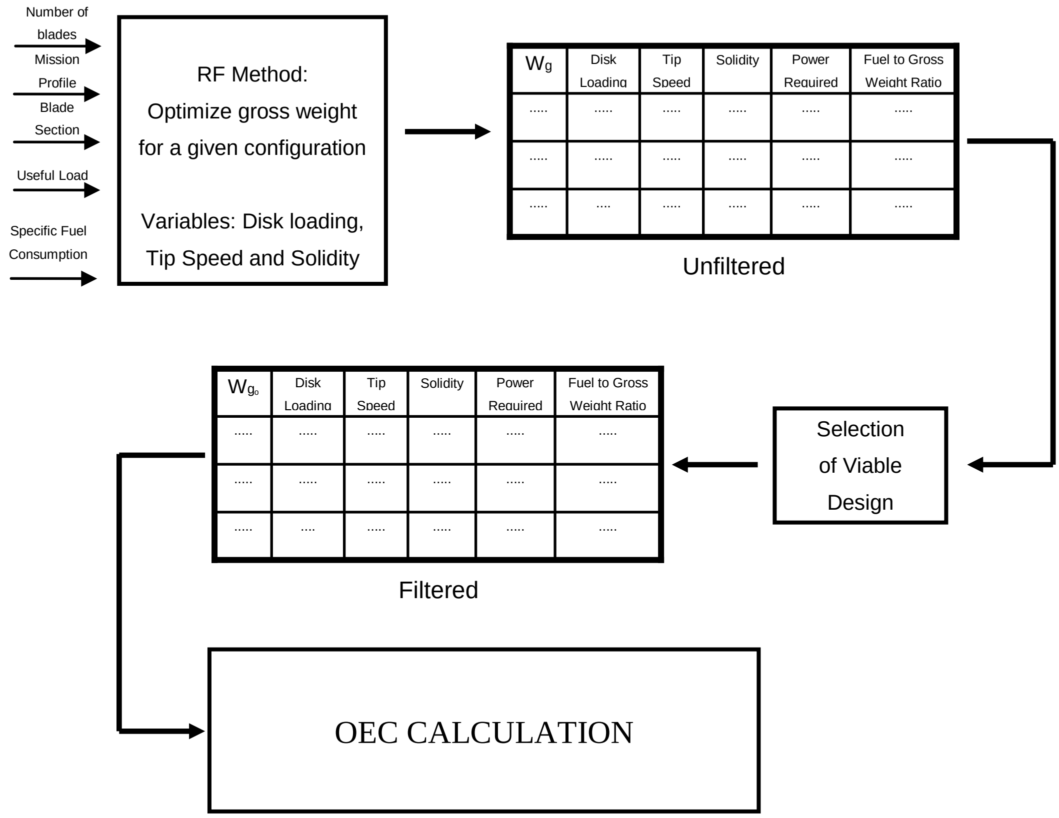

Figure 2.1 Configuration Selection and Evaluation Method

Initially, it is desired to investigate the variation of the disk loading, solidity and tip speed as design variables. The choice of these variables stems from the fact that these are considered as the most critical design parameters defining the characteristics of the main rotor [1].

The design variables such as airfoil type and number of blades are external inputs or can be selected before by just considering the competitors and have less importance in the conceptual sizing process.

The program (RF code) determines the point, where the required and available fuel to gross weight ratios are equal. Then, that point becomes a design point candidate. In order the point to qualify as a design point, it is checked against various design constraints. For instance, the design is checked against available thrust in hover, rotor RPM limits, upper radius limit, etc. When a point qualifies as a design point, an overall evaluation score is calculated at that design point to evaluate that specific configuration in terms of the customer requirements.

2.2.1 Fuel Fraction (RF) Method Based Sizing and Overall Evaluation Criteria

Generally, the design requirements include range and endurance performance parameters of the helicopter. By implementation of parametric analysis a minimum required R_F can be defined as a function of selected major design variables. On the other hand, the maximum available R_F can also be evaluated with the same parameters. The feasible helicopter configuration is the one with minimum required R_F is no less than the maximum R_F available.

After the determination of all feasible configurations in design space, further analyses is conducted to decide which configuration is the optimum in terms of the selected Overall Evaluation Criteria and some other constraints.

2.2.1.1 Fuel Fraction (RF) Analysis for Hover Performance

In some applications, the RF analysis is applied for only disk loading variation. An example RF analysis is given in

Figure 2.2. In this figure both locus of minimum gross weight and the feasible design area for disk loading w_1 (shaded area) are presented.

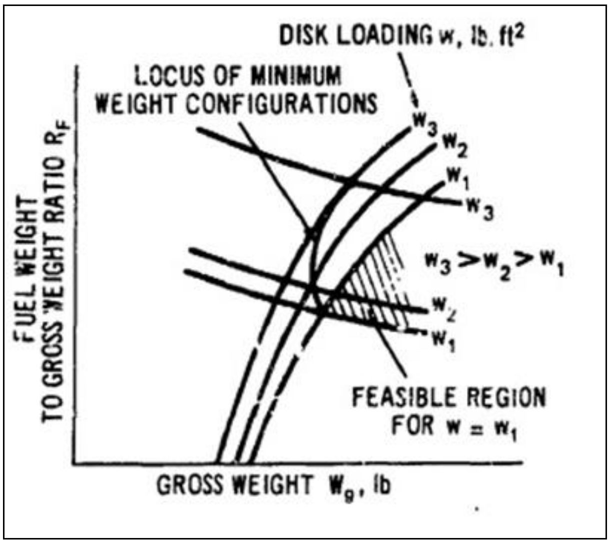

Figure 2.2 RF Method [10]

Intersection of R_{Fr} and, R_{Fav} for each disk loading defines a minimum gross weight for that configuration. If the objective of the design is to select the minimum gross weight configuration, the optimum configuration could be determined with this analysis only.

The RF (Fuel Fraction) Method employed in this study is an extended version which investigates the effect of different main rotor configuration variables on helicopter design gross weight. These variables are disk loading, solidity and tip speed.

The following equations ((2.1) and (2.2)) are the main equations which are employed to estimate the minimum design gross weights for different configurations [10]:

$$R_{F,R} = \frac{C \times HP_R \times T_H}{W_G} \tag{2.1}$$

Where, $R_{F,R}$ is required fuel to gross weight ratio, C is specific fuel consumption in lb/hp/lb, HP_R is required power in hover horse power, hp, T_H is required thrust at hover and W_G is gross weight.

$$R_{F,AV} = 1 - \frac{W_{useful}}{W_G} - \frac{W_{empty}}{W_G} \qquad \textbf{(2.2)}$$

Where, $R_{F,AV}$ is available fuel to gross weight ratio, W_{useful} is useful load including only payload and crew, W_{empty} is the empty weight and W_G is gross weight of the aircraft.

In R_F equations (2.1) and (2.2), the weight terms W_{useful}, W_{empty} and W_G are all interrelated and W_{useful} is a known parameter from the design requirements. The power parameters, hp and T_H are determined with the utilization of Blade Element Moment Theory [1] in the RF code. During the analysis, the specific fuel consumption (C) is assumed to be the average of the competitor helicopters' specific fuel consumptions.

After a number of iterations, the gross weight, at which the required fuel to gross weight ratio is equal to available fuel to gross weight ratio (minimum gross weight point), is found as a feasible design point. For some points iterations may not converge. This occurs when there is no feasible design point in that specific range of gross weight for that configuration of design variables.

2.2.1.2 Overall Evaluation Criterion (OEC)

The need for an overall evaluation method arises when there is more than one objective that a product or process is expected to satisfy. Situations of this nature are common in many areas of aerospace applications.

In this thesis, since the main goal is to meet the customer requirements, utilization of a multi objective method (OEC) which is based on the most significant requirements becomes necessary.

$$OEC = \alpha \frac{A_{ref}}{A} + \beta \frac{B_{ref}}{B} + \theta \frac{C_{ref}}{C} + \varphi \frac{D_{ref}}{D} \tag{2.3}$$

Equation (2.3) illustrates the structure of an OEC. In this equation, the Greek symbols α, β, θ and φ stand for the weight of significant design parameters (A, B, C and D) which are non-dimensionalized with their reference values. Significant parameters and weight of them are determined through QFD analysis. Reference values, on the other hand, are selected to be the value of that parameter for a competitor helicopter.

2.2.1.3 RF Analysis for Forward Flight

Forward flight performance is yet another flight condition to be analyzed. The dynamics of forward flight are quite different from the dynamics of hover. Thus, in order to improve conceptual sizing and to account for the forward flight performance, a new RF code is developed to see if the forward flight performance requirements are satisfied.

Method employed for the forward flight RF analysis is the same as RF analysis for hover. That is, when required fuel to gross weight ratio is equal to available fuel to gross weight ratio the corresponding gross weight becomes the minimum gross weight point for that configuration of variables. The derivation of the equations that are used in the code can be found in [2].

For this analysis, the performance of the selected (for the hover performance) configuration is inspected for the forward flight covering the whole mission profile.

$$W_G = \frac{W_U}{\dfrac{1-A_R \;\; 1+K}{1+A_R \;\; 1+K} - \dfrac{A_T \;\; 1+K \;\; w^{1/2}}{1+A_R \;\; 1+K}\left\{1+1.05\left[\dfrac{1}{\left(\dfrac{W_G}{W_U}\right)}+\phi\right]^{3/2}\right\}-\phi} \tag{2.4}$$

In equation (2.4), A_R and A_T are range and hover parameters, respectively [2]. The range parameter A_R depends on mission range, specific fuel consumption, cruise velocity and lift to drag ratio at that velocity. A_T, on the other hand, depends on hover time, hover efficiency, disk loading and Figure of Merit. K represents the weight correction factor and for this analysis it is taken to be 0.06 (value for self sealing tanks) [2]. W_G and W_U are gross and useful loads in lb. Φ stands for the empty to gross weight ratio and given as an initial guess which is close to the competitors values. Since the gross weight appears at both sides of the equation, the solution is iterative.

2.3 Parameter Sensitivity Analysis

Parameter sensitivity analysis is a method to determine system sensitivity to changes in design variables values. This information can be used to decide which parameters should be optimized or determined more accurately through further design studies.

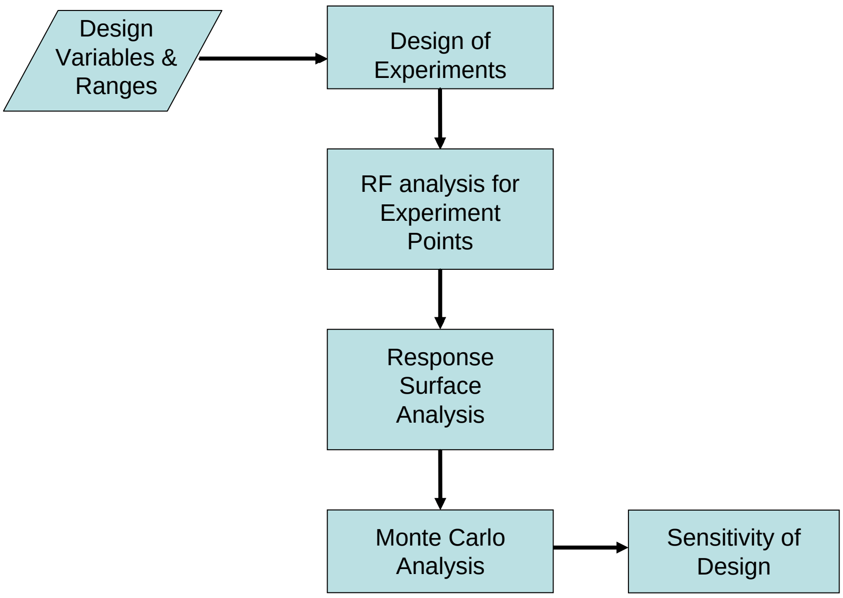

Figure 2.3 Sensitivity Analysis Method

In this thesis, a statistical parameter sensitivity analysis methodology is employed to determine the sensitivity of the design to possible changes of design variables. The flowchart of the method adopted is given in Figure 2.3).

First, with the utilization of Design of Experiment entire design space is explored in a more time effective manner when compared to traditional (Full Factorial) methods. After the experiment points are determined, the RF code is employed for all these design points and the responses (Gross Weight, Horse Power and OEC) are collected. Next, the design points and the corresponding response values are inserted to JMP program for the generation of Response Surface Equations for each response. Finally, these equations are fed into Monte Carlo Analysis to find out how the design is sensitive to the changes in design variables.

2.3.1 Design of Experiment (DOE)

With the ever-increasing complex and numerically time consuming models, design of experiment has become an essential part of the modeling process. One way to run tests is to test every possible combination of variables. In that case, the problem grows very rapidly, especially for aerospace applications since they are multidisciplinary problems. When the number of variables is high, it becomes very cumbersome to compute all the possible combinations of the variables at three levels. Consequently, a full factorial analysis becomes impractical. For instance, a problem with six variables all having three levels, a full factorial design needs $3^5 = 243$ runs. On the other hand, with the use of DOE methods such as Box-Behnken (BB) design or Central Composite Design (CCD), one would need 46 or $2^n + 2n + 1 = 43$ runs, respectively.

In this thesis, for the DOE, BB method is selected to be employed for some of its advantages which will be explained in the following section.

2.3.1.1 Box-Behnken (BB) Designs

BB designs are rotatable and for a small number of factors (four or less), they require small number of runs. By avoiding the corners of the design space, they allow designers to work around extreme factor combinations. As it can be seen in the BB geometry shown in Figure 2.4, the axes show the variation of design variables (for this case, 3 variables) while the points on the cube illustrate the experiment points.

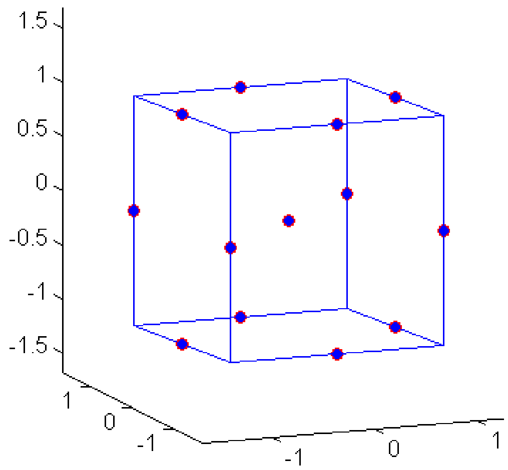

Figure 2.4 BB Design Points

2.3.2 Response Surface (RS) Analysis

Most engineering design problems require experiments and/or simulations to evaluate design objective and constraints as functions of design variables. For example, in order to find the optimal airfoil shape for an aircraft wing, an engineer simulates the air flow around the wing for different shape parameters (length, curvature, material, etc.). On the other hand, a single simulation run can take many minutes, hours, or even days to complete. As a result, routine tasks such as design optimization or sensitivity analysis become impossible since they require thousands or even millions of simulation evaluations. One way of alleviating this burden is to construct approximation models, known as surrogate models (Response Surface

Equations) that mimic the behavior of the simulation model as closely as possible while being computationally cheap to evaluate. Surrogate models are constructed employing a data-driven, bottom-up approach. The exact, inner working of the simulation code is not assumed to be known (or even understood), only the input-output behavior is important. A model is constructed based on modeling the response of the simulator to a limited number of intelligently chosen data points by the use of the DOE. This approach is also known as behavioral modeling or black-box modeling [4].

The accuracy of the surrogate models depends on the number and location of samples in the design space. Various designs of experiments (DOE) techniques cater to different sources of errors, in particular errors due to noise in the data or errors due to an improper surrogate model [5]. The most popular surrogate models are polynomial response surfaces. For most problems, the nature of true function is not known a priori; thus it is not clear which surrogate model will be most accurate. In addition, there is no consensus on how to obtain the most reliable estimates of the accuracy of a given surrogate.

The simplest such model has the quadratic form containing linear terms for all factors, squared terms for all factors, and products of all pairs of factors. Designs for fitting these types of models are known as response surface designs.

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=j}^{k} b_{ij} x_i x_j \qquad \textbf{(2.5)}$$

An example formulation of a second order Response Surface Equation (RSE) is given in Equation (2.5) [6]. In this equation, b_i's are regression coefficients for the first degree terms, and x_i, x_j's are the design variables. b_{ii}'s are coefficients for the pure quadratic terms, b_{ij}'s are coefficients for the cross-product terms (second order interactions), and b_0 is the intercept term. The x_i terms are the main effects, the x_i^2 terms are the quadratic effects, and the $x_i x_j$ are the second order interaction terms. In this study a statistical analysis program, JMP, is employed to ease calculations.

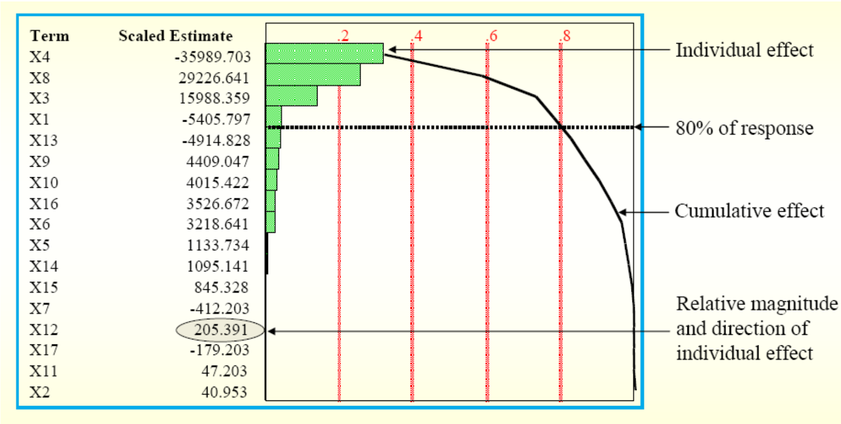

Figure 2.5 Pareto Plot [4]

Figure 2.5 represents an example of Pareto Plot. In this plot, the green bars show the individual effect of parameters on the response. Scaled estimate column, on the other hand, shows the relative magnitude and direction (sign) of corresponding term (parameter). In the generation of Pareto plots, the effects of all parameters on a response are evaluated separately using statistical methods and the data provided in the DOE chart. This is held automatically by JMP program. Pareto plots provide an insight about the sensitivity of a response to selected variables. These plots are also employed to determine if a parameter has a contribution in variation of a response. This property enables designer eliminate some insignificant variables.

In Figure 2.6, properties of an “actual by predicted” plot is given. In this plot, Data (experiment) points from DOE, perfect fit for that case, mean of response and 95% confidence lines are included. The DOE data points should be scattered evenly along and very close to the Perfect Fit line if the assumed form of the analysis is correct. If there is clumping or patterns, or the data is not close to the Perfect Fit line, the order of the fit model may be inadequate (transformations or HOT (Higher Order Terms) may be needed) or some variables may be set at their extreme values (upper or lower bound) dominating the behavior.

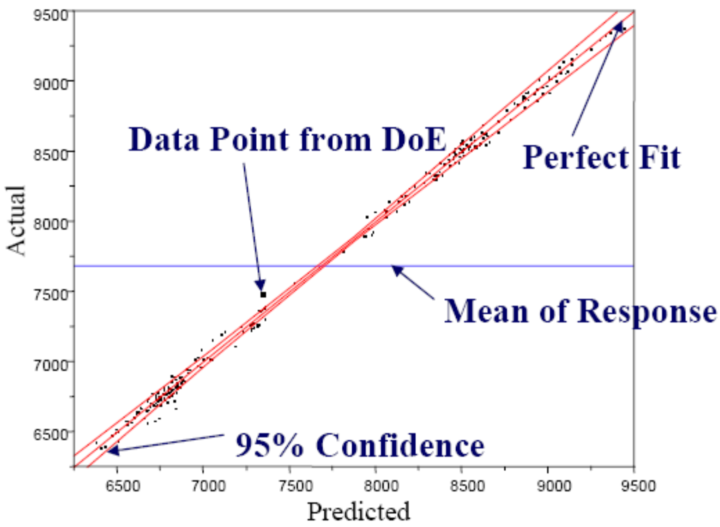

Figure 2.6 Actual by Predicted Plot [5]

Below, an example prediction profiler is given as Figure 2.7 illustrating the interactions of design variables with selected system responses. On this chart, one can see the ranges of design variables and system response values at a fixed variable-set setting (in the example, setting of variables are weight=450, Diameter=10, Nose Length=22). These setting of variables can be altered by just dragging the dashed red lines in right-left direction and the results can be seen instantaneously.

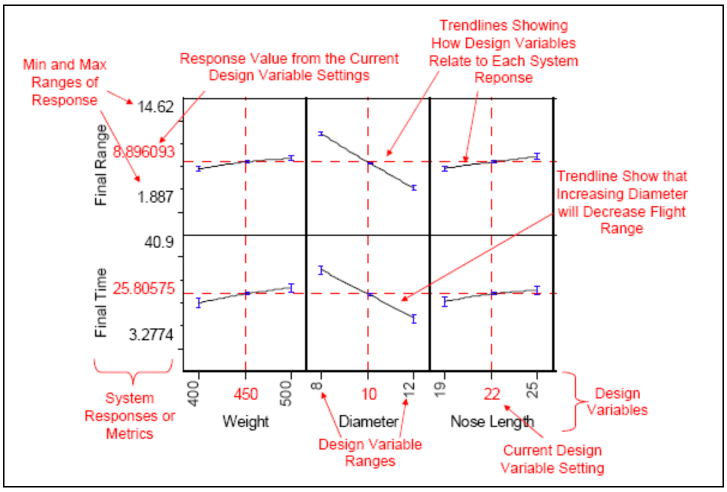

Figure 2.7 Prediction Profiler [6]

At the end of this analysis, if the fits for selected responses are accurate enough, the equations of these fits (RSEs) can be employed instead of simulation runs, so that, the time spent is decreased.

2.3.3 Monte Carlo Simulations

Monte Carlo Simulations are computer-based method of analysis developed in the 1940's. This method uses statistical sampling techniques in obtaining a probabilistic approximation to the solution of a mathematical equation or model. They are widely used for sensitivity analysis.

Generally, Monte Carlo simulations are characterized by a large number of unknown parameters, many of which are difficult to obtain experimentally. Implementation of this method is mainly accomplished by giving a random distribution [11] (gaussian for our case) to design variables (main rotor radius, chord etc.) and looking after the response/system behavior for these cases.

2.4 Conseptual Sizing of Main Components of Helicopter

2.4.1 Component Weights

The individual weights of main components can be estimated using emprical formulations [2]. The equations are given below.

- Main Rotor

$$W_R = 1.7 W_G^{\,0.342} R^{1.58} \sigma^{0.63} \tag{2.6}$$

- Tail Rotor

$$W_{TR} = 7.12\left(\frac{W_G}{1000}\right)^{0.446} R_{TR}{}^{1.62}\sigma_{TR}{}^{0.66} \tag{2.7}$$
$$where\ \sigma_{TR} = 2\sigma;\ and\ R_{TR} \approx 0.2R$$

- Power Plant Section Group

$$W_{PS} = 2.5*\left(\frac{W_G}{1000}\right)^{1.07} * dl^{0.54} \tag{2.8}$$

- Flight Control Group

$$W_{FC} = 0.0226 W_G{}^{0.712} V_c{}^{0.653} \tag{2.9}$$
$$where\ V_c\ is\ cruise\ speed\ in\ knots.$$

- Landing Gear

$$W_{LG} = 0.0475\left(\frac{W_G}{1000}\right)^{0.975} \tag{2.10}$$

- Fuselage

$$W_F = 0.37 W_G{}^{0.598} R^{0.942} \tag{2.11}$$

Using above equations, a first estimation for conceptual sizing of the main components is done (section 3.5).

2.4.2 Dimension Characteristics

Similar to the weight estimations, there are some empirical equations presented in the literature to make a first estimation of general dimensions of a helicopter in conceptual design phase. Some of those equations [2] were given below.

- Fuselage

$$L_F = 1.6R \tag{2.12}$$

- Tail to Main Body

$$L_{T2M} = 1.23R \tag{2.13}$$

- Tail Rotor Radius

$$R_{TR} = 0.36R \tag{2.14}$$

- Clearance

$$L_{Cl} = 0.05R \tag{2.15}$$

- Total Length

$$L_{Total} = 1.91R \tag{2.16}$$

CHAPTER 3

CONCEPTUAL SIZING AND ANALYSIS

In this thesis, the multidisciplinary and probabilistic design approach is utilized. This section provides an overview of this design procedure.

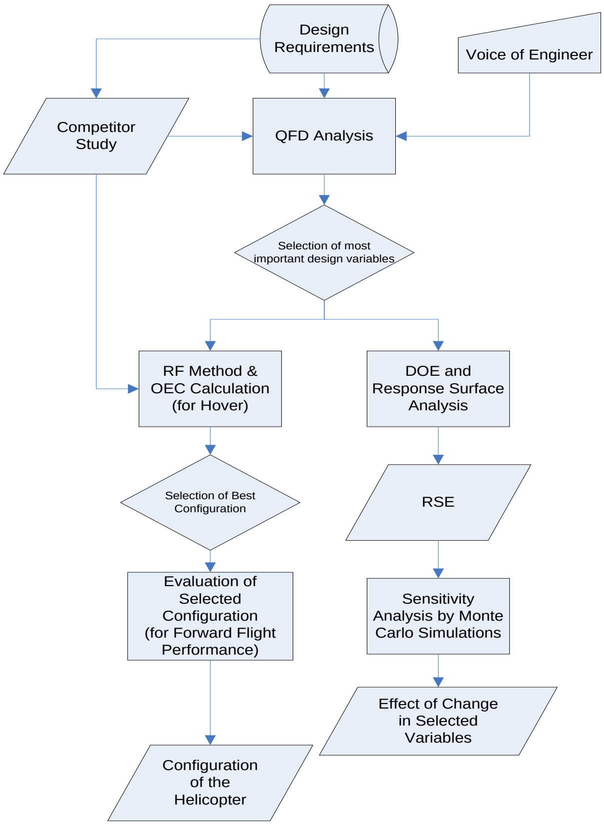

Figure 3.1 Flowchart of the Design Method

In Figure 3.1, steps of the conceptual sizing and analysis are illustrated. The design requirements are treated as the “voice of the customer” and translated to the “voice of the engineer” through a Quality Functional Deployment (QFD) Matrix (House of Quality). The QFD matrix provides a market awareness of the proposed product as well as showing the most dominant design parameters. The weighted sums are then used to establish an “Overall Evaluation Criteria” (OEC) to rank different helicopter configurations.

Since the main rotor is known to be the heart of a helicopter design and a major contributor to almost every aspect of the helicopter, the design space is swept for disk loading, tip speed and solidity, and their design viability is checked. These three parameters are known to be the core design parameters in main rotor design [1]. For each main rotor configuration an in-house developed helicopter design algorithm is employed. This algorithm sizes the helicopter and calculates parameters like gross weight, radius, power required, range, endurance, etc. [2]. Also the OEC for all the points in design space are evaluated in this code. The higher the OEC, the better the performance of the helicopter, in terms of customer needs, where OEC parameter weight values are determined based on the outcome of the QFD solution. On the other hand, there are some other constraints to be considered in helicopter design such as structural issues. As a result, in the light of OEC results and constraints, the best configuration is selected for the hover performance.

Then, the relationship of disk loading, tip speed, solidity and some other design variables to the target design drivers, such as gross weight, are fit into a DOE scheme. Next, Response Surface Equations are generated. Then, using these equations, Monte Carlo Simulations are performed to evaluate the sensitivities of the design variables to the target values. Finally, the performance of the selected configuration is checked for forward flight.

After the final configuration of the desired helicopter is attained, the conceptual sizing of some main components is performed utilizing some empirical formulas.

3.1 Design Requirements

Considering the necessities and the geographical conditions of Turkey, the following sample requirements are selected for this study:

- Service Ceiling: 15.000ft
- HIGE: 10.000ft
- Operational Temp: ISA+35
- Endurance: 180 min.
- Range: 600km
- Payload: 1pilot + 5 passengers + 200kg
- Improved Safety
- Multi-function capability
- Low vibration
- Fast forward speed
- Rugged design

A helicopter with the above-mentioned specifications can be employed for multi-purposes such as rescue, air ambulance and commercial transportation etc. missions. Figure 3.2 shows a sample mission profile for the helicopter considered.

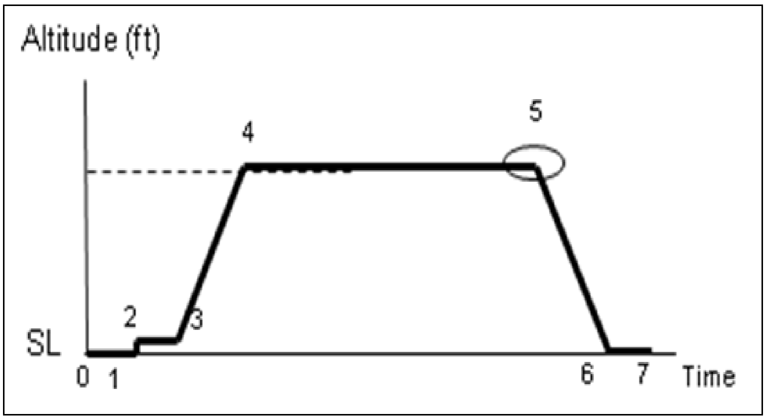

Figure 3.2 Reference Mission Profile

The details of the mission profile are given in Table 3.1.

Table 3.1 Mission Profile Segments

Segment	Description	Altitude (ft)	Speed	Time (min)
0 – 1	Warm-up	0	-	2
1 – 2	Takeoff. Vertical Climb	0 – 5	-	2
2 – 3	Acceleration Ground Effect	5	0 - 50 knots	1
3 – 4	Climb	5 – 6000	10 ft/s (R/C)	10
4 – 5	Cruise	6000	100 knots	15
5	Hover	6000	-	5
5 – 6	Descend	6000 – 0	10 ft/s (R/C)	10
6 – 7	Landing	0	-	5

3.2 Competitor Study

In this section, a competitor study is performed. This study is an initial step for most of the engineering conceptual design work. Searching for similar helicopters, in terms of mission and performance requirements, Eurocopter AS350 B3 and EC 120 are selected to be the two competitors. Some of the specifications [9] of these helicopters are given in the Table 3.2. Reference values of some unknown parameters are adapted from these helicopters' data to be employed as initial value in the analyses.

Table 3.2 Competitor Helicopters' Specifications

Competitor	**Eurocopter AS350 B3**	**Eurocopter EC 120**
General Characteristics		
Crew	1 Pilot	1 or 2 Pilots
Capacity	6 passengers	4 passengers
Length	10.93 m (35 ft 10.5 in)	9.6 m (31 ft 5 in)
Rotor diameter	10.69 m (35 ft 1 in)	10 m (32 ft 8 in)
Height	3.14 m (10 ft 3.5 in)	3.4 m (11 ft 2 in)
Empty weight	1174 kg (2588 lb)	991 kg (2185 lb)
Gross weight	2250 kg (4960 lb)	1715 kg (3781 lb)
Powerplant	1 Turbomeca Arriel 2B turboshaft, 632 kW (847 shp)	1 Turbomeca Arrius 2F turboshaft, 376 kW (504 shp)
Performance		
Never exceed speed	287 km/h (155 kts, 178 mph)	278 km/h, (150 kts, 172 mph)
Cruise speed	245 km/h (132 kts, 152 mph)	223 km/h, (120 kts, 138 mph)
Range	662 km (357 nmi, 411 mi)	710 km, (383 mi, 440 nm)
Service ceiling	4600 m (15100 ft)	5182 m (17000 ft)
Rate of climb	8.5 m/s (1675 ft/min)	5.84 m/s (1150 ft/min)

3.3 Quality Functional Deployment Analysis

A QFD Matrix, a concurrent engineering tool, is employed to translate the customer requirements to engineering parameters. The engineering parameters are weighted according to significance of their effects on the costumer requirements.

Figure 3.3 shows the QFD Matrix prepared for the requirements introduced in the section 3.1.

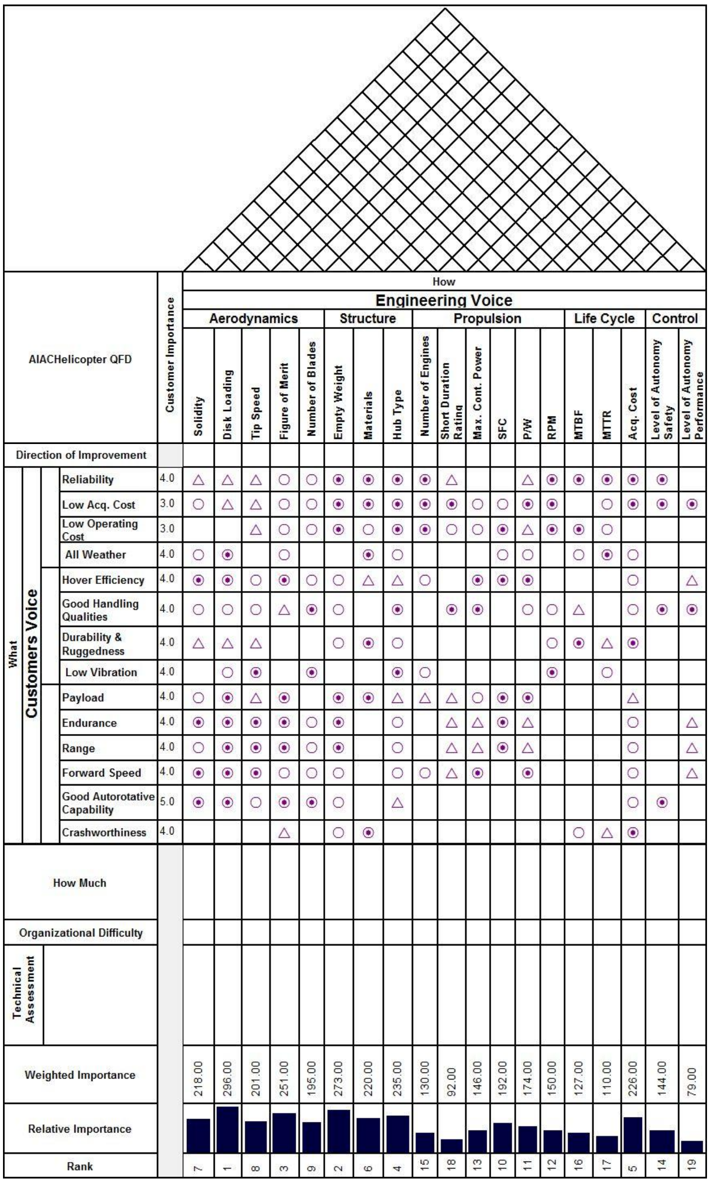

Figure 3.3 QFD Matrix

Filling out the QFD matrix requires experience and a strong foundation in helicopter theory [7]. The QFD matrix is created using the package program QFD Designer V4 (A.1).

First, the customer importance parameters are determined. In the determination of this parameter customer requirements are considered in terms of their relative importance. All the parameters under the "Customers Voice" heading are given a weight between 1 and 5, from least important to the most important. For instance, the weight of good autorotative capability is selected to be 5 since it is a crucial parameter for the safety of helicopters. Then, the relation between customer requirements and engineering parameters are determined[1]. For example, if the hover efficiency row in the customer voice is inspected it is seen that this requirement has a strong relationship with solidity, disk loading, figure of merit, maximum continuous power, specific fuel consumption and power to weight ratio parameters. On the other hand, it has a moderate relationship with tip speed, number of blades, empty weight, number of engines and acquisition cost parameters. The relation of hover efficiency with materials, hub type and level of autonomy performance is a weak one with respect to other parameters. Finally, the empty spaces show that there are no direct relationships between hover efficiency and short duration rating, RPM, Mean Time Between Failure (MTBF), Mean Time To Repair (MTTR) and level of autonomy safety parameters. After the QFD Matrix is filled out, the relative importance of the engineering parameters appears at the QFD matrix in the weighted importance, relative importance and rank rows.

As a result the QFD analysis yields following parameters as the most important design drivers in significance order:

- Disk Loading
- Empty Weight
- Figure of Merit
- Hub Type

[1] The weight of symbols in the QFD Matrix is as: △ = 1 (weak), ○ = 3 (moderate) and ⊙ = 9 (high).

Based on this analysis, a preliminary sizing is done and a first configuration is selected as it will be explained in the following sections.

3.4 Selection of Helicopter Configuration

3.4.1 Helicopter Preliminary Sizing Using OEC and RF-Optimization

In accordance with the output of the QFD analysis performed in the previous section, the following OEC is used to evaluate the performance of different configurations.

$$OEC = \alpha \frac{GW_{ref}}{GW} + \beta \frac{hp_{ref}}{hp} + \theta \frac{dl_{ref}}{dl} + \varphi \frac{RF_{ref}}{RF} \qquad \textbf{(3.1)}$$

where the letters α, β, θ and φ indicate the weights of the parameters, gross weight (GW), required horse power (Hp), disc loading (DL) and Required Fuel Weight Ratio in hover (RF), respectively. Each of these parameters is normalized with their reference values (values for AS 350 2B see Table 3.2). The weight of each ratio is obtained from the corresponding weights acquired through the QFD results. The RF analysis for hover is employed.

As a result, a number of helicopter designs are obtained and ranked according to OEC scores. In Figure 3.4, a 3-D plot of the design space indicates the performance of different configurations, based on the OEC (evaluation) score.

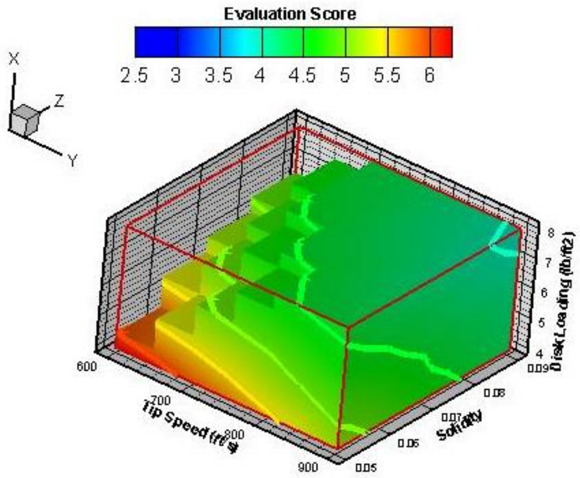

Figure 3.4 OEC Variation

It is observed that as the tip speed, solidity, and disc loading decreases, the configuration approaches to an optimum in terms of OEC. In Figure 3.4 the cube presented by red lines designates the range for solidity, tip speed and disk loading in this analysis. The empty parts inside the cube are due to the fact that no viable design points were obtained at that region. In terms of the color codes, a better design (high OEC) is obtained while going from blue to red regions.

On the other hand, helicopter design is limited by some other constraints. This is an expected issue since physically; there should be a limitation on the desirable design. For instance, for some points, the main rotor radius becomes too long and this leads to structural problems. Another problem is that, an increase in blade radius causes a decrease in the rigidity of the blade, therefore, a higher rotor RPM is required to keep the blades rigid. However, with long blades and low tip speeds, the rotor RPM would be relatively low, so rigidity cannot be maintained for such configurations.

Consequently, when the configurations are sorted for decreasing evaluation score (first fifteen are given in Table 3.1). The tenth configuration is selected since it has a considerably high evaluation score and rational physical properties. Note that, choices with higher scores tend to have low chord numbers making the rotor design difficult from a structural stand-point. Since the RF method has no structural models such decisions are made off-line. Of course it would be possible to include a structural model in the methodology.

Table 3.3 First Fifteen Configurations in terms of OEC Score

Rank	Evaluation Score	DL (lb/ft^2)	TS (ft/s)	SLD	GW (lb)	Radius (ft)	chord (ft)	RPM	hp
1	6.23	4	600	0.05	3450	16.57	0.65	345.78	278.7173
2	6.12	4	650	0.05	3475	16.63	0.65	373.24	288.9547
3	6.1	4	600	0.06	3500	16.69	0.79	343.29	290.2042
4	5.99	4.5	600	0.05	3425	15.56	0.61	368.22	283.6378
5	5.95	4	650	0.06	3550	16.81	0.79	369.24	306.1738
6	5.94	4	700	0.05	3525	16.75	0.66	399.07	309.2835
7	5.93	4	600	0.07	3575	16.86	0.93	339.83	307.0874
8	5.87	4.5	600	0.06	3475	15.68	0.74	365.40	295.5514
9	5.86	4.5	650	0.05	3450	15.62	0.61	397.37	298.3276
10	5.83	4	600	0.08	3625	16.98	1.07	337.43	316.9268
11	5.79	4	750	0.05	3575	16.87	0.66	424.53	327.4265
12	5.78	4	650	0.07	3625	16.98	0.93	365.55	324.8547
13	5.77	4	700	0.06	3600	16.93	0.8	394.83	328.3605
14	5.75	4.5	650	0.06	3500	15.73	0.74	394.59	308.8868
15	5.74	4.5	600	0.07	3525	15.79	0.87	362.86	309.1467

Up to this point of the study, the RF analysis was utilized for all of the possible design configurations. The RF code was run for every case and the results were collected. This was a full factorial experiment and was time consuming. In the following part, to be able to make the sensitivity analysis in a time efficient manner, Design of Experiment (DOE) and Response Surface methods will be employed.

3.4.2 DOE & Response Surface (RS) Analysis

In this section, first the design variables are determined. The selection of variables may affect the accuracy of the Response Surface fits. In order to account for this issue, two different set of variables are generated and employed. First set of (CASE1) design parameters are blade twist, tip speed, disk loading and solidity. Second set (CASE2) includes blade twist, main rotor radius, RPM, chord parameters. CASE1 parameters are a combination of rotor geometric parameters and generally give better physical inside to the design. CASE2 variables are the base variables for a helicopter main rotor.

After the experiments are designed, a response surface analysis is conducted. In this analysis, gross weight, horse power and evaluation score are selected to be the responses.

In the beginning, for both cases, a first order estimation is carried out to see if it would be accurate enough and to make an initial sensitivity analysis. Purpose of this rough sensitivity analysis is to retrieve some clue about the effects of the selected design variables on the responses. Much better information about the sensitivity will be gathered from the Monte Carlo analysis.

Since the fits for first order estimation are not accurate enough to be employed in Monte Carlo simulations, second order estimations are done in order to improve the accuracy of fits (response surface equations).

3.4.2.1 Analysis with CASE1 Parameters

In this analysis, the variables which are listed in the Table 3.4 below are inserted and 27 experiments are generated with DOE tool of JMP program. The second column of Table 3.4 illustrates the pattern of the design variables for each experiment points. It should be noted that for five of the experiments the pattern index is found as “0”. At these points all the design variables have their average values. The reason behind repeating the same experiment at this point for five times is just to check the reliability of the supplied data. This is an embedded property of JMP program and whenever a DOE is generated these check points are included in the experiments automatically.

After the DOE is ready, hover RF code is run for these experiment points.

Next, the outputs of the RF code are implemented to the JMP data table as the actual responses. At some experiment points (experiments 17 and 24 for this analysis) there is no rational solution from the RF code. Consequently, these points were excluded from the analysis.

Table 3.4 CASE1 BB Design Variables

		Design Variables (Factors)				Responses		
Experiment Number	Pattern[2]	Twist (°)	TS	DL	Solidity	Gweight	HP	Evaluation Score
1	−0+0	-8	750	8	0.07	3580	404.317	4.47
2	−00−	-8	750	6	0.05	3490	347.7	5.1
3	0	-6	750	6	0.07	3630	390.603	4.81
4	0+−0	-6	900	4	0.07	4640	730.168	4.18
5	0	-6	750	6	0.07	3630	390.603	4.81
6	−−00	-8	600	6	0.07	3480	331.562	5.21
7	0+0−	-6	900	6	0.05	3640	407.358	4.73
8	+00−	-4	750	6	0.05	3510	356.24	5.04
9	0	-6	750	6	0.07	3630	390.603	4.81
10	00−+	-6	750	4	0.09	4060	466.921	4.93
11	+00+	-4	750	6	0.09	3770	434.367	4.56
12	00++	-6	750	8	0.09	3690	440.23	4.27
13	+0−0	-4	750	4	0.07	4030	491.838	4.86
14	0−0+	-6	600	6	0.09	3580	359.366	4.99
15	0	-6	750	6	0.07	3630	390.603	4.81
16	0−−0	-6	600	4	0.07	3570	309.542	5.91
17[3]	0−0−	-6	600	6	0.05	10010	819.227	-9

[2] "0" means average value of the variable, "+" means maximum value of the variable, "-" means minimum value of the variable.

[3] The RF code finds no solution at this point.

Table 3.4 Continued

		Design Variables (Factors)				Responses		
Experiment Number	Pattern	Twist (°)	TS	DL	Solidity	Gweight	HP	Evaluation Score
18	0+0+	-6	900	6	0.09	4060	548.618	4.1
19	0++0	-6	900	8	0.07	3740	472.413	4.14
20	−00+	-8	750	6	0.09	3750	423.358	4.61
21	−+00	-8	900	6	0.07	3830	473.198	4.4
22	00−−	-6	750	4	0.05	3580	330.68	5.76
23	−0−0	-8	750	4	0.07	3780	383.291	5.38
24[4]	0−+0	-6	600	8	0.07	10010	892.977	-9
25	+−00	-4	600	6	0.07	3500	339.572	5.14
26	00+−	-6	750	8	0.05	3520	386.341	4.58
27	0	-6	750	6	0.07	3630	390.603	4.81

Then using JMP, a first order response surface analysis is performed. Results of this analysis can be summarized as follows.

Term	Orthog Estimate
TS(600,900)	150,5956
DL(4,8)	-124,2313
Solidity(0,05,0,09)	104,7996
twist(-8,-4)	32,3316

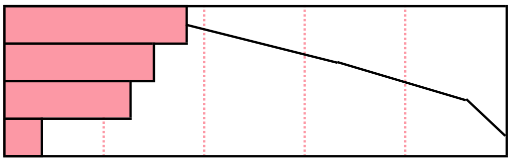

Figure 3.5 Pareto Plot for Gweight Response for CASE1

[4] The RF code finds no solution at this point.

Figure 3.5 shows the effect of each variable on the gross weight. According to this analysis, tip speed seems to be the most significant parameter in gross weight estimation. Disk loading and solidity also seem to have comparable effects on gross weight. Twist, on the other hand, has the lowest effect on this response.

Term	Orthog Estimate
TS(600,900)	64,62573
Solidity(0,05,0,09)	32,56990
DL(4,8)	-17,07320
tw ist(-8,-4)	14,06166

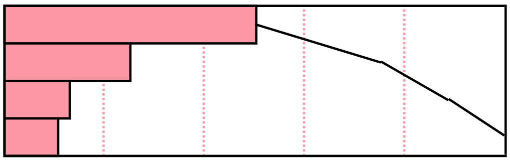

Figure 3.6 Pareto Plot for Horse Power Response for CASE1

Similar to the gross weight response, again tip speed appears to be the most and twist appears to be the least effective parameter for horse power response with a higher percentage (Figure 3.6). Only difference is that the ranks of DL and solidity are changed.

Term	Orthog Estimate
TS(600,900)	-0,3309023
DL(4,8)	-0,2314476
Solidity(0,05,0,09)	-0,1843044
tw ist(-8,-4)	-0,0640859

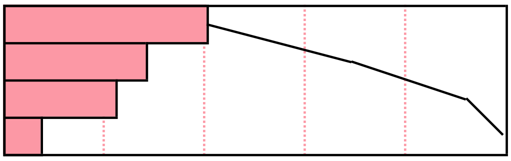

Figure 3.7 Pareto Plot for Evaluation Score Response for CASE1

This time, for the evaluation score response, in Figure 3.7, again the tip speed is the dominating factor. Actually, the order of variables is the same with the horse power response, but the relative effect of the variables is different for the two responses.

From the three Pareto plots above, it can be concluded that, twist has a negligible effect on all of responses. Thus, if the number of variables and experiments were large, the blade twist parameter could be excluded for the following parts of the analysis. Contrarily, since the number of experiments is small enough to be handled, the twist is maintained as a design variable in order to be able to make more reliable comparisons.

Summary of Fit	
RSquare	0,752774
RSquare Adj	0,703329
Root Mean Square Error	143,4714
Mean of Response	3734
Observations (or Sum Wgts)	25

a)GW

Summary of Fit	
RSquare	0,71147
RSquare Adj	0,653764
Root Mean Square Error	53,87868
Mean of Response	423,7541
Observations (or Sum Wgts)	25

b) HP

Summary of Fit	
RSquare	0,885734
RSquare Adj	0,86288
Root Mean Square Error	0,180099
Mean of Response	4,77
Observations (or Sum Wgts)	25

c) OEC

Figure 3.8 Summary of Fits for CASE1

Above charts are taken for the first order fits of three responses (Figure 3.8). As it can be expected, first order fit is not adequate for all of our responses (RSquare terms are much less then 1). On the other hand this is a very useful analysis to have a first idea about the sensitivity of the responses to given factors. After this point, for a finer estimate, a second order response surface analysis is performed for the same data given in Table 3.1.

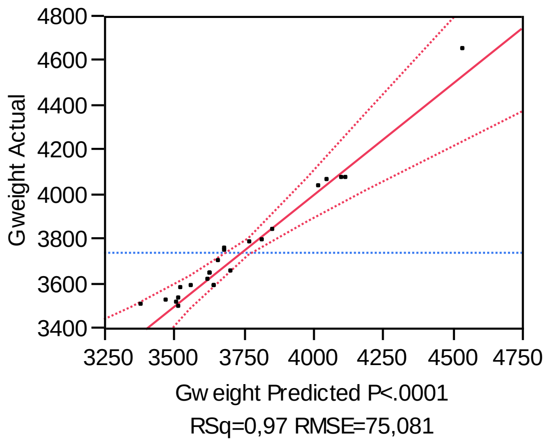

Figure 3.9 CASE1 2nd Order Fit for Gross Weight Response

Figure 3.9 reveals that, for a second order estimation, gross weight response can be fitted with an adequate accuracy (RSquare = 0.97).

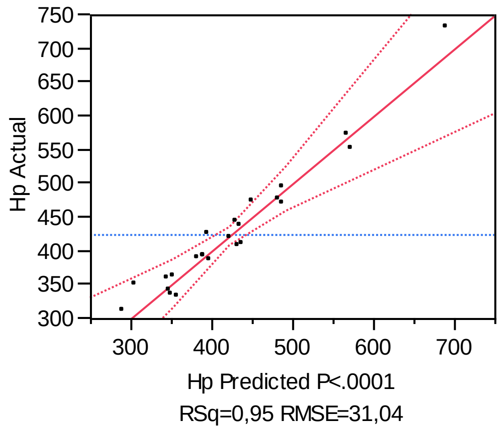

Figure 3.10 CASE1 2nd Order Fit For Horse power

Similar to gross weight response, also the accuracy of second order fit seems to be sufficient for horse power response (Figure 3.10).

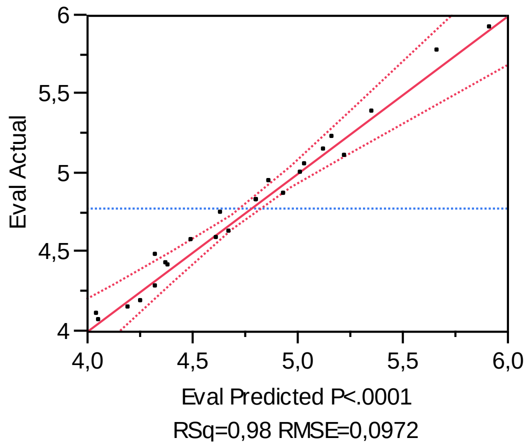

Figure 3.11 CASE1 2nd Order Fit for Evaluation Score

For evaluation score response, a value 0.98 for the RSquare parameter is estimated (Figure 3.11) which shows that evaluation score prediction is good enough for further analyses.

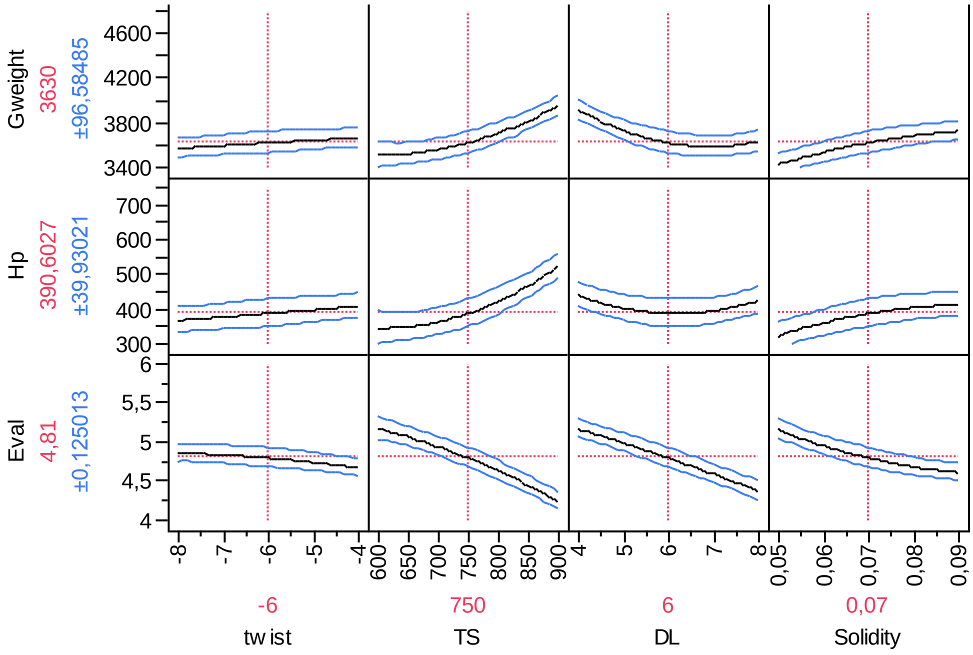

Figure 3.12 Prediction Profiler for CASE1

In Figure 3.12, Prediction profiler a visual tool of JMP is shown. Using this tool, values of the responses for different input settings can be monitored. Besides, the relationship of all variables with the responses can be seen and evaluated by just inspecting the behavior of the curve of the corresponding parameter and the response. For instance, if the relation of tip speed with the evaluation score is questioned, the second variation among the bottom reveals that as the tip speed increases the evaluation score decreases almost linearly. Also, the distance between the two blue lines, for each response, shows how good the estimations are (the closer the better).

3.4.2.2 Analysis with CASE2 Parameters

In this part, CASE2 variables are chosen to be DOE factors and the analysis is performed for the same responses. In Table 3.5, design variables Rad and Chord stand for main rotor radius and root chord respectively. There is a no solution point (Experiment number 7) for this case either, and it is excluded from the analysis.

Table 3.5 CASE2 BB Design Variables

		Design Variables (Factors)				Responses		
Experiment Number	Pattern	Rad	Chord	RPM	Twist (°)	Gweight	HP	Evaluation Score
1	+0−0	20	0.9	300	-6	3640	292.648	6.7
2	−00−	15	0.9	400	-8	3560	334.45	5.38
3	0	17.5	0.9	400	-6	3730	364.212	5.55
4	110+0−	17.5	1.2	400	-8	3930	423.191	5.1
5	+00−	20	0.9	400	-8	4000	439.547	5.51
6	00−−	17.5	0.9	300	-8	3510	276.905	6.39
7[5]	−0−0	15	0.9	300	-6	10010	268.733	-9
8	+00+	20	0.9	400	-4	4550	701.243	4.44
9	0−+0	17.5	0.6	500	-6	3750	402.122	5.35
10	0+0+	17.5	1.2	400	-4	4170	541.501	4.54
11	0++0	17.5	1.2	500	-6	4720	785.062	3.76
12	+−00	20	0.6	400	-6	3710	350.196	6.22
13	−+00	15	1.2	400	-6	3690	372.877	5.05

[5] The RF code finds no solution at this point.

Table 3.5 Continued

		Design Variables (Factors)				Responses		
Experiment Number	Pattern	Rad	Chord	RPM	Twist (°)	Gweight	HP	Evaluation Score
14	00+−	17.5	0.9	500	-8	4060	509.961	4.71
15	0+−0	17.5	1.2	300	-6	3640	308.983	5.99
16	0	17.5	0.9	400	-6	3730	364.212	5.55
17	0−0−	17.5	0.6	400	-8	3530	305.124	6.13
18	0	20	1.2	400	-6	4640	692.671	4.39
19	−0+0	15	0.9	500	-6	3760	418.688	4.78
20	−−00	15	0.6	400	-6	3430	299.773	5.74
21	−00+	15	0.9	400	-4	3570	341.174	5.33
22	00++	17.5	0.9	500	-4	4670	802.34	3.77
23	0	17.5	0.9	400	-6	3730	364.212	5.55
24	0−0+	17.5	0.6	400	-4	3540	310.937	6.08
25	0−−0	17.5	0.6	300	-6	3390	250.83	6.79
26	00−+	17.5	0.9	300	-4	3520	282.34	6.33
27	17.5	0.9	400	-6	3730	364.212	5.55	17.5

Similar to CASE1, Pareto plots are taken from first order fit to be able to see direct effects of the CASE2 variables on each response.

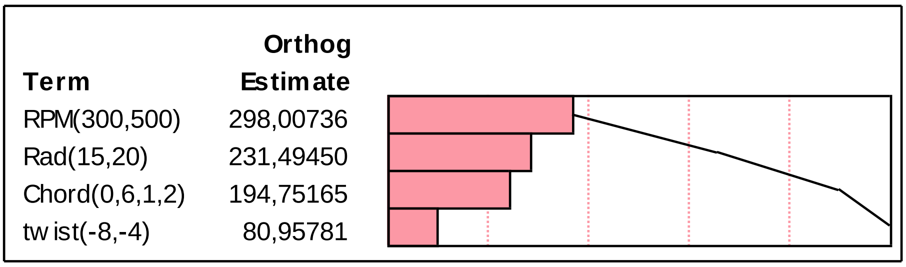

Figure 3.13 Pareto Plot for Gweight Response for CASE2

Figure 3.13 shows the effect of each CASE2 variable on the gross weight. Among the four factors, RPM is the most significant and the twist is the least. Since the product of RPM and the radius gives the tip speed, this is an expected result if we look at the same analysis for CASE1 variables.

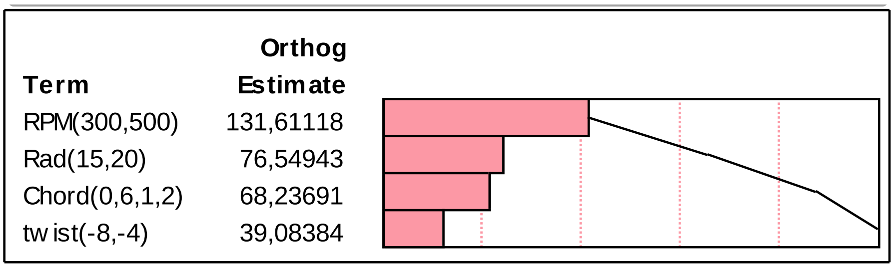

Figure 3.14 Pareto Plot for Horse Power Response for CASE2

For the horse power response, again the RPM comes out to be the most effective parameter (Figure 3.14) and its relative effect is higher when compared to its effect in gross weight response.

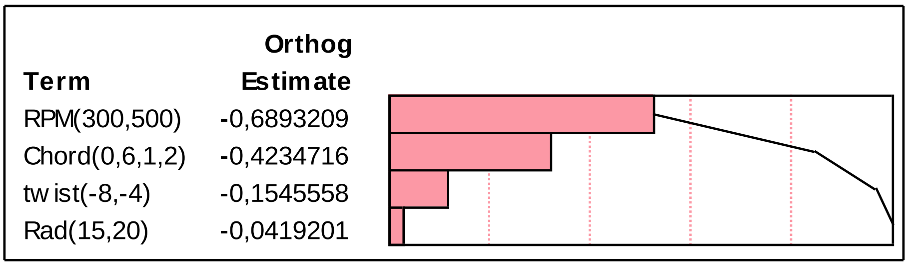

Figure 3.15 Pareto Plot for Evaluation Score Response for CASE2

Figure 3.15 illustrates the effect of parameters to evaluation score. RPM is again the most effective one here, but the order of other variables is altered. Also, this is the first time at which twist is not the least effective parameter for a response. Effect of the main rotor radius on evaluation score response seems to be negligible when compared to other design parameters.

Summary of Fit	
RSquare	0,828907
RSquare Adj	0,796318
Root Mean Square Error	218,5354
Mean of Response	3901,923
Observations (or Sum Wgts)	26

a)GW

Summary of Fit	
RSquare	0,782303
RSquare Adj	0,740837
Root Mean Square Error	100,5846
Mean of Response	444,7264
Observations (or Sum Wgts)	26

b) HP

Summary of Fit	
RSquare	0,895448
RSquare Adj	0,875534
Root Mean Square Error	0,31356
Mean of Response	5,337692
Observations (or Sum Wgts)	26

c) OEC

Figure 3.16 Summary of Fits for CASE2

Although the Pareto plots of the first order estimation are useful and to be taken as a check point for the sensitivity analysis, from the data given in Figure 3.16, it can be concluded that the fits are not accurate enough. Therefore, a second order estimation analysis is performed in order to have an improved accuracy.

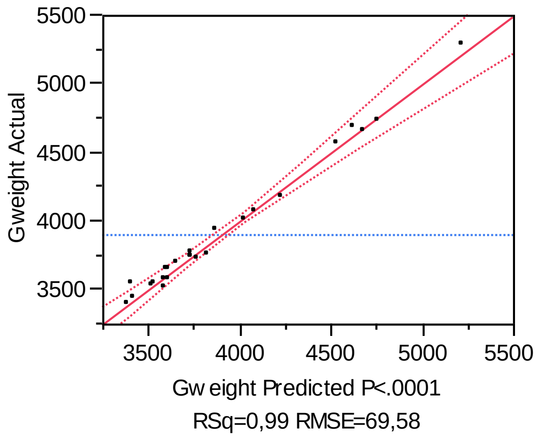

Figure 3.17 CASE2 2nd Order Fit For Gross Weight

In Figure 3.17, variation of actual gross weight with respect to the predicted one for CASE2 is illustrated. When compared to same figure for CASE1, the difference is obvious. In this case prediction curve is very close to the experiment points. The gross weight fit for this case has an RSquare value of 0.99 (very close to 1) and a

RMSE value of 69.58 for the gross weight response. This result unveils that, the gross weight prediction with these (CASE2) variables is better than the prediction obtained the CASE1 variables.

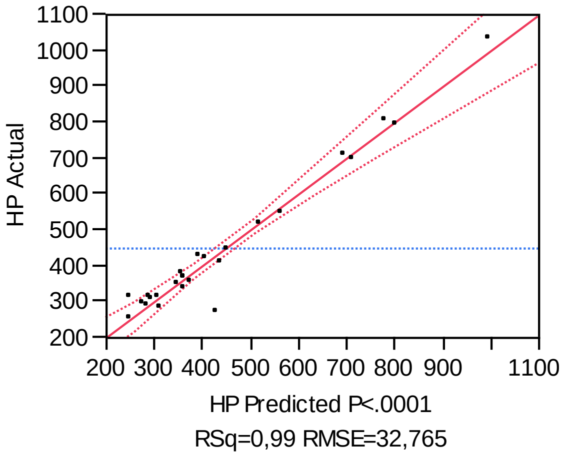

Figure 3.18 CASE2 2nd Order Fit For Horse Power

Similarly, fit for the horse power response is better than the one for the CASE1 fit (Figure 3.18). While the RSquare value is 0.95 for the CASE1, it is 0.99 for this case.

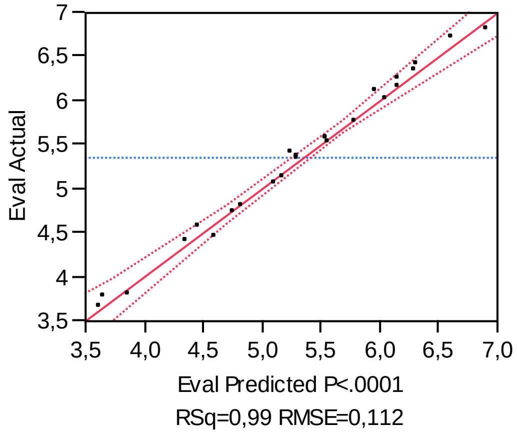

Figure 3.19 CASE2 2nd Order Fit For Evaluation Score

In the Figure 3.19, fit for the evaluation score is given. RSquare value for this case comes out to be 0.99 which is closer to 1 when compared the CASE1 fit.

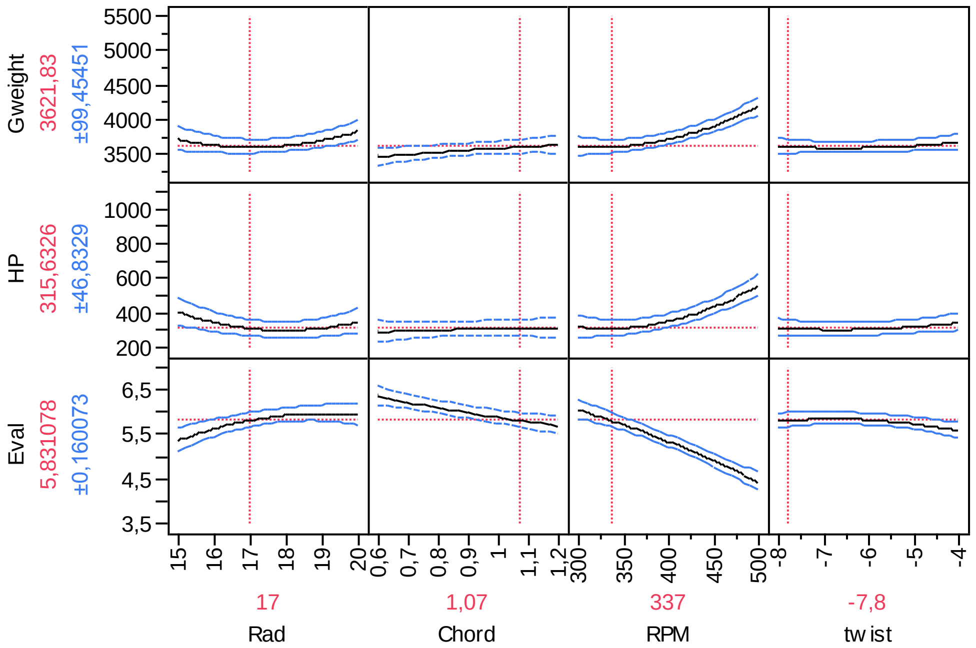

Figure 3.20 Prediction Profiler for CASE2

When Figure 3.20 and Figure 3.12 are inspected closely, it is obvious that, the fits are much better for this case (the blue curves are closer to each other than they were in CASE1).

Up to this point, first a full factorial analysis was performed for sizing based on the hover performance (section 3.4). Next, with the use of RSM and DOE, an initial sensitivity analysis (with Pareto plots) and RSE generation were performed for two different cases. After this point, CASE2 design variables will be employed in further analysis since it results in a more accurate fits for the selected responses.

RSE coefficients for the second order fit for CASE2 analysis, are given in

Table 3.6, where intercept term corresponds to b_0 of Equation 2.4.

Table 3.6 RSE Coefficients

Term	Gweight	Hp	Eval
Intercept	3730	364.21249	5.55
Rad(15.20)	339.41667	108.91243	-0.09825
Chord(0.6.1.2)	286.66667	100.44202	-0.623333
RPM(300.500)	400.25	175.33972	-0.999083
twist(-8.-4)	119.16667	57.529854	-0.2275
Rad*Chord	167.5	67.342819	-0.285
Rad*RPM	404.25	186.60813	-0.50525
Chord*RPM	180	81.196713	-0.1975
Rad*twist	135	63.743187	-0.255
Chord*twist	57.5	28.124428	-0.1275
RPM*twist	150	71.736046	-0.22
Rad*Rad	164.33333	76.342655	-0.230917
Chord*Chord	-14.04167	-5.878535	0.0367083
RPM*RPM	178.08333	87.169238	-0.102167
twist*twist	44.708333	22.302413	-0.142042

In RSE, all the variables are taken with their non-dimensional values. These non-dimensional terms are given as follows;

$$R_{nonDim} = Rad - 17.5 \ / 2.5$$
$$c_{nonDim} = c - 0.9 \ / 0.3$$
$$RPM_{nonDim} = RPM - 400 \ / 100$$
$$twist_{nonDim} = twist + 6 \ / 2$$

Since the RSE is ready, Monte Carlo analysis can be held. Results of Monte Carlo analysis are presented in the following section.

3.4.3 Monte Carlo Analysis

In section 3.4, an optimum configuration is selected for the hover performance analysis. Since the conceptual sizing is an early phase of helicopter design, some chosen parameters cannot be maintained during the considerably long period of design effort. On the other hand, evaluation score should be kept around some optimal point to ensure the satisfaction of design requirements.

Monte Carlo analysis is used to make a sensitivity analysis to find out the sensitivity of the evaluation score to the CASE2 design variables for the configuration found before (Table 3.3).

In this section, RSE generated in previous section is employed in the Monte Carlo analysis.

First, each of the CASE2 variables is given a normal distribution (Figure 3.21 a, b, c, d). Changing only one of the variables (10000 run for each variable) and keeping the others constant, four evaluation score distributions are found. The 3σ values for these variables were given in the table below.

Table 3.7 Monte Carlo Parameters

	Radius (ft)	Chord (ft)	RPM	Twist (deg)
Base Value	16.984	1.07	337	-7.8
3σ value	1.7	0.107	33.7	0.78

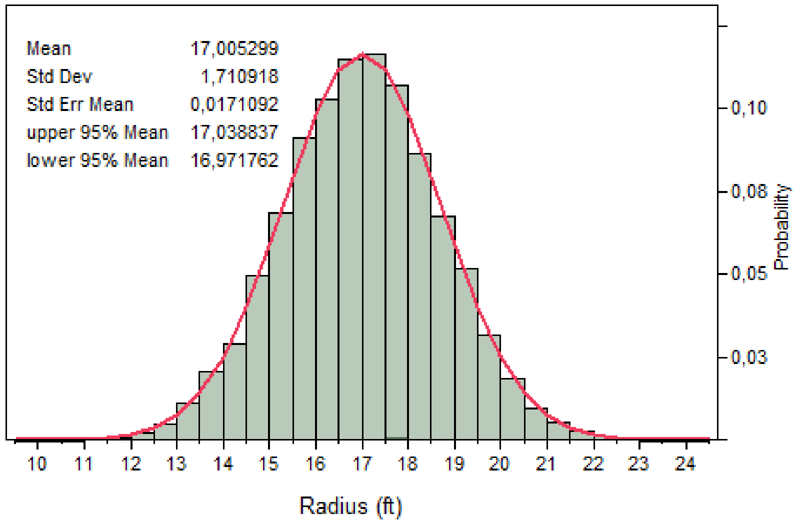

Figure 3.21.a Distribution of Radius

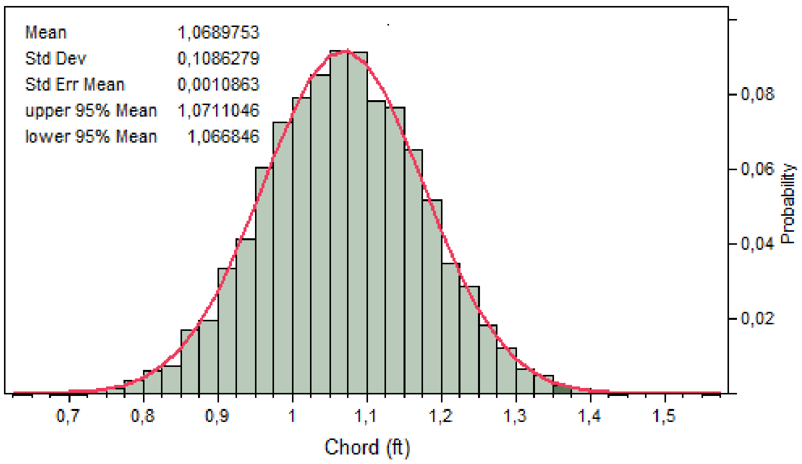

Figure 3.21.b Distribution of Chord

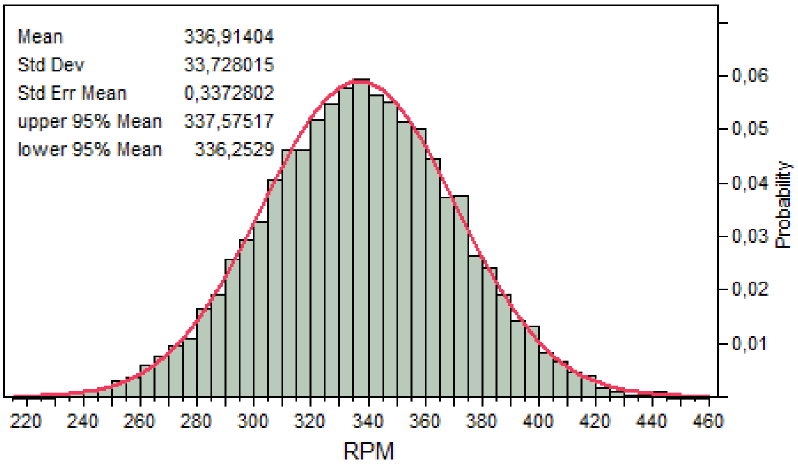

Figure 3.21.c Distribution of RPM

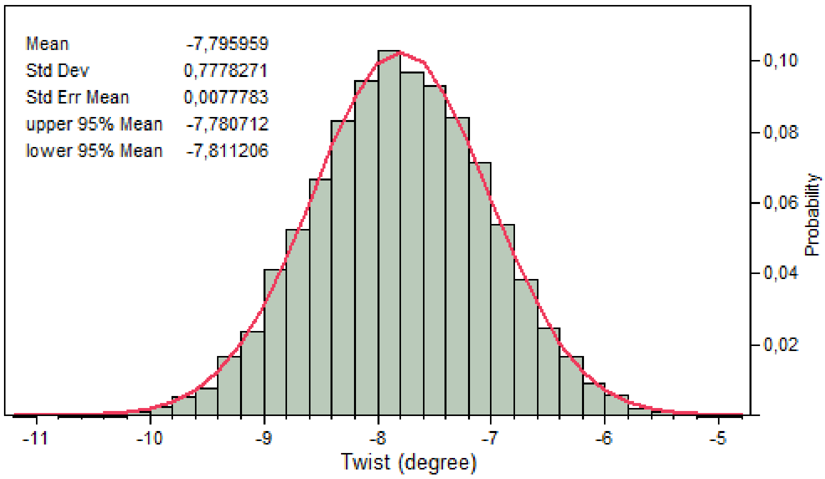

Figure 3.21.d Distribution of Twist

Evaluation scores, calculated by the implementation of the RSE, have a distribution as follows.

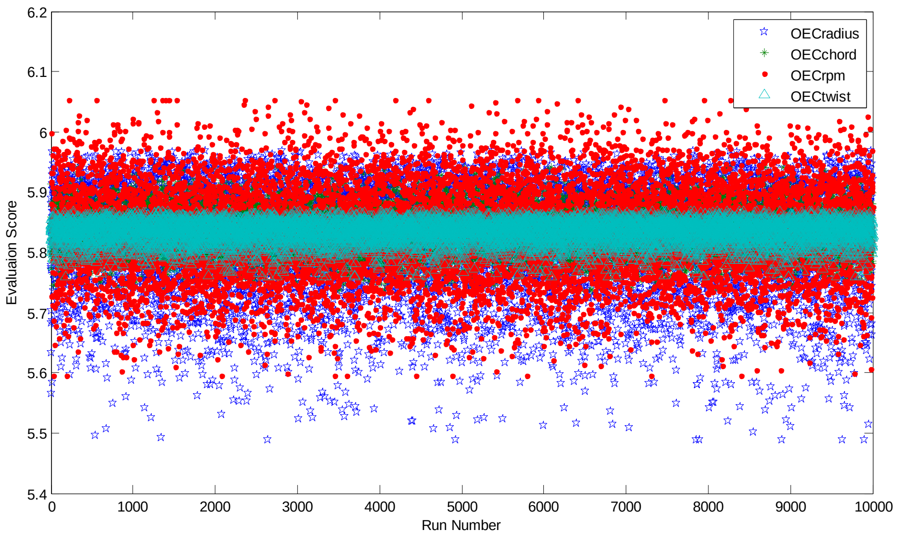

Figure 3.22 Monte Carlo Results

As it can be seen in Figure 3.22, effect of change of the twist seems to be minimal when compared to the others. On the other hand, chord distribution has a bigger effect on OEC score than the twist does. Also, RPM and radius distributions are resulted in a wider range of change evaluation score.

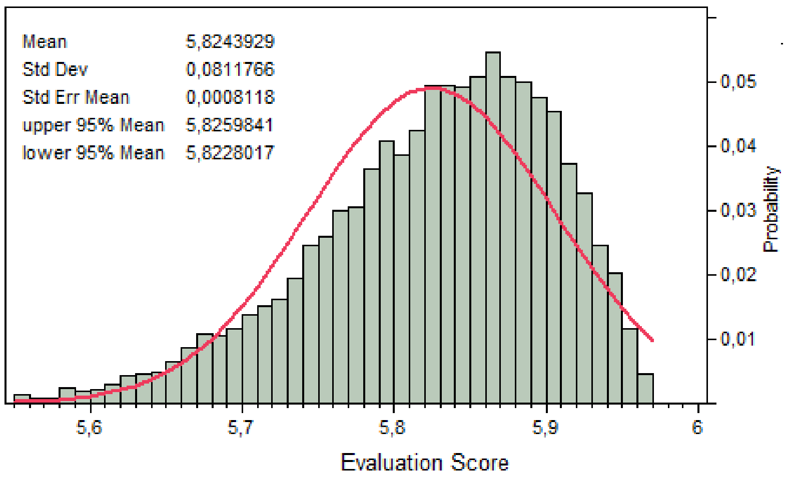

Figure 3.23.a OEC PDF with variation in radius

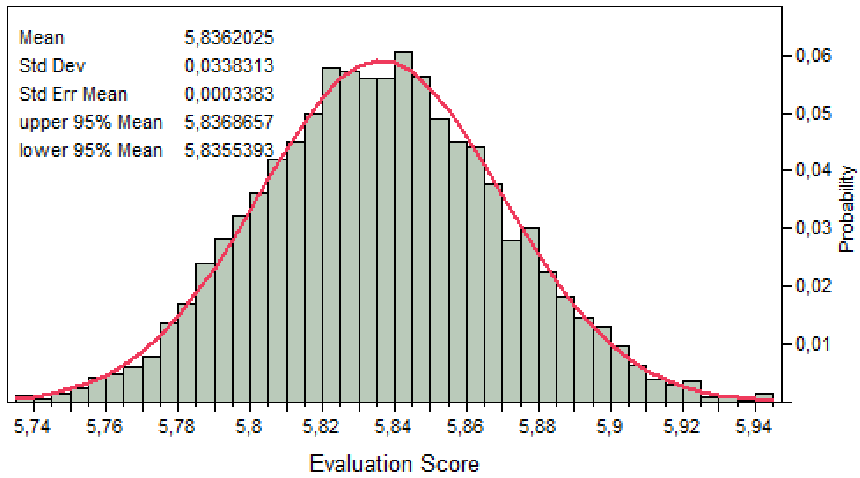

Figure 3.23.b OEC PDF with variation in Chord

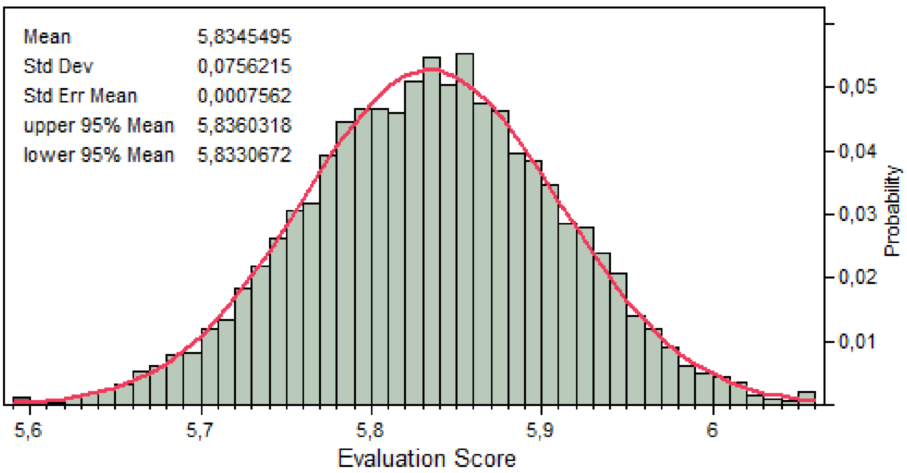

Figure 3.23.c OEC PDF with variation in RPM

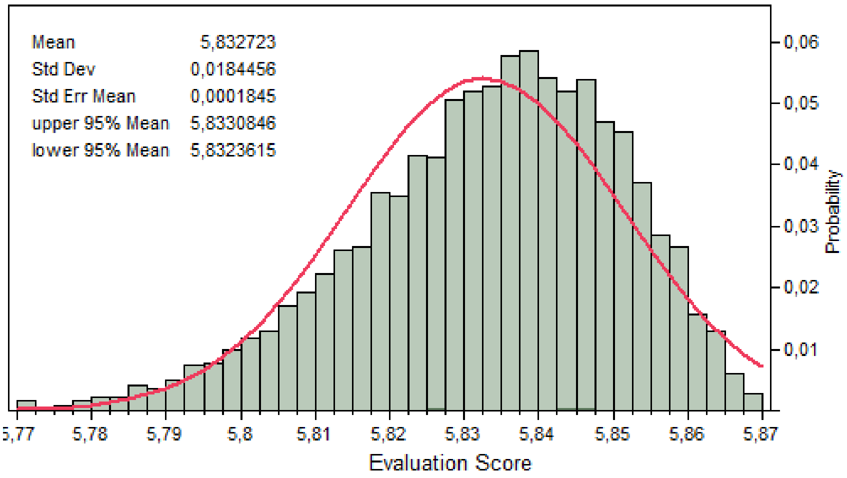

Figure 3.23.d OEC PDF with variation in Twist

Monte Carlo results are illustrated as probability density distributions. All these distributions resembles to a normal distribution since skewness values are about zero (Figure 3.23 (a,b,c,d)).

Consequently, in terms of the sensitivity of the evaluation score to the change in parameters, the design variables can be ordered as; RPM, radius, chord and twist from the most to the least effective.

To be able to monitor the effect of all variables together, another Monte Carlo analysis is carried out. In this analysis, all of the variables have their Monte Carlo distribution (Figure 3.21 a, b, c, d).

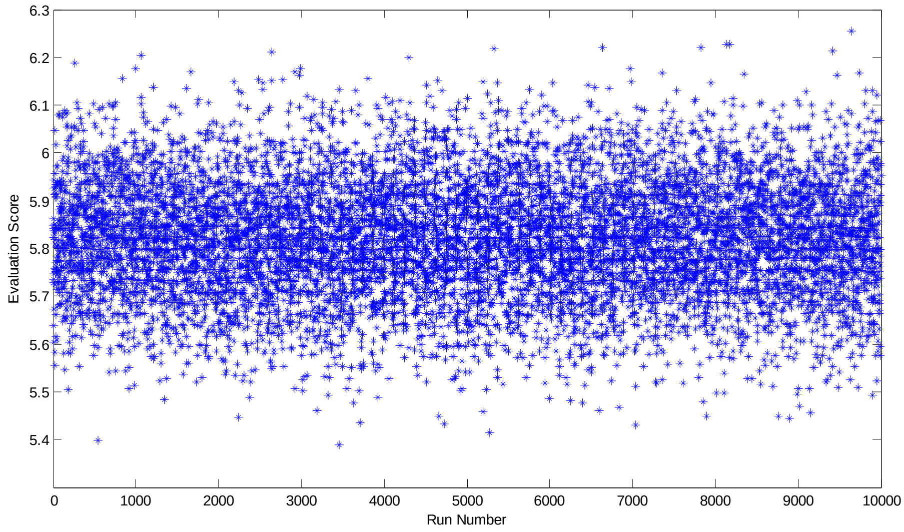

Figure 3.24 MC results when all variables changed

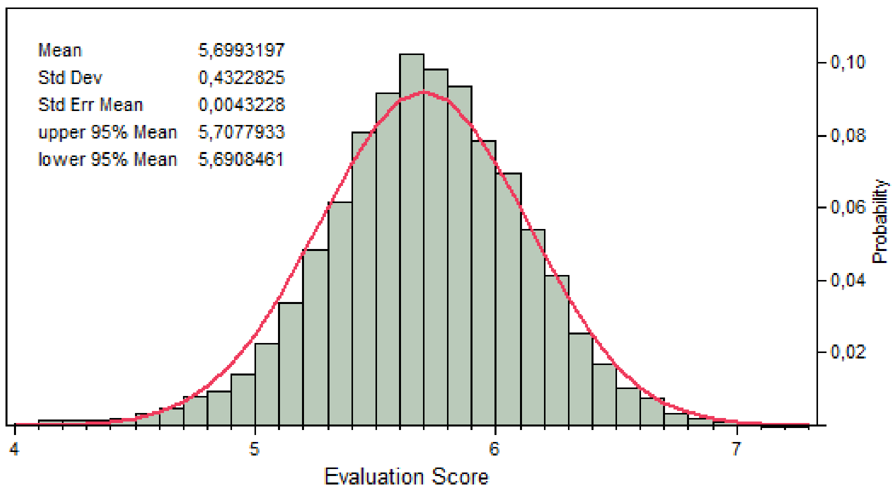

Figure 3.25 OEC PDF distribution (all variables changed)

Compared to the distributions given in Figure 3.22, variation of the evaluation score values come out to be in a wider range as expected (Figure 3.24) when all variables changed. The PDF distribution of evaluation score values for this case is also in Gaussian form (Figure 3.25).

To sum up, results of the Monte Carlo analyses illustrate that the selected configuration is quite sensitive to the changes in RPM and radius. Consequently, the design is also sensitive to tip speed since this parameter is directly the product of the two (RPM and radius). During the design procedure (preliminary and detailed design phases), the changes in these parameters should be inspected carefully in order to keep the design in the neighborhood of meeting the customer requirements.

3.4.4 Analysis for Forward Flight Performance

Until this part of the study, all the analysis was carried out for hover. In order to improve conceptual sizing and to account for the forward flight performance, a new RF code is developed.

The new RF code is first tested for AS350, one of the competitor helicopters (Table 3.2), to be able to validate the code. The gross weight estimation for AS350 is presented in Figure 3.26.

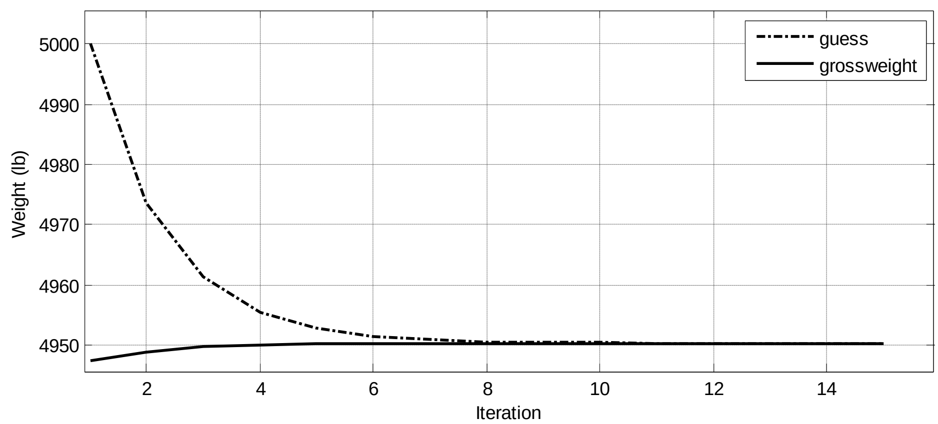

Figure 3.26 Example gross weight estimation for AS350 3B

Estimations are converged to a minimum gross weight value about 4950 lb (after 15 iterations). The real maximum gross weight of AS350 3B is 4960 lb (Figure 3.26). Although the performance of the estimation is good enough for this case, it should not be concluded that final gross weight of any helicopter can be evaluated by just using this code. On the other hand, the reliability of forward flight RF code is checked with this analysis.

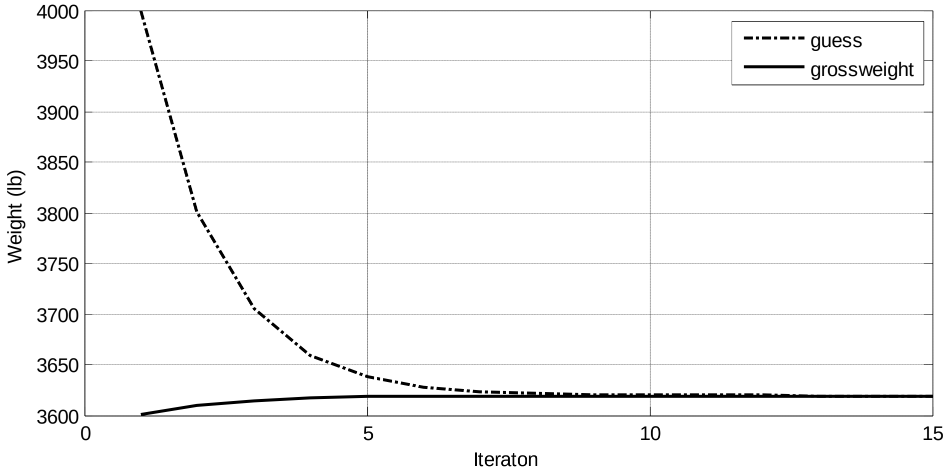

Figure 3.27 Gross weight estimation for selected configuration

Same analysis is conducted for the selected configuration (rank 11 of Table 3.3) and given performance requirements (section 3.1). Iterations are resulted in a gross weight of 3620 lb (Figure 3.27). This value is quite close to the gross weight estimation (3625 lb) of the hover analysis part. Thus, it can be concluded that, the selected configuration is also capable of satisfying the mission requirements in terms of the forward flight performance.

3.5 Weight and Dimension Estimations

3.5.1 Weights

Now that the configuration of helicopter is fixed, sizing of the main components of this configuration can be held.

In the calculation of the size of these components the equations given in section 2.4.1 are employed. The results are collected and given in the table below.

Table 3.8 Calculated size of main components of helicopter

Component	Weight (lb)
Main Rotor	551.76
Tail Rotor	35.95
Power Plant Section Group	20.66
Flight Control Group	201.24
Landing Gear	132.28
Fuselage	386.23

These values of component weights of course are not the final ones but for an initial sizing these can be used as reference.

3.5.2 Dimensions and Configuration Layout

In this section, the equations listed in paragraph 2.4.2 are employed and some characteristic dimensions of selected configuration are illustrated in Table 3.9

Table 3.9 Dimensions of Selected Configuration

Dimension	Size (ft)
Main Rotor Radius	16.98
Fuselage	26.99
Tail to Main Rotor	20.75
Tail Rotor	6.07
Clearance	0.84
Total Length	32.22

CHAPTER 4

CONCLUSIONS

A new sizing methodology is employed for the conceptual design of a helicopter. This multidisciplinary and probabilistic conceptual design and helicopter sizing methodology is developed and shown on a helicopter design for Turkey as a case study.

First, the requirements are determined for a Turkish Civilian Helicopter Market. Next, a competitor study is carried out to have some insight about the final product. Then a Quality Functional Deployment (QFD) Matrix is generated in order to relate the requirements with the engineering parameters. The outputs of the QFD matrix provided the dominant design parameters and the weighted sum of those parameters is then utilized to establish an "Overall Evaluation Criteria" (OEC) to rank different helicopter configurations. At that point, the design space is swept for disk loading, tip speed and solidity and their design viability is checked. For each configuration an RF sizing algorithm which sizes the helicopter and calculates parameters like gross weight, power required, range, endurance, etc. using RF-Method based helicopter sizing optimization is employed [2].

The helicopter configuration with the highest OEC is concluded to be the best helicopter in terms of customer requirements. On the other hand, in the selection of "the best" configuration some other constraints are also taken into account.

Considering both the OEC results and other constraints the best helicopter configuration is selected.

Afterwards, the relationship of disk loading, tip speed, solidity and some other design variables to the target design drivers, such as gross weight, are fit into Response Surface Equations. Next, utilizing these equations, Monte Carlo Simulations are performed to evaluate the sensitivities of the design choices to the target values. At this point the RSE came into play shortening the time spent analyses. In sensitivity analysis study, 50000 Monte Carlo Simulations are held. Normally, these simulations would take days or even weeks to be conducted but with the employment of RSE this time is reduced to minutes. According to Monte Carlo results, the sensitivity of OEC to the changes is higher for the changes in RPM and radius. Thus, the variation of these parameters should be monitored carefully to meet the customer requirements.

Finally, the performance of the selected configuration is checked for forward flight, the final configuration of the desired helicopter is attained. At the end, some of the main components' weights and characteristic lengths are estimated and presented using empirical relations.

Table 4.1 Comparison with the competitor helicopters

General	**Designed Helicopter**	**Eurocopter AS350 B3**	**Eurocopter EC 120**
Crew	1 Pilot	1 Pilot	1 or 2 Pilots
Capacity	5 passengers	6 passengers	4 passengers
Length (ft)	32.22	35.88	31.46
Rotor diameter (ft)	33.96	35.1	32.67
Gross weight (lb)	3625	4960	3781
Performance			
Cruise speed (kts)	100	132	120
Range (miles)	323.97	357	383
Service ceiling (ft)	15000	15100	17000

In Table 4.1 some of the important parameters of the final configuration are given together with the competitor helicopters' specifications. When this table is inspected closely for most of the parameters all helicopters have comparable values but for the gross weight, the selected configuration is the lightest which makes this helicopter more preferable than the others.

To conclude, in this thesis, conceptual sizing of a helicopter suitable for Turkish Market is accomplished by the implementation of multidisciplinary and probabilistic design methods.

As future works, further studies such as preliminary and detailed design can be conducted taking the results of this study as a basis.

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APPENDIX A

DESCRIPTIONS AND DEFINITIONS FOR THE QFD DESIGN TOOL

In this section how the QFD design tool used is described. The various regions which comprise charts and the types of data each region can express will be described. A basic chart or matrix is often referred to as the House Of Quality(HOQ) because it looks like a house with its triangular roof region at the top of the diagram. Expanding upon that analogy of building a "house", the various regions of these charts are referred to as "rooms." A basic House of Quality chart is shown below. The various room types that make up the chart are labeled.

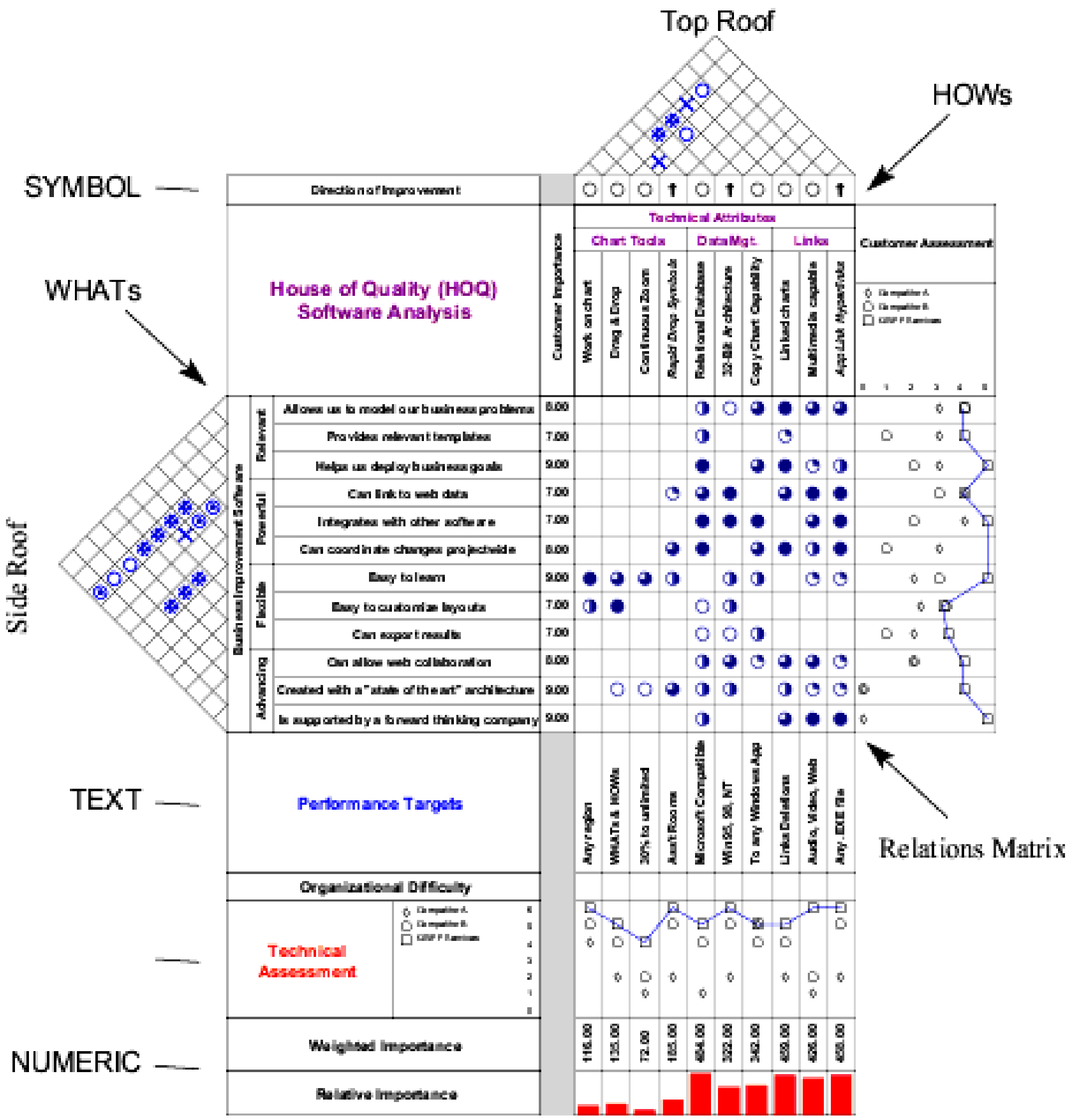

Figure A.1 Example QFD Matrix

Your chart will always have WHAT and HOW rooms though either can be hidden from view.

WHATs, which are usually expressed hierarchically, are the row entries on the left where your goals are listed. HOWs, also expressed hierarchically, are the column entries on the top where the factors or measures are normally listed.

In addition, you may use a Side Roof left of the WHATs and a Top Roof above the HOWs. These roof regions allow you to explore interactions between items of the same type like (WHATs vs. WHATs) or (HOWs vs. HOWs) to find positive and negative effects. Most users employ the Top Roof more often than the Side Roof so, on many templates, the Side Roof is hidden.

Every chart, no matter how basic, has a Relations Matrix between WHATs and HOWs.

There is always a WHAT room on each chart. It is mandatory though it can be hidden if desired. In this region you enter "WHAT you want to accomplish." WHATs are the goals of your improvement effort, usually needs voiced by customers. They are the "effects" you want to obtain.

Side roof, the optional triangular region, allows you to compare the WHATs to each other to see if they reinforce or hinder one another. Normally you will look for either positive (reinforcing) or negative (contradictory) correlations. WHATs that are positively related may be reflecting the same requirement. In addition, if you are able to provide a WHAT to a high satisfaction level, check for other positively correlated WHATs as you may get a performance bonus.

There is always a HOW room on each chart. It is mandatory though it can be hidden if desired. Here, you enter "HOW you will accomplish the WHATs." It is a list of the factors or causes which will lead to your goals. HOWs should be measurable objective design or technical factors that affect the outcome of the WHATs.

Top roof, another optional triangular region, allows you to compare the HOWs to each other to see if they reinforce or hinder one another. Sometimes, improving one HOW improves other ones. In the roof, this would be expressed with a positive correlation symbol. If improving one HOW negatively affects another HOW, this would be noted as having a negative relationship and the corresponding symbol would be entered in the roof. Consult the top roof if the HOWs are modified. Especially check negatively correlated items. These are factors which may be at odds with your design objectives. As such, negative symbols are a sort of "red flag" to the designer to encourage a thorough assessment of the implications of design changes. An example of a negative relationship may be between "Fuel Economy" and "Horsepower." As one goes up, the other goes down. If you change Horsepower in your design, you had better double-check that you can still meet Fuel Economy performance. Negative relationships can suggest the need for innovation or invention. You may wish to desensitize your design to eliminate or at least reduce the effect of negative relationships.

Since every chart has a WHATs region (formed of row entries) and a HOWs region (formed of column entries), there is always a Relations Matrix. It is the intersection region where every WHAT and HOW intersect. This regions records the relationships between all the WHAT and HOW pairs. Usually, the WHATs and HOWs are compared to find the strengths of their relationship to one another. That strength is entered symbolically. To determine the strength of the relationship, consider "If the design requirement (HOW) is met at the right target value, how strong will be the effect on the customer's perception that the WHAT (at the intersection) has been accomplished?" Usually, one of three classic relationship symbols is inserted at the intersection of the WHAT and HOW or, it is left blank. Additionally, text can be entered into the matrix or any number can be typed in. This is the classic use for the matrix though you may define and enter custom symbols to use it for most any analysis of WHAT vs. HOW interactions.