DEVELOPING AN INVESTMENT DECISION METHODOLOGY FOR HELICOPTER SYSTEMS RELATED TO TECHNOLOGY FACTOR AND BASE PRICE

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Approval of the thesis:

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ABSTRACT

DEVELOPING AN INVESTMENT DECISION METHODOLOGY FOR HELICOPTER SYSTEMS RELATED TO TECHNOLOGY FACTOR AND BASE PRICE

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In this thesis, a decision methodology is generated using purchase price of a helicopter related to its geometry sizing and performance parameters during design and technology factors in order to compare these prices with investment costs. MATLAB® and Minitab® software were used for technical computing and methodology implementation. Firstly, helicopter base price formulation was verified by 21 helicopters. Then, technology parameters were defined which effect base price value. After that, total base price was generated which contains R&D investments. Finally, the methodology was implemented on real samples, BELL429 composite shaft and Sikorsky UH-60 composite tail cone, in order to show that the methodology can be used as a practical tool for decision makers.

Keywords: Base Price Estimation, Decision Making, Technology Factor

ÖZ

HELİKOPTER SİSTEMLERİ İÇİN TEKNOLOJİ VE AR-GE YATIRIM KARARLARI İÇİN BİR METODOLOJİ GELİŞTİRİLMESİ

Kara, Gözde
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Ağustos 2014, 57 sayfa

Bu tezde, bazı helikopter geometrik boyutlandırma ve performans parametreleri ve teknoloji faktörleri kullanılarak helikopter satış fiyatı belirlenmiş, ardından bu fiyatın ihtiyaç duyulan teknolojilerin yatırım maliyetleri ile kıyaslamasını yapılabilecek bir karar verme metodolojisi oluşturulmuştur. Teknik hesaplamalar ve metodolojinin uygulanması kısmında MATLAB® ve Minitab® yazılımları kullanılmıştır. İlk olarak, helikopter satış fiyatı denkleminin 21 helikopterin verileri ile doğrulaması yapılmıştır. Ardından, helikopter satış fiyatını etkilediği düşünülen teknoloji faktörleri belirlenmiştir. Sonrasında, Ar-Ge yatırımını da içerecek şekilde Toplam Satış Fiyatı denklemi oluşturulmuş ve teknoloji faktörlerinin Toplam Satış Fiyatına olan etkileri incelenmiştir. Son olarak, metodolojinin, karar vericiler tarafından pratik bir araç olarak kullanılabileceğini göstermek üzere metodoloji gerçek örnek olan BELL429 kompozit şaft ve Sikorsky UH-60 kompozit kuyruk konisi üzerinde gösterilmiştir.

Anahtar kelimeler: Satış Fiyatı Hesaplama, Karar Verme, Teknoloji Faktörü

To my family

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NOMENCLATURE

SYMBOLS

c	Chord
k	Technology Factor Related To Empty Weight Reduction
ρ	Density
P	Power
r	Radius
$R_{F,}$	Fuel Available to Gross Weight Ratio
$R_{F,}$	Fuel Required to Gross Weight Ratio
U	Useful Load
V_{tip}	Tip Velocity
W	Gross Weight
W	Empty Weight
W	Useful Load

ABBREVIATION

CER	Cost Estimate Relations
DL	Disk Loading
DOE	Design of Experiments
FM	Figure of Merit
HP	Horse Power
LCC	Life Cycle Cost
MIT	Massachusetts Institute of Technology
MDO	Multidisciplinary Decision Optimization
OEC	Overall Evaluation Criteria
QFD	Quality Functional Deployment
R&D	Research and Development
RSM	Response Surface Methodology
TAI	Turkish Aerospace Industries

CHAPTERS

INTRODUCTION

1.1 Problem Statement

In aerospace sector, helicopter development and modernization periods can be quite long and costly. To make right decisions according to development processes, helicopter base price and technology investment costs become important challenges [1]. For helicopter developers, return of investments generally depends on the total R&D investment and how many helicopters take how much revenue after this investment. In reality, R&D outputs are calculated by performance metrics not economic metrics.

In order to make right decisions both using performance and economic metrics, performance earns coming from R&D investments should be made in relation with economic earns and how much the technology development issue can be handled.

Within the context, a methodology which can link performance and economic metrics of helicopter systems is a necessity for decision makers especially who has to decide technology development projects such as helicopter development, modernization or modification.

1.2 Literature Survey

In this section literature survey on helicopter design and cost analysis methods is presented.

1.2.1 Helicopter Design

Helicopter design can be generated by using probabilistic design methods such as Response Surface Methodology and Monte Carlo Analysis and also concurrent engineering tools such as Quality Functional Deployment (QFD) and Overall Evaluation Criteria (OEC).

In Shrange's lecture notes on Rotorcraft Systems Design [2], simultaneous solutions to both weight and aerodynamic performances of helicopters called the Fuel Fraction (RF) method are given. This method provides to evaluate helicopter gross weight which is conducted by some basic performance parameters.

In Tishchenko, Nagaraj and Chopra's study [3], the relationship between some basic characteristics of transport helicopters such as take-off weight, rotor diameter and also range relation with payload were examined related to different payload quantities. They compared different existing helicopters related to their energy efficiency specifications such as specific range per unit weight of fuel consumed.

According to Laurentis, Mavris, and Shrange's study [4], an approach to conceptual and early preliminary aircraft design is documented in which system synthesis is handled using statistical methods, such as Design of Experiments (DOE) and Response Surface Methodology (RSM). In this study, an improved design methodology developed which provides bringing sophisticated analyses to a Multidisciplinary Decision Optimization (MDO) problem.

Rand and Khromov [5] used vast helicopter database to size the helicopter in the preliminary design stage which includes geometry parameters, weight of components, and preliminary power and flight performance estimation. This approach helps designers to do basic sizing of the helicopter rapidly.

Xin-lai, Hu, Gang-lin and Zhe [6] showed that some of basic parameters such as solidity and rotor diameter are directly related to helicopter performance during the preliminary design process. Consequently, they thought improving the precision of estimating these parameters is considered to be quite important. Thus, they used Neural Network approach by taking nonlinear effects. Into account since Neural Network is claimed to overcome the limitations of traditional statistical methods. Then they applied the approach on flying vehicle designs.

1.2.2 Helicopter Price Estimation

Helicopter price estimation issue is not easily accessible. Generally there are commercial tools models or databases to calculate helicopter cost and price. Besides this, cost analysis methods are used in order to calculate program costs.

In Engineering Design Handbook [7], cost concepts of helicopter systems such as life cycle cost, incremental cost, real resource utilization, joint costs and other concepts are described.

Harris and Scully's [8] collected statistical data from both civil and military helicopters to create an equation which provides a link between performance and economic parameters. This equation contains helicopter weight, diameter and some other performance parameters to find base price of a single helicopter.

According to Willcox [10], aircraft cost estimation depends on several basic steps: taking empirical data from past programs, performing regression to get variation with selected parameters such as cost vs. weight, applying "judgment factors" for the specific case such as configuration factors, complexity factors and use of composite. This approach's basic elements and the flow between input to output can be seen in Figure 1.

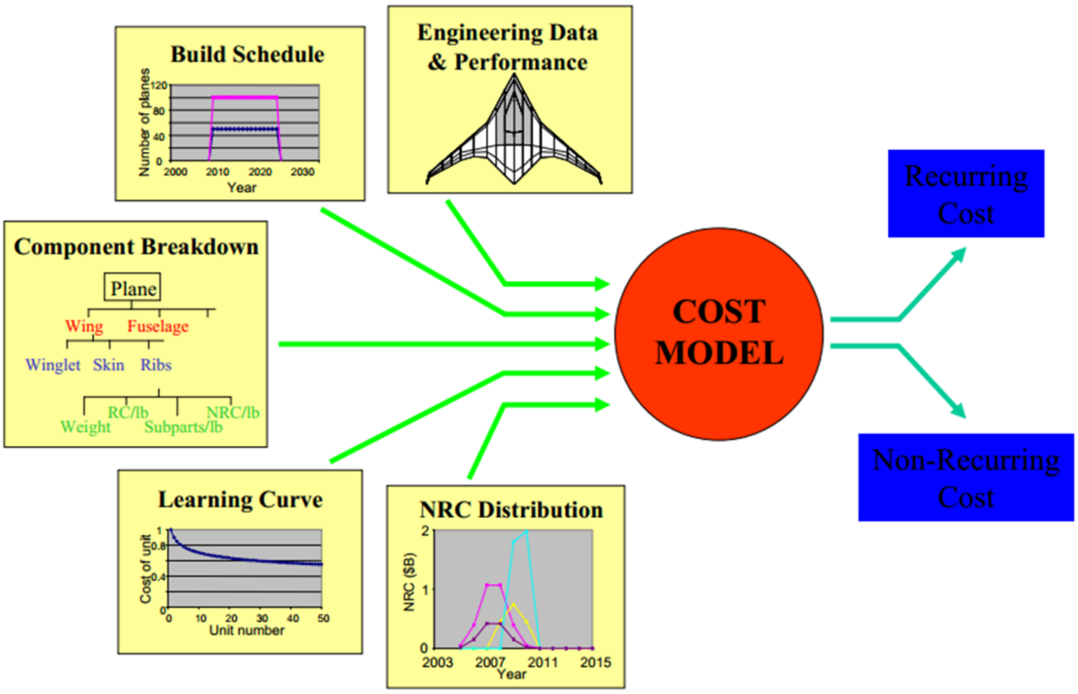

Figure 1 Elements of Cost Model [9]

Ritschel's [11] Cost Estimating Relations (CER) is another aircraft cost estimation method. This method is formally using an established relationship with an independent variable in order to estimate a particular cost or price. In this study, Ritschel looked cost estimation error risks of recurring costs for several levels of work brake down structure of an aircraft.

Furthermore, every year Forecast International company publishes online data related to helicopter unit prices. The data also contains some parameters such as engine type (piston or turbo shaft), engine quantity, producer country (US, Europe or Russia), customer type (military or civil), helicopter class (light, medium, heavy or intermediate) and mission (utility or lift) of a helicopter related to price value. Using these data, it is possible to see changes related to performance parameters and unit prices of different kind of helicopters. According to the data in 2010 [9], a relation between unit price and maximum take-off weight of different kind of helicopters can be seen in Figure 2.

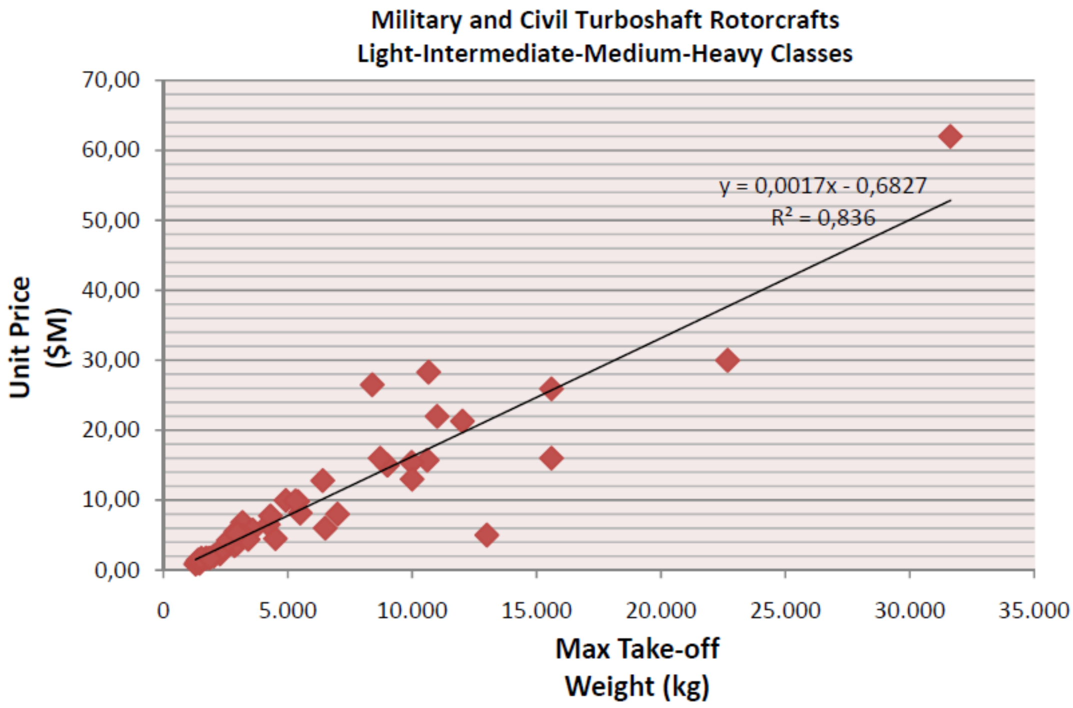

Figure 2 Elements of Cost Model [9]

1.3 Motivation and Contributions of The Thesis

The motivation behind the study in this thesis is to generalize a methodology that supports decision making processes related to technology development of helicopter systems. In this approach it is important that, economic and performance metrics should be handled in a balance as seen in Figure 3.

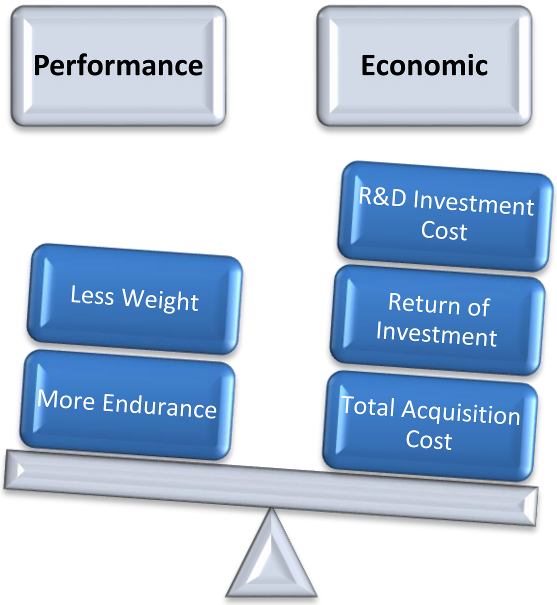

Figure 3 The Balance Between Performance and Economic Metrics

Performance metrics can contain decreasing weight, increasing hover capacity, decreasing fuel consumption and decreasing noise generation. Also, economic metrics can contain total cost, investment cost and return of investment information.

The methodology can support decision makers at the beginning phase of technology development processes for helicopter systems in order to decide rapidly and more accurately while evaluating the investment-technology tradeoffs.

1.4 Scope of The Thesis

In Chapter 1, the problem is introduced and literature survey is given.

The theoretical background on helicopter design and price estimation is examined in Chapter 2. Also verification of the base price estimation method is developed from helicopter performance and economic data from 21 separate helicopters.

Chapter 3 presents a methodology that includes total base price estimation and the relations between the total base price value and technology factors.

In Chapter 4, the methodology is applied to test two applications: BELL429 composite shaft and Sikorsky UH-60 composite tail cone.

In Chapter 5, the final comments on thesis are shared and recommendations for future work are given.

CHAPTER 2

THEROTICAL BACKGROUND

In this section, the theoretical background of the methods which are utilized in this thesis is presented. First, helicopter sizing and performance parameters to be employed for in the determination of the size of main helicopter components are given. Then helicopter base price estimation method is given which can be used to estimate helicopter base price relevant to its geometry sizing and performance parameters. And also, verification for the base price estimation method was generated with 21 different helicopters. Finally, Fuel Fraction (RF) method is presented together with the general cost and price estimation approaches.

2.1 Helicopter Geometry Sizing Parameters

Helicopter design involves a compromise between many various and different requirements such as performance, cost and safety. One of the most important stages of the preliminary design process consists of the basic sizing of the vehicle. According to Rand and Khromov's study [5], more than 180 helicopter configurations, which contain both civil and military types, are used to define conventional single rotor helicopter configuration. The design parameters or helicopter geometry sizing parameters are based on multiple regression analysis. These parameters are important in the early preliminary stages where sizing issues are discussed to initiate preliminary design. The sizing scheme is presented in Figure 3, shows all relations between the input requirement and the resulting estimated parameters.

According to the Figure 4, gross weight has an important relation with all kind of parameters that can affect helicopter's performance.

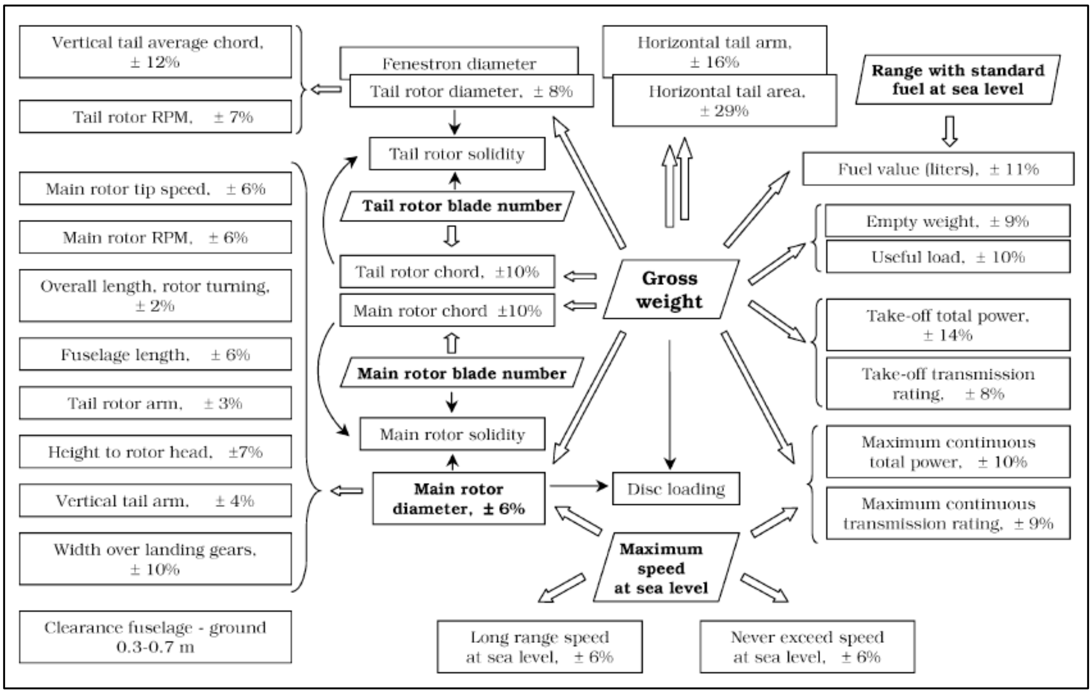

Figure 4 Main scheme of helicopter sizing guidelines [5]

Using the sizing guidelines, helicopter geometry sizing and performance parameters are generated using basic parameters such as gross weight, diameter, tip speed, blade number and chord of a helicopter system. The maximum change between the values is %29.

The parameters which are related to the study do not result in big changes related to gross weight value. Main rotor diameter shows a difference between negative and positive of %6. The empty weight parameter shows a difference between negative and positive of %9. Also, main rotor tip speed shows a difference between negative and positive of %6.

The relations between parameters were obtained from the regression analyses of 180 helicopter data by Rand and Kromov. The helicopter geometry sizing parameters can be seen in Figure 5.

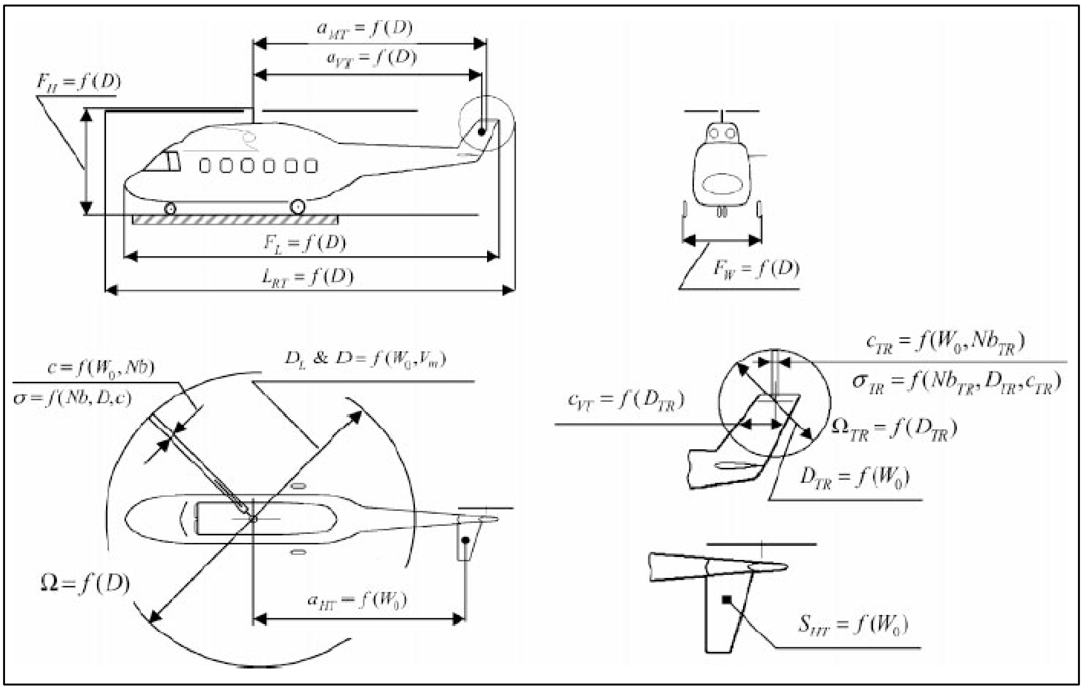

Figure 5 Helicopter Geometry Sizing Parameters [5]

According to these relations, the equation (2.1.1), (2.1.2), (2.1.3) and (2.1.4) can be stated.

$$D = 0.977.W_G^{0.308} \qquad (2.1.1)$$

$$c = 0.0108.\frac{W_G^{0.539}}{Nb^{0.714}} \qquad (2.1.2)$$

$$V_{tip} = 140.D^{0.171} \qquad (2.1.3)$$

$$W_E = 0.4854.W_G^{1.015} \qquad (2.1.4)$$

2.2 Helicopter Cost Estimation Methods

In literature, there are several cost estimation methods are available. However, for helicopter systems it is quite hard to find detailed information related to this. In this part, some approaches for helicopter cost estimation are given.

2.2.1 Cost Concepts

According to Engineering Design Handbook [7], there are 15 cost concepts which are used for cost and price estimation. These concepts and their definitions are listed below [7].

- **Life Cycle Cost:** Summation of all expenditures required from conception of a system until it is cancelled from operational use. For an Army helicopter, this cost can be divided into four steps; R&D, initial investment, operations and maintenance.
- **Incremental Cost:** It involves the comparative use of the increment in costs between alternatives.
- **Real Resource Utilization:** It can be stated as maintenance hours per flight hour, pounds of consumed fuel per flight hour, or number of required quality control inspections per assembled component.
- **Joint Costs:** They are calculated when more than one system uses a specific resource. Generally, joint resources are involved related to command or support.
- **Amortized Cost:** It is found by dividing costs by the estimated service life of the system constant dollar cost. Constant dollar cost may be affected by inflation or deflation, but these effects are separated.
- **Direct Cost:** Direct cost often is used to distinguish operating unit costs from support costs.
- **Discounted Cost:** It is used to show the time preference for postponed commitments to expenditures.

- **Inflated Cost:** Inflated cost uses an estimated inflation factor to increase present day estimates of expenditures which will be made in later years.
- **Indirect Cost:** Indirect cost is a joint cost.
- **Investment Cost:** It is nonrecurring costs which is required to increase the capability within a force. It consists of costs for operating capability within a force.
- **Operating Cost:** It is a recurring cost required to keep a system in an active force.
- **Opportunity Cost:** Cost of resources consumed in following one course of action.
- **Price:** Price is the dollar amount which is paid to a seller. The price is only part of the cost which is related to the buyer. Because the buyer also must pay the ownership cost.
- **Residual Value:** The estimated current price of remaining assets when a system is removed from an active inventory.

These cost and price data can be used to estimate the total helicopter cost during its life cycle period. In this study investment cost and price concepts are selected the as the fundamental parameters to estimate helicopter base price.

2.2.2 Conklin and de Decker Life Cycle Cost Tool

Conklin and de Decker [12] is an aviation research, consulting and education company which focuses on fixed and rotary wing aircraft operating cost, performance and specification database, maintenance management software, financial management, fleet planning, market research and aviation tax issues.

Company's Life Cycle Cost (LCC) Tool contains a database to carry out detailed financial analysis and to estimate budget and residual value data for more than 500 fixed and rotary wing aircraft. These tools are used for quick and easy aircraft operating cost comparisons, performance and specifications, or to benchmark the existing aircraft cost.

The LCC tool can be used in order to calculate helicopter total acquisition cost, total variable cost, total fix cost and annual budget information. LCC Tool’s interface is shown in Figure 6.

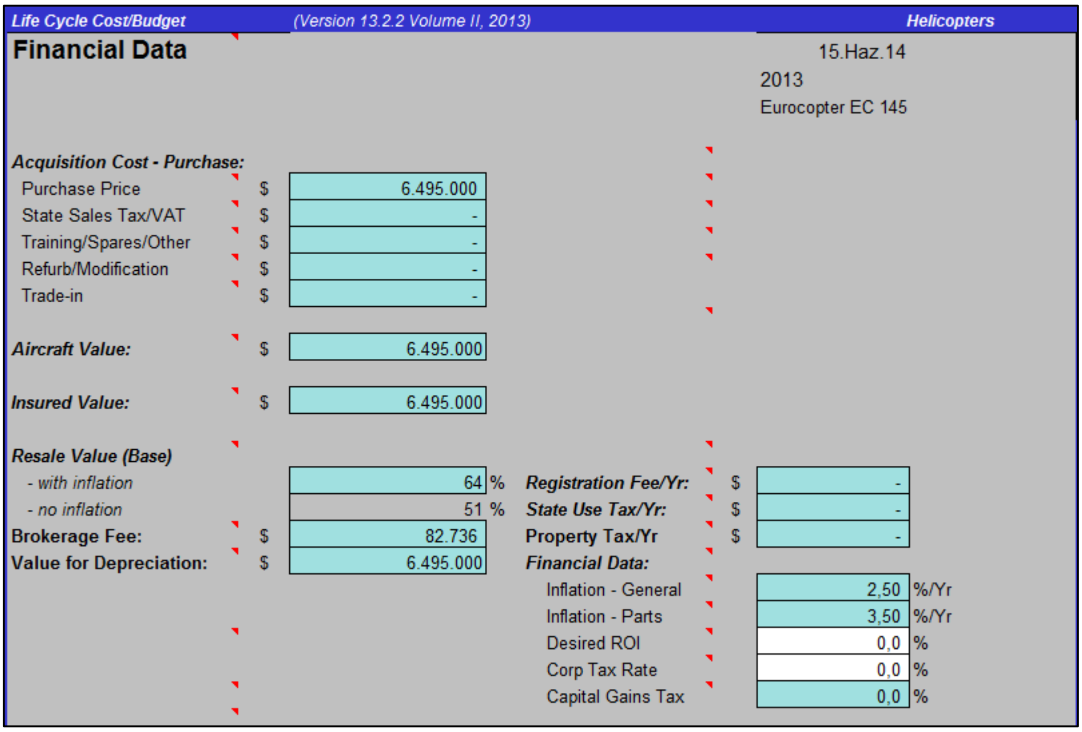

Figure 6 Conklin and de Decker LCC Tool Interface Sample [12]

In this study, the base price data were taken from Conclin de Decker LCC Tool.

2.2.3 Helicopter Base Price Estimation Method

Designing a helicopter with minimum weight does not give the minimum purchase or base price of the helicopter for a commercial operator. There are more complex relationships that include other major design parameters in addition to weight.

Harris and Scully [8] used 119 helicopters statistical data in order to show which design parameters has a strong relation with helicopter purchase price. They results presented in Figure 7, they showed that the base price increase due to six major steps such as piston to gas turbine, single to twin, disk loading with 2.5 to 5 and blades with 2 to 4. But, there are only two areas of base price decreases which are useful load over gross weight with 0.4 to 0.5 and figure of merit (FM) with 0.52 to 0.62.

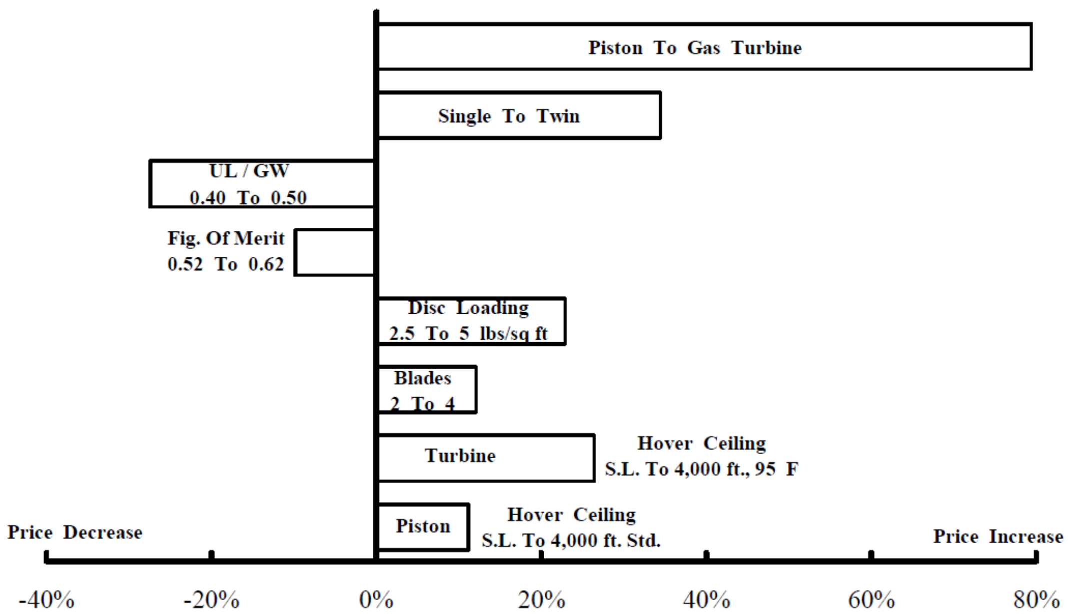

Figure 7 Base Price Changes Related to Helicopter Design Parameters [8]

Harris and Scully [8] also looked the effect of empty weight on base price values of 119 helicopters. The distribution can be seen in Figure 8. According to this distribution, when helicopter size gets bigger, empty weight directly increases and as a result actual base price increases.

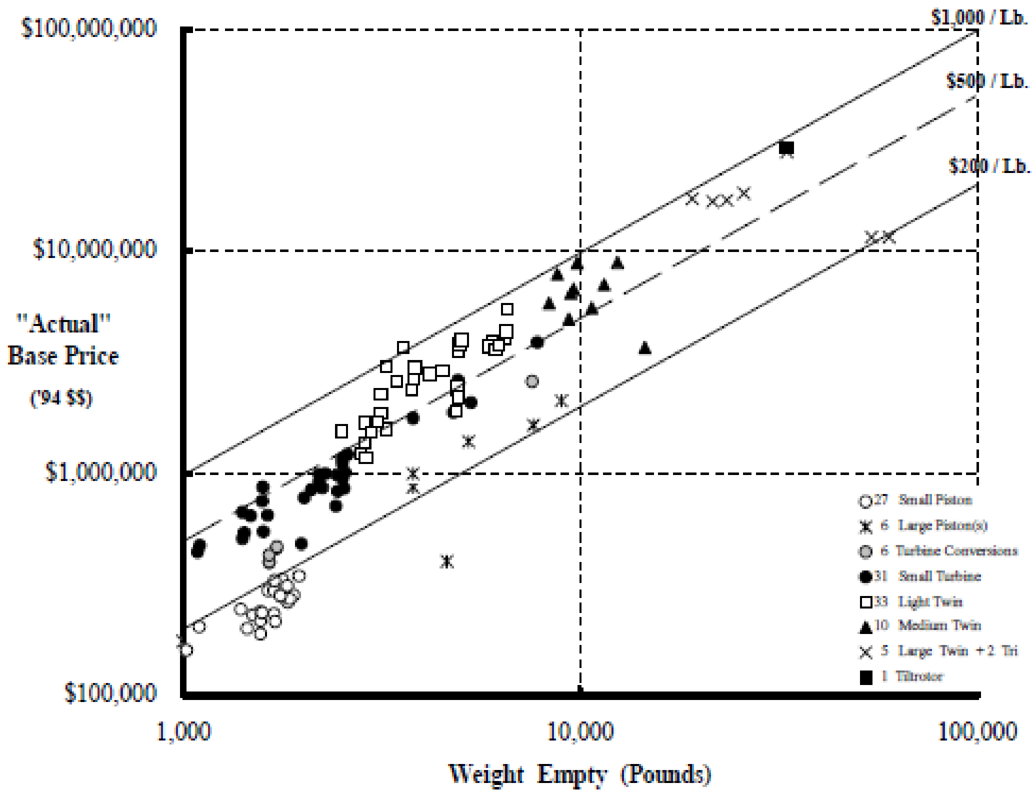

Figure 8 Estimating Purchase Price Using Dollars Per Pound [8]

According to the statistical data, Harris and Scully [8] generated equation (2.3) which shows design parameters to helicopter base price. “Blades per rotor” expresses number of blades. Blades per rotor and empty weight are the geometry sizing parameters of a helicopter. Engine rated horse power is a performance parameter that affects base price value.

$$Price = \$236.77\ .\ H\ .\ BladesPerRotor^{0.2045}\ .\ {W_E}^{0.4845}\ .\ Eng(s)RatedHP^{0.5843} \quad (2.2.3.1)$$

where, H is the product of six factors and computed by equation (2.2.3.2).

$$H = EngineType\ .\ EngineNo\ .\ Country\ .\ Rotors\ .LandingGear\ .\ Pressurization (2.2.3.2)$$

The factors used in computing H are listed in Figure 9.

Engine Type		Engine Number		Country	
Piston	1.000	Single	1.000	U. S. Commercial	1.000
Piston (Converted to Turbine)	1.180	Multi	1.352	Russia	0.330
Gas Turbine	1.779			France/Germany	0.860
				U. S. Military	0.838

No. of Main Rotors		Landing Gear		Pressurized	
Single	1.000	Fixed	1.000	No	1.0
Twin	1.046	Retractable	1.104	Yes	1.135

Figure 9 Factors Used in H Parameter [8]

Engine rated horse power can be written as equation (2.2.3.3).

$$\text{EngineRatedHP} = \frac{W_G}{550\,.\,FM}\sqrt{\frac{DL}{2\rho}} \qquad (2.2.3.3)$$

Disk Loading (DL) is defined as equation (2.2.3.4).

$$DL = \frac{W_G}{\pi\frac{D^2}{2}} \qquad (2.2.3.4)$$

As seen in equation (2.2.3.3), Engine Rated Horse Power parameter has a relation with W_G, DL and FM parameters. In Figure 10, the relation between W_G and Engine Rated HP can be seen. According to the figure, when gross weight starts to increase, engine rated horse power value also increases.

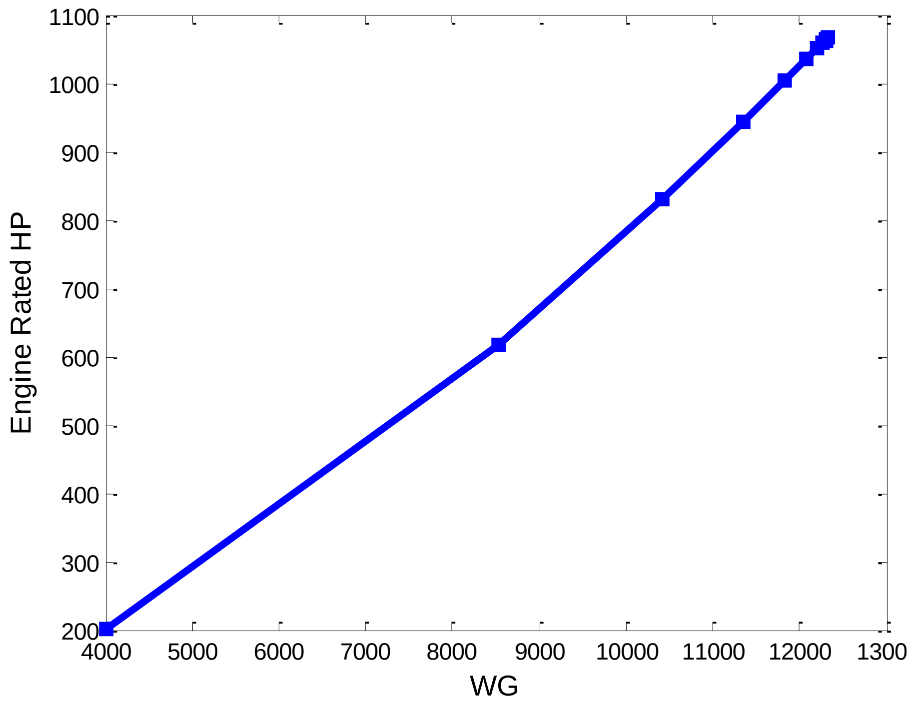

Figure 10 Relation Between WG and Engine Rated HP

According to Figure 11, the relation between DL and Engine Power HP can be seen. As seen in previous figure, when DL starts to increase engine rated HP also increases. It is probably caused the effect of W_G parameter.

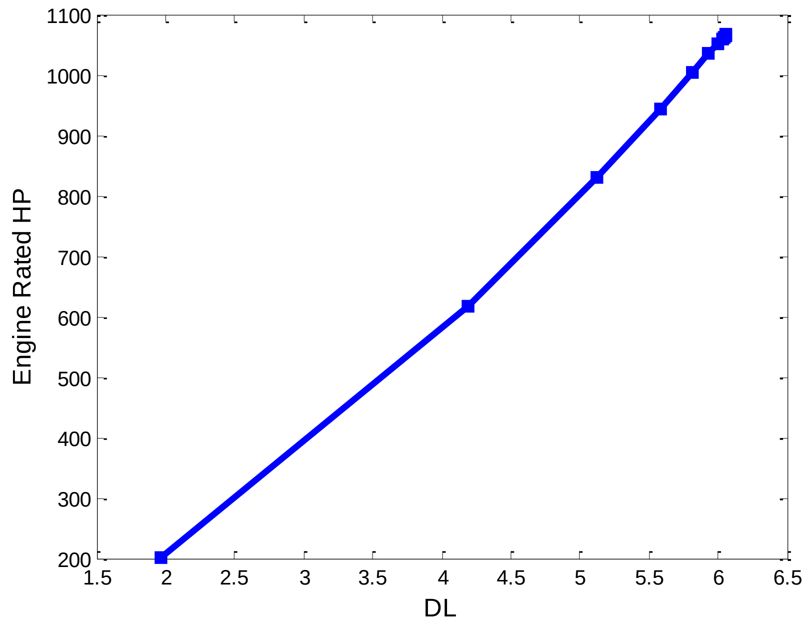

Figure 11 Relation Between DL and Engine Rated HP

According to Figure 12, the relation between FM and Engine Power HP can be seen. As seen in previous figure, when DL starts to increase engine rated HP also increases. Again, it is probably caused the effect of W_G parameter.

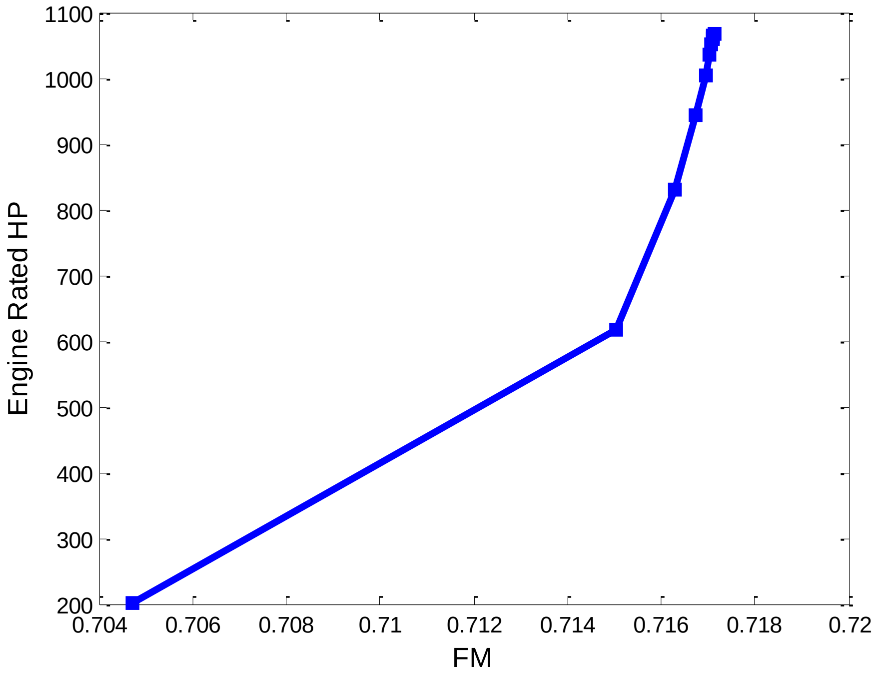

Figure 12 Relation Between FM and Engine Rated HP

Figure of Merit (FM) which is given in equation (2.2.3.5), is a measure of hovering efficiency where a value of FM = 1.0 is ideal. Practical FM values are generally between 0.50 and 0.65.

$$FM = \frac{1.08}{\frac{0.0085 \,.\, Solidity}{4\sqrt{2} \,.\, (Wgt\,Coeff.)^{1.5}} + 1.5} \tag{2.2.3.5}$$

The relation between FM and weight coefficient can be seen in Figure 13. According to the figure when weight coefficient starts to increase FM also increases. But after the greater values than 0.025 for weight coefficient, then FM values starts to increase fewer.

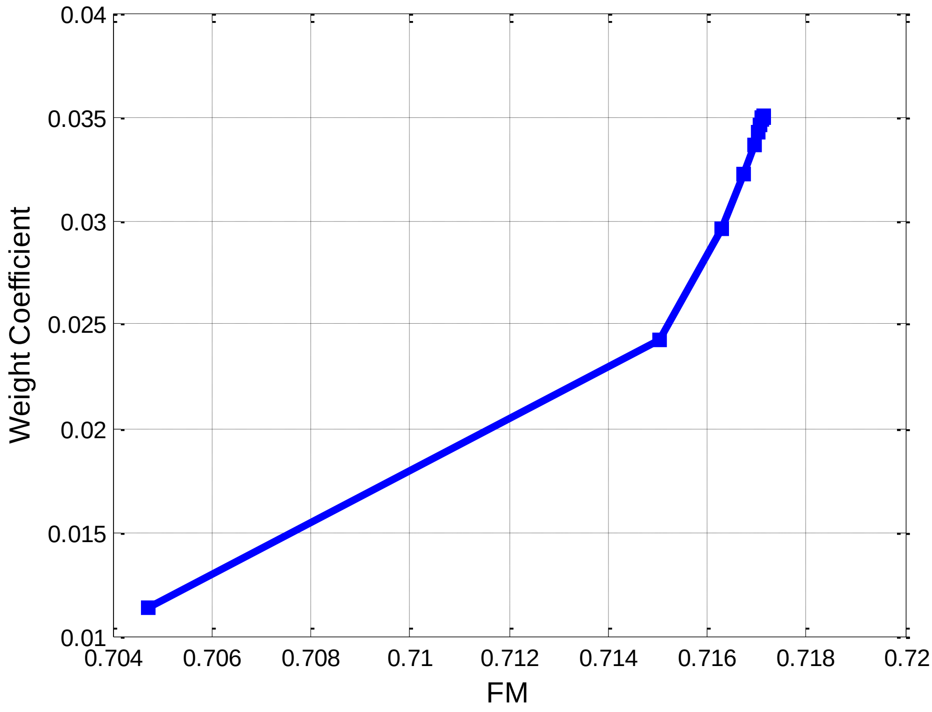

Figure 13 Relation Between FM and Weight Coefficient

Weight coefficient can be written as equation (2.2.3.6) and solidity can be written as equation (2.2.3.7).

$$Wgt.Coeff. = \frac{W_G}{\rho\ .\ RotorArea\ .\ (V_{tip})^2} \qquad (2.2.3.6)$$

$$Solidity = \frac{BladesPerrotor\ .\ c}{\pi\ .\ r} \qquad (2.2.3.7)$$

where c is chord of the blade and r is radius of the rotor. The density of air (ρ) has a value of 0.002378 slugs per cubic foot at sea level and 59°F.

The relation between W_G and weight coefficient can be seen in Figure 14. According to the figure, when gross weight starts to increase, automatically weight coefficient increases. These two parameters are directly connected to each other as seen in equation (2.2.3.6).

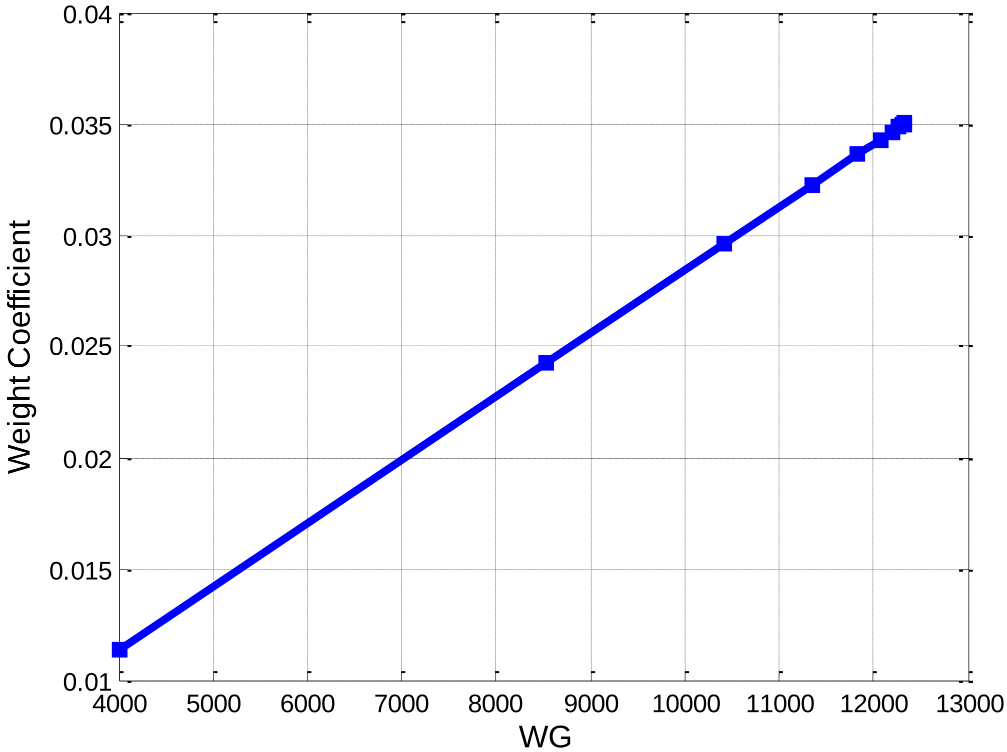

Figure 14 Relation Between W_G and Weight Coefficient

2.2.3.1 Verification of The Helicopter Base Price Estimation Method

This part of the thesis is devoted to verifying the base price approach using 21 helicopters performance and economic data.

The current base price values are taken from Conklin & De Decker ACE software program. Then using gross weight, DL, FM and power parameters of the 21 helicopters, the base prices were calculated with using the equation (2.2.3.1).

After the calculation, base price values were converted into dollars of 2014 because of the original base price equation used 1994 values.

21 helicopters and their relevant parameters are listed in Table 1. According to the table, percentage of the differences between Base Price Value and Calculated Base Price Value can be seen in the last column.

Table 1 Values of Performance and Economic Metrics of Helicopters

	Military / Commercial	W_G (lb)	D (ft)	DL (lb/ft^2)	Power (HP)	Base Price from ACE Program	Calculated Base Price With Eqn. (2.2.3.1)	% Difference Between Base Price and Calculated Base Price
AW101	Military	34392	61	11,77	5100,05	27000000	26295521	2,61
Sikorsky S92	Commercial	26500	56	10,61	3493,87	24960000	19276436	22,77
AW139	Commercial	14991	45	9,31	2136,95	11900000	9595816	19,36
Bell429	Commercial	7500	36	7,37	714,02	5000000	3769557	24,61
Kaman K-Max	Commercial	12000	48	6,55	1353,67	4150000	4344990	-4,70
Eurocpter BK117C1	Commercial	7385	36	7,26	872,70	3350000	2931001	12,51
Sikorsky S76A++	Commercial	8400	42	6,06	899,03	3000000	2955288	1,49
AW119	Commercial	6283	36	6,31	647,88	2610000	1949362	25,31
Bell407	Commercial	6000	35	6,24	644,78	2540000	1761352	30,66
Eurocopter AS355N	Commercial	9480	39	7,86	542,29	2350000	1667309	29,05
Eurocopter AS350B3e	Commercial	6172	35	6,42	679,48	2300000	1719214	25,25
Eurocopter EC130T2	Commercial	6724	35	6,95	753,29	2100000	1960143	6,66
Eurocopter AS350B2	Military	5512	35	5,73	561,39	2065000	1498405	27,44
MD600N	Commercial	4500	28	7,58	497,46	1700000	1702447	-0,14
MD530F	Commercial	3750	28	6,31	432,02	1400000	1320007	5,71
Bell206B3	Commercial	3350	33	3,82	294,37	1170000	897568	23,28
MD500E	Commercial	3000	26	5,48	285,45	1150000	1000726	12,98
Enstrom 480B	Commercial	3000	32	3,73	249,79	1128800	921566	18,36
Sikorsky S333	Commercial	2550	28	4,26	221,98	900000	705549	21,61
R66	Commercial	2700	33	3,16	206,18	839000	639201	23,81
R44	Commercial	2500	33	2,92	175,74	447000	352897	21,05

The percentage of differences changes between base price and calculated base price values between 0% and 30%. The average difference is 15% and it can be added to calculated base price value in order to increase the accuracy of the result.

The main reason why the difference is large many be due to the avionics technology has shown great improvements from 1994 to 2014. Glass cockpit and fiber optic are good examples of the advanced avionic technologies.

On the other hand, with this supposition, it is thought that the difference between current and calculated base price values do not create a critical restriction when using this method for helicopter systems.

Using these values, the relation between gross weight, disk loading and power with calculated base price was evaluated. According to Figure 15, when power increases the calculated base price starts to increase, too.

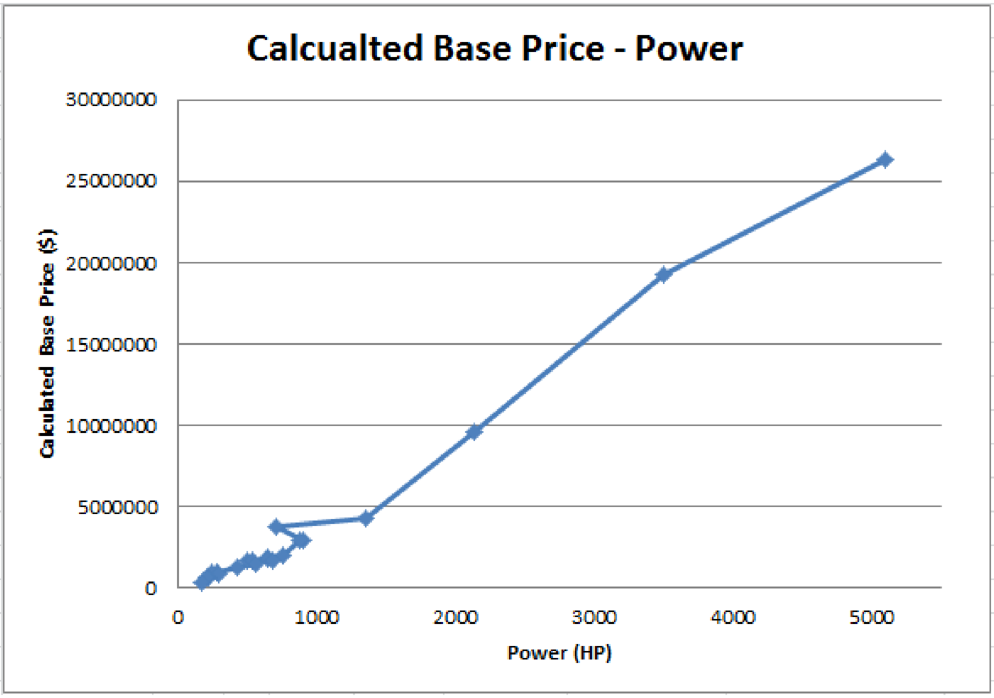

Figure 15 The Relation Between Power and Calculated Base Price

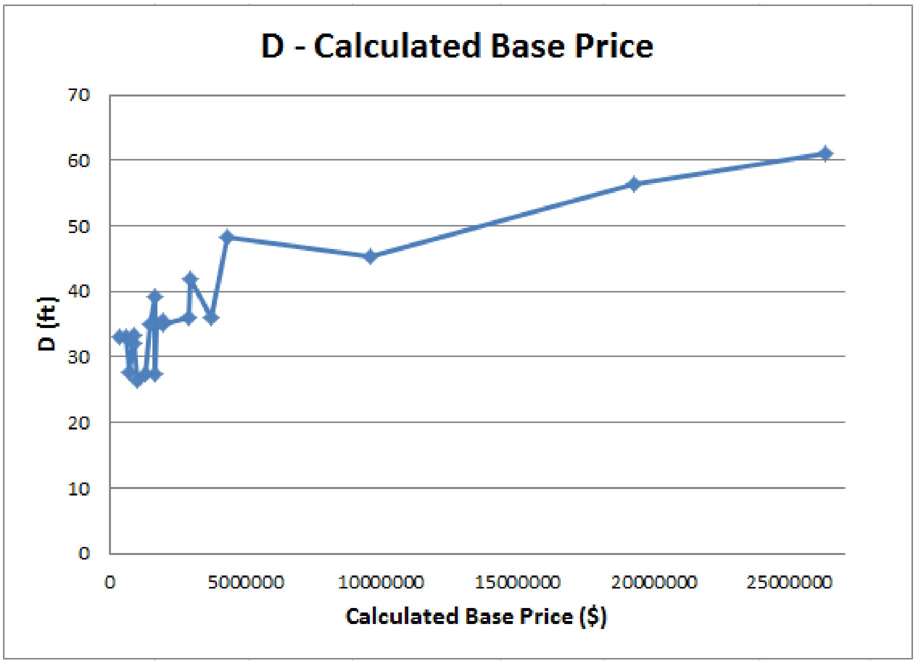

Figure 16 The Relation Between D and Calculated Base Price

According to Figure 16, it is not easy to say that when diameter of helicopter rotor increases the calculated base price also increases. Because the curve does not show a linear behavior. But after that diameter gets bigger numbers than 45 ft. calculated base price permanently starts to increase.

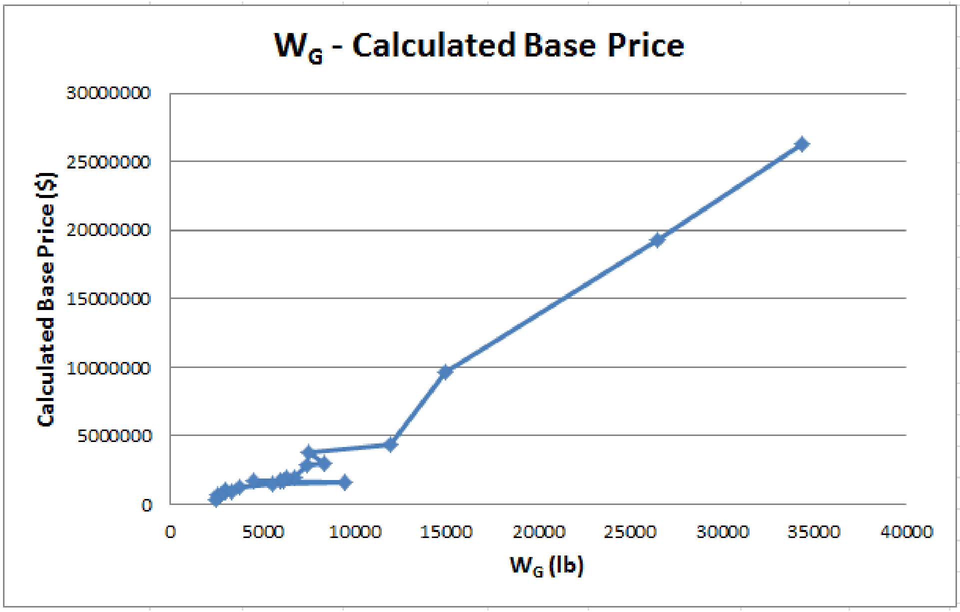

Figure 17 The Relation Between Gross Weight and Calculated Base Price

According to Figure 17, when gross weight of a helicopter increases, the calculated base price also increases. Especially after 1200 lb. for gross weight, calculated base price shows a sharper increment.

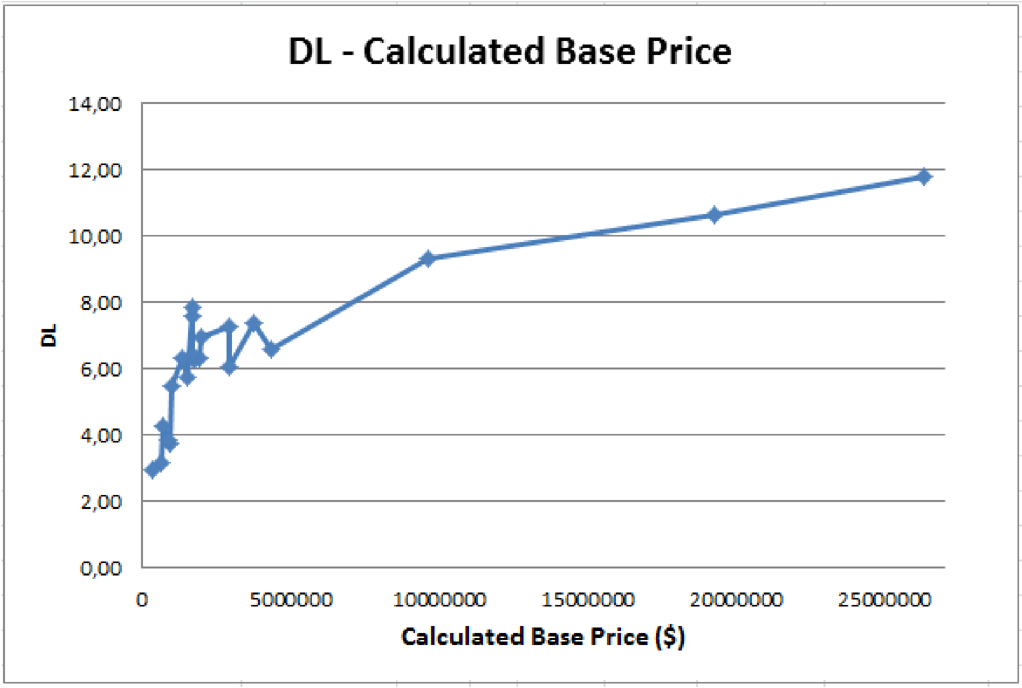

Figure 18 The Relation Between Disk Loading and Calculated Base Price

According to Figure 18, when disk loading of a helicopter increases, the calculated base price also increases. When DL takes value greater than 8, calculated base price value shows sharper behavior. Probably it is caused because of the gross weight effect on the calculated base price.

Related to this approach, disk loading and gross weight relation is plotted in Figure 19. It can be seen that, for disk loading greater than 8, gross weight starts to increase permanently.

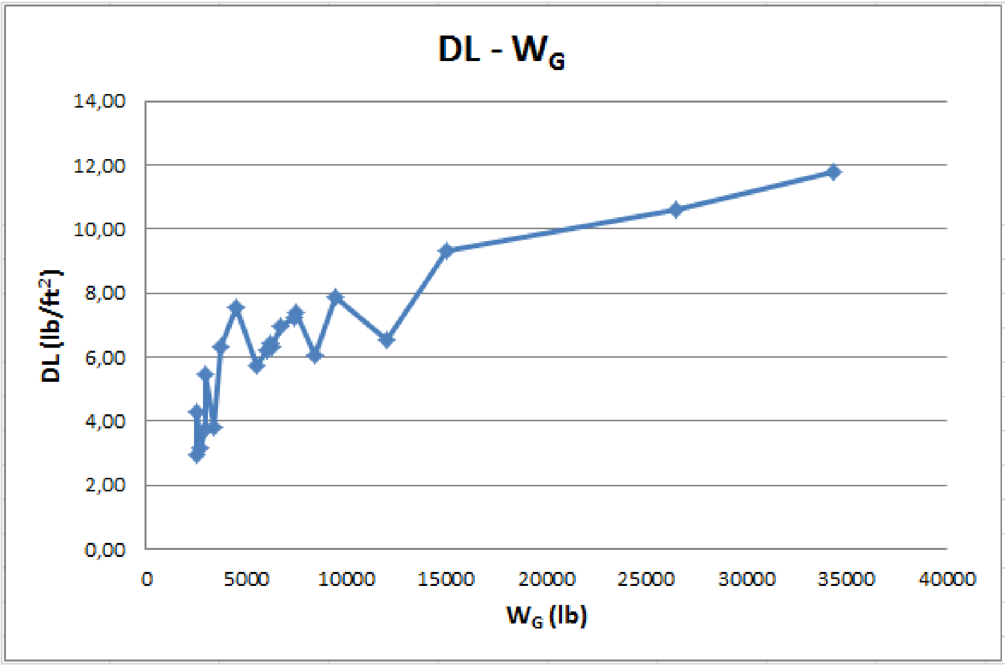

Figure 19 The Relation Between Disk Loading and Gross Weight

2.3 RF Method

The RF Method is used to determine feasible helicopter configurations while optimizing gross weight for a given configuration. In RF method, the point where the required and available fuel to gross weight ratio ($R_{F,AV}$) is equal to be determined.

Generally, range and endurance performance parameters of the helicopter are looked as the design requirements. By using parametric analysis minimum required RF and also the maximum available RF can be evaluated with the parameters. The feasible helicopter configuration has to provide that the minimum required RF ($R_{F,R}$) is no less than the maximum RF available ($R_{F,AV}$). For each disk loading intersection area of $R_{F,R}$ and, $R_{F,AV}$ defines minimum gross weight for that configuration. This relation can be seen in Figure 20. The shaded area represents both location of minimum gross weight and the feasible design area for disk loading.

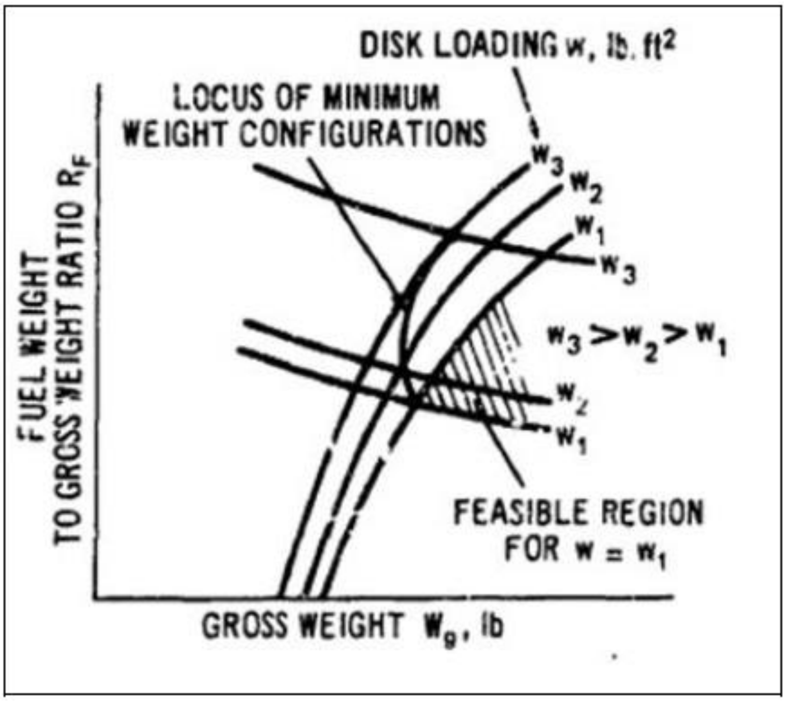

Figure 20 RF Method [2]

In order to estimate the minimum design gross weights for different configurations (2.3.1) and (2.3.2) are the main equations as shown below [2].

$$R_{F,R} = \frac{C \, . \, HP_R \, . \, T_H}{W_G} \tag{2.3.1}$$

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

$$R_{F,AV} = 1 - \frac{W_{useful}}{W_G} - \frac{W_{empty}}{W_G} \tag{2.3.2}$$

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

2.3.1 RF Method and Base Price Estimation Method Integration

In order to show the relation between helicopter development process and helicopter base price estimation, the base price estimation equation (2.2.3.1) was used with a RF code on MATLAB software [13] which was adapted by Selvi [14].

In this process, FM, DL and W_G parameters are changed related to RF method itself. In order to find some parameters such as chord or tip velocity, geometry sizing parameters method was used.

Other geometry sizing and performance parameters are fixed related to selected helicopter. The fix and changeable variables can be seen in Table 2.

Table 2 Fix and Changeable Parameters in RF Code

Fix Parameters
Solidity
Lift/Drag
Number of Engines
Range
Air Density
Hover Efficiency
Hover Altitute
Hover Time
Hover Temperature
Rate of Climb
Payload
Fuel Consumption
Cruise Speed
Cruise Altitude
Cruise Temperature
Changeable Parameters
W_G
W_E
Disk Loading (DL)
Figure of Merit (FM)
Base Price

In this process, BELL 429 helicopter was used as a reference helicopter.

The base price estimation is done in the following way: Firstly the optimum value of WG for the BELL429 helicopter is found using iterations for disc loading, DL, in the RF code. The parameters needed for this optimization is given in Table 2, i.e. range, payload, fuel consumption, cruise speed, hover altitude, etc. The equations used for this process are Appendix RF Method Code.

After finding W_G, the empty weight, W_E, is evaluated using the weight fraction' phi' calculated in the RF method:

$$phi = \frac{W_G}{W_E} \quad (2.3.1.1)$$

Next, eqn. (2.2.3.3) is used to find the disk loading, DL, and equation (2.2.3.6) is used to find the weight coefficient, Wgt. Coeff.

Then, eqn. (2.2.3.5) is used to find FM.

Next, using FM and DL along with eqn. (2.2.3.4), required engine horse power is evaluated.

Finally, using required horse power and WE in eqn. (2.2.3.1), the base price of BELL429 helicopter is found.

The whole process is illustrated in Figure 21.

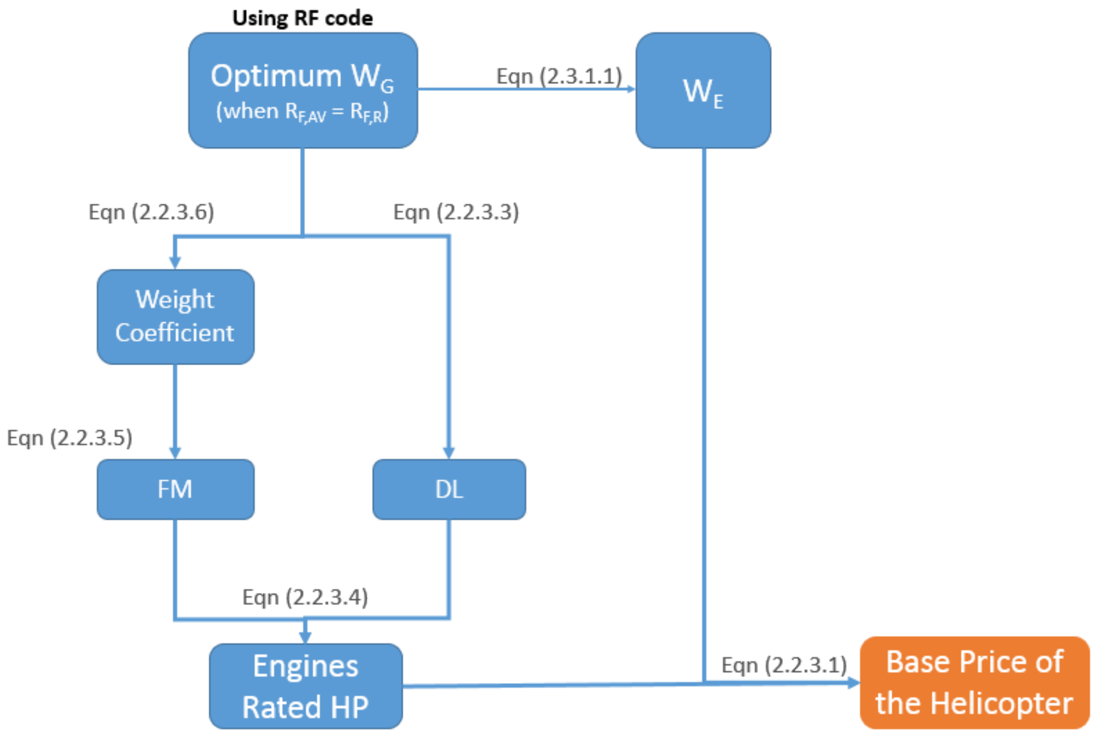

Figure 21 Base Price Estimation Flow Using RF Method Code

Related to the process, relations between gross weight, FM, DL and the base price of BELL429 helicopter are evaluated.

In Figure 22, the base price and gross weight relation can be seen. According to this figure, when grow weight starts to increase linearly base price values increase.

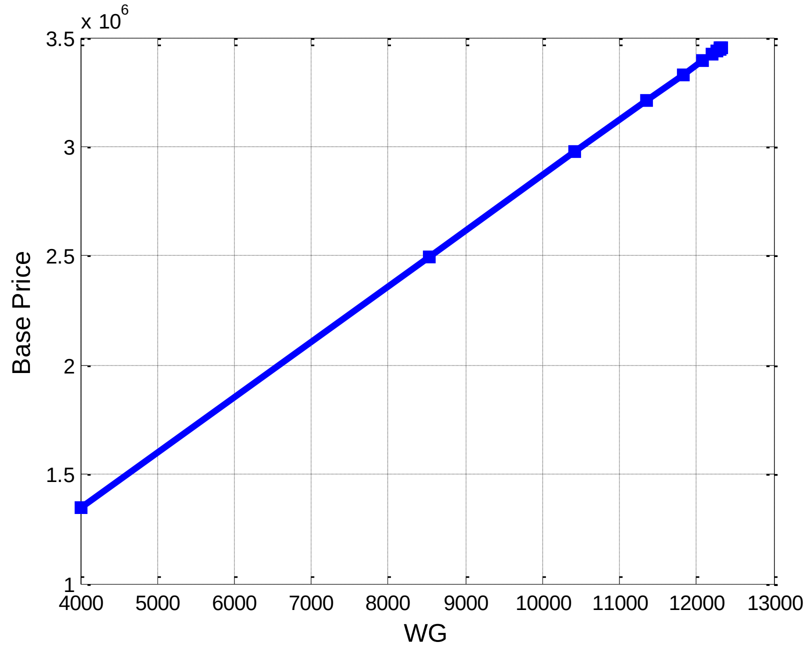

Figure 22 Relation Between W_G and Base Price

Furthermore, the relation between FM and base price is shown in Figure 23. According to the figure, when FM increases, base price of a helicopter also increases. But, when FM takes values greater than 0.75, base price shows sharper increment.

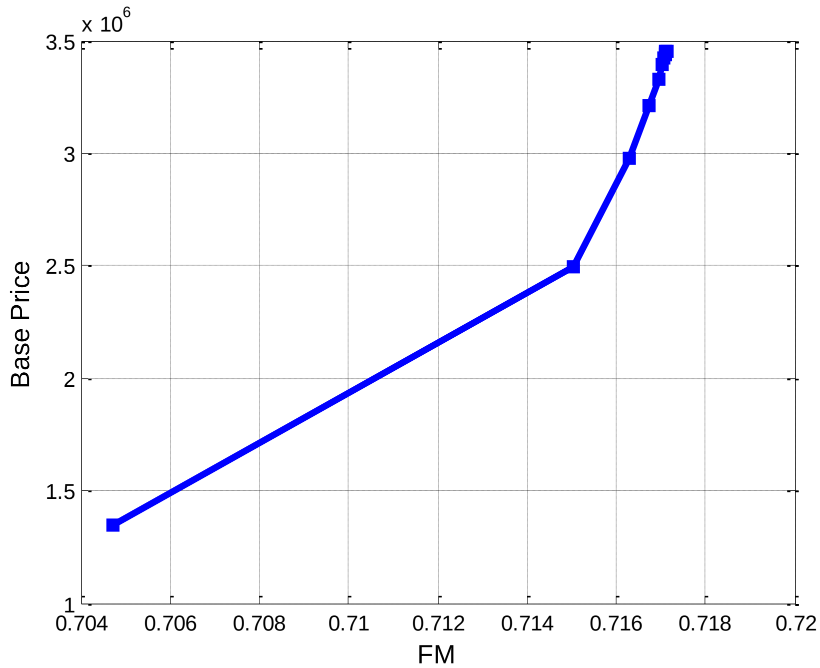

Figure 23 Relation Between FM and Base Price

Also, the relations between DL and base price can be seen in Figure 24. According to the figure, when DL increases, base price of a helicopter also increases. Probably, it is caused because of the gross weight effect on DL.

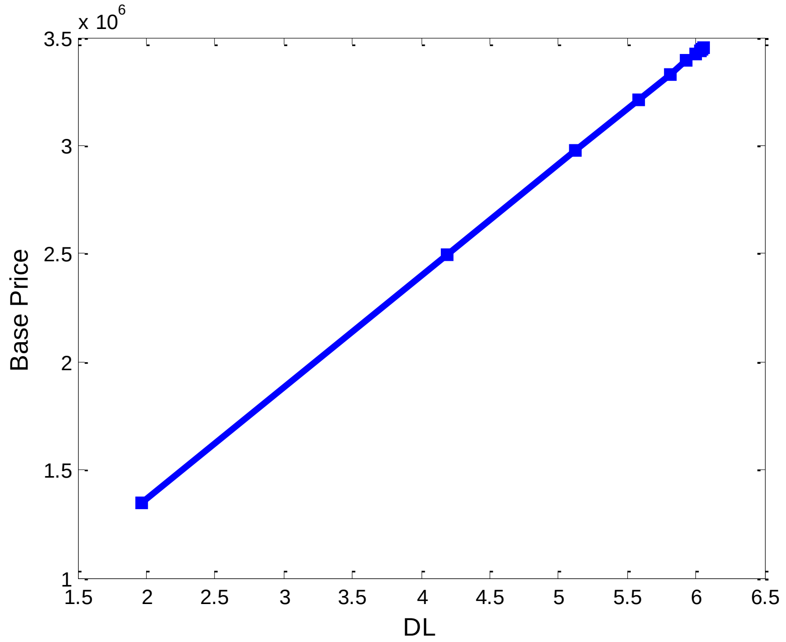

Figure 24 Relation Between DL and Base Price

CHAPTER 3

METHODOLOGY

In this chapter, firstly technology factor approach is examined first. Then the formulation of total base price approach is presented. Finally, related to these approaches the decision making methodology is given.

3.1 Technology Factor Approach

Technologic improvements may decrease product cost. For helicopter systems, cost is usually related to the helicopter empty weight. Because of this, if a technology can be implemented on a helicopter which reduces helicopter empty weight substantially, investment on this technology may be very cost effective.

Furthermore, a technology that changes blade performance may also affect helicopter cost value. Since the flight performance, fuel consumption starts to decrease and weight will be reduced. Thus, helicopter base price can be reduced.

To decrease the helicopter weight, k technology factor was used. k means the percentage of empty weight reduction for one helicopter. With using k parameter, the new empty weight of a helicopter was found by using the equation below.

$$\text{New } W_E = (1 - \text{k}).W_E \qquad (3.1.1)$$

According to equation (3.1.1), weight coefficient (Wgt.Coeff.) which takes part in Engine rated horse power related to FM, and base price equations can be seen below.

$$Wgt.Coeff. = \frac{\frac{((1-k).W_E)^{\frac{1}{1.015}}}{0.4854}}{\rho \, . \, RotorArea \, . \, (V_{tip})^2} \quad (3.1.2)$$

$$Price = \$236.77 \, . H \, . BladesPerRotor^{0.2045} \, . \left((1-k)W_E{}^{0.4845}\right) . Eng(s)RatedHP^{0.5843} \quad (3.1.3)$$

To improve airfoil and planform design to achieve better performance, FM parameter was used which is directly relevant to chord value of the helicopter. FM parameter was used in engine rated horse power equation (2.2.3.3) which takes place in the base price estimation equation (2.2.3.1).

Using BELL429 helicopter data, k parameter was analyzed while taking the values between %2 and %20. According to Figure 25, k parameter is directly related to decreasing base price value, because it affects the empty weight of a helicopter.

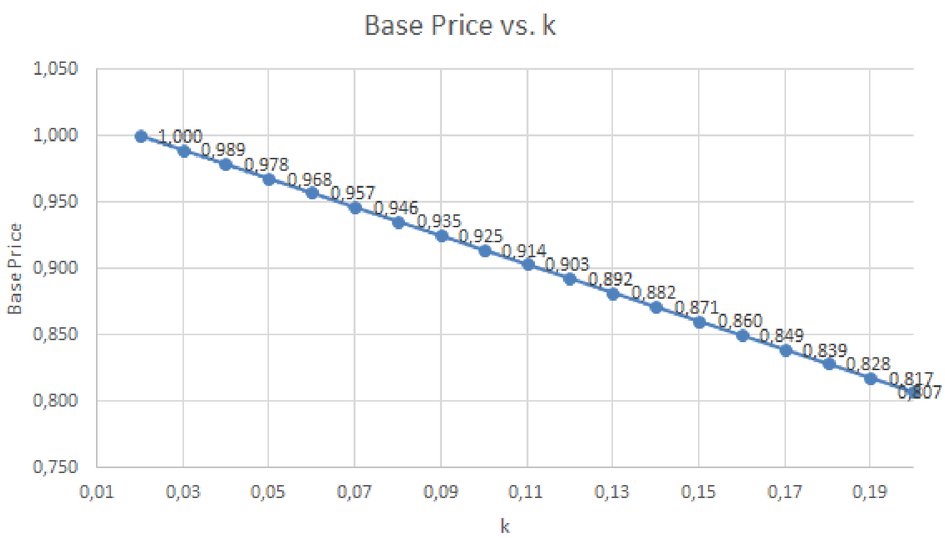

Figure 25 Base Price as a Factor of k Factor

Then for FM parameter which takes the values between 0.5 and 0.77 was taken to the analysis. FM factor directly affect the engine rated horse power parameter which takes place in base price estimation equation (2.2.3.1).

As seen in Figure 26, FM parameter is more effective between 0.50 to 0.64 values for base price value.

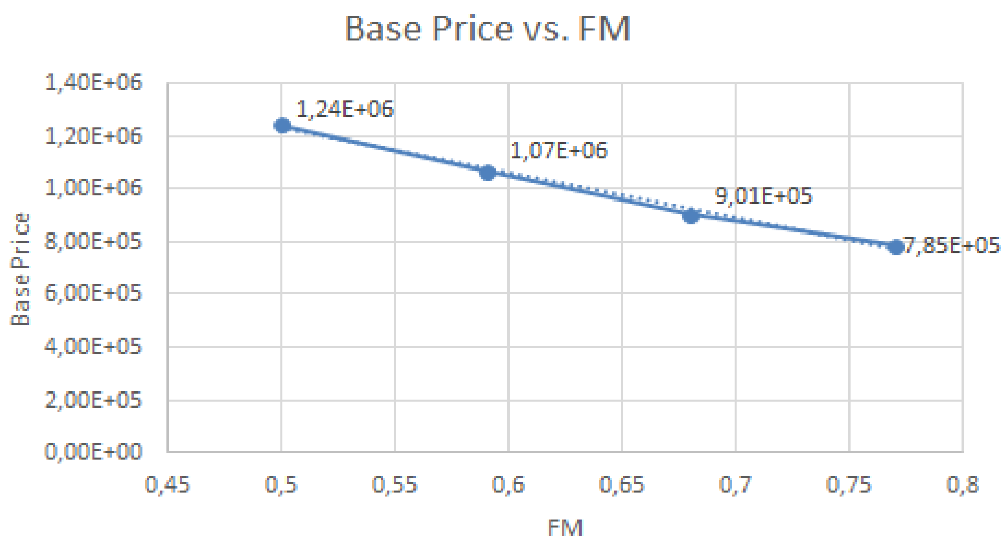

Figure 26 Base Price as a Factor of FM Factor

3.2 Total Base Price Estimation Approach

Technology factor, k, is used to decrease empty weight and base price. However it also indicates that an investment on R&D is needed to develop the related technology to decrease helicopter empty weight. The R&D investment and per helicopter should be added to the base price or for the total base price the following equation is used.

FM technology factor cannot be used because of deficient information relevant with rotor performance improvement and base price reduction.

$$Total\ Base\ Price = (Number of Helicopter . Base Price) + R\&D\ Investment \quad (3.2.1)$$

For the development of the necessary technology, several data are collected from Turkish Aerospace Industries database and also from the Sikorsky's S-75 project [15]. In conformance to this, a relation between k and R&D investment is proposed.

$$R\&D\ Investment = 7891.e^{((37.31).\mathrm{k})} \quad (3.2.2)$$

The equation is plotted in Figure 27. Thus improvement more than 30%-35% of k parameter needs excessive R&D investment. After the reductions on empty weight below 30%, the technology development process may not be quite cost effective.

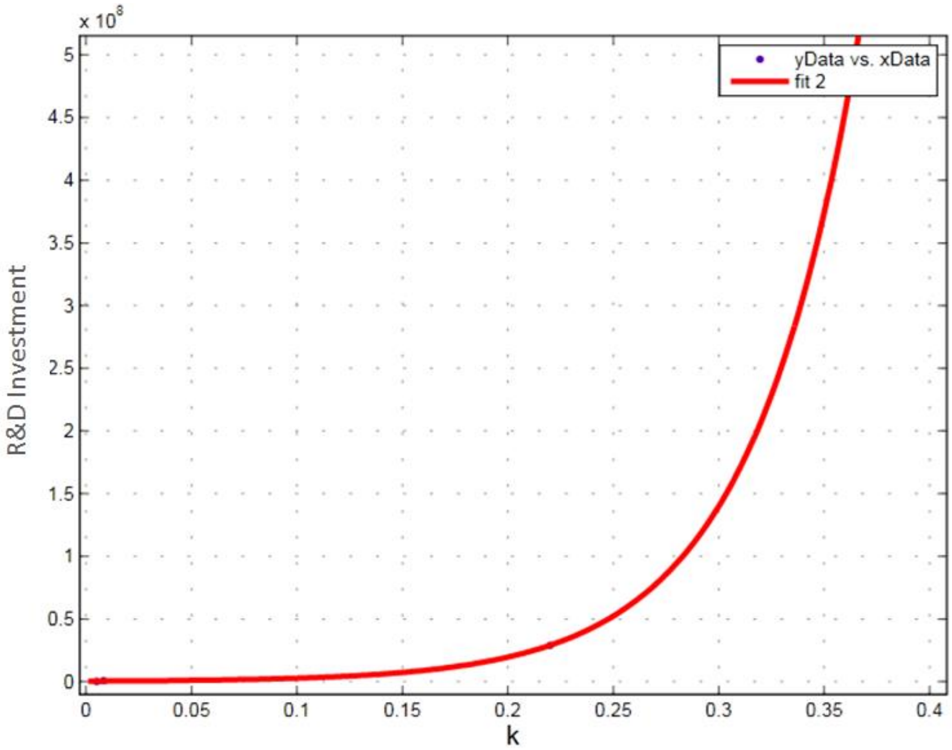

Figure 27 The Relation Between k and R&D Investment

With R&D investment equation is added into total base price equation (3.2.1), the relation between k and total base price values as plotted in Figure 28 is obtained. The orange area in the graph shows the ideal range of k. Thus, in order to reduce total base price, percentage of empty weight reduction (k) should be between %15 and %25 for a helicopter.

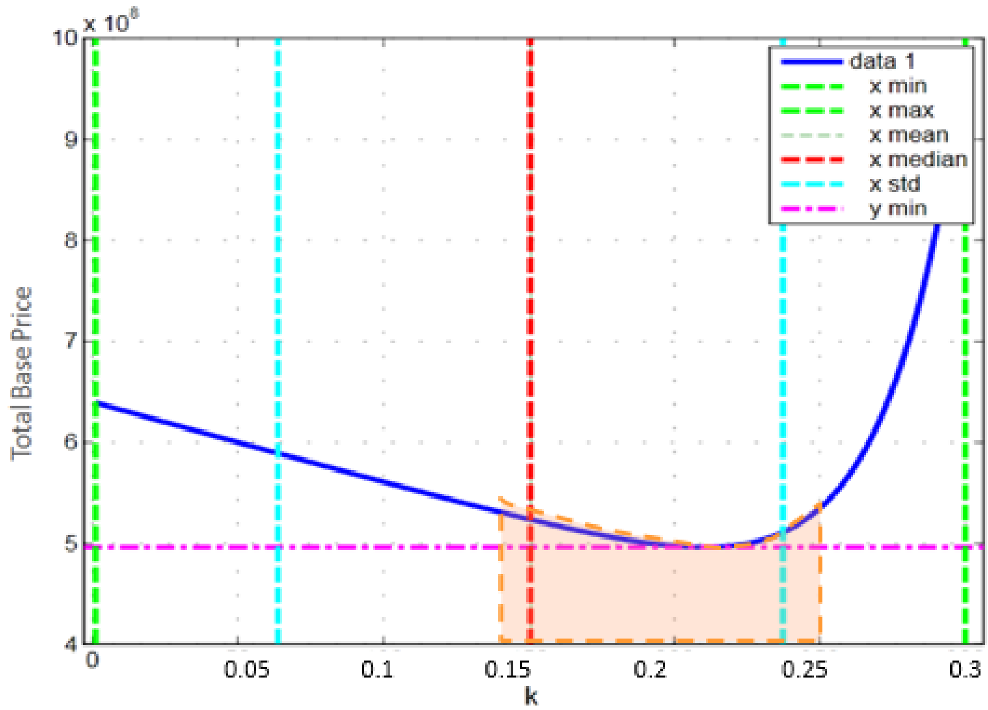

Figure 28 The Relation Between k and Total Base Price

In Figure 29, the relation between number of helicopter and total base price may also be observed for a fixed k value, number of helicopter directly affects the total base price value and it can be used in order to minimize R&D investment amounts.

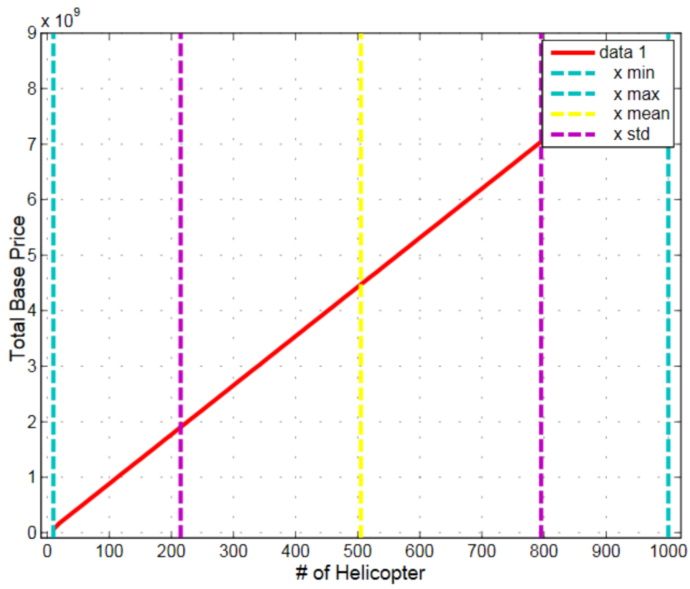

Figure 29 The Relation Between Number of Helicopter and Total Base Price

Also in Figure 30, the relation between number of helicopters to be produced on the k factor as well as the total base price is shown. This graph is quite important because it shows to the decision makers that how many helicopters can change total base price value relevant to weight reduction.

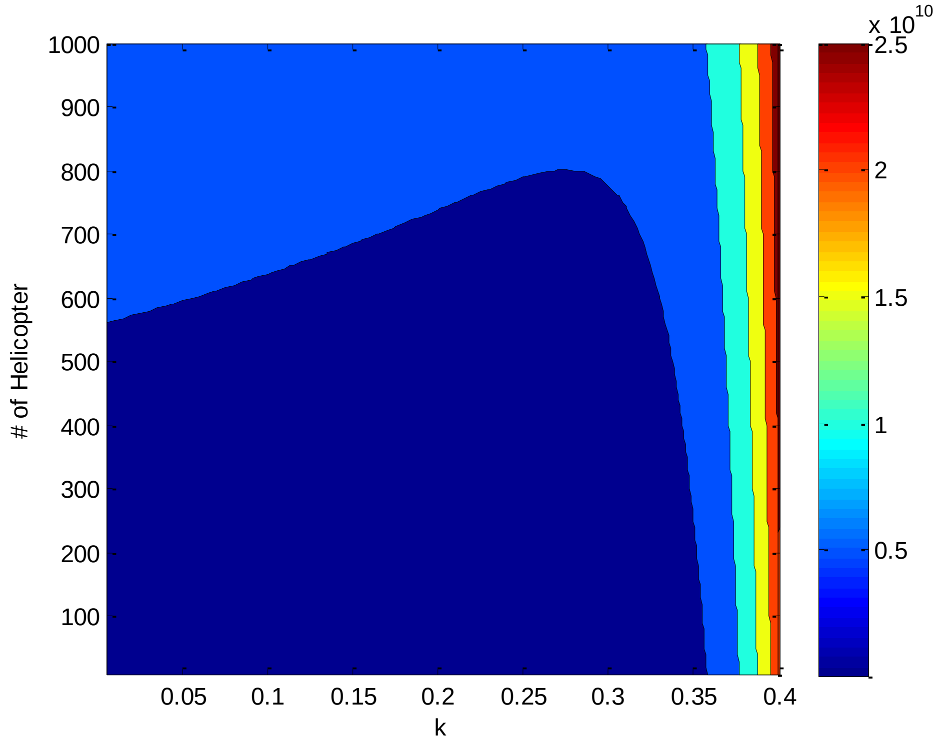

Figure 30 The Relation Between Number of Helicopter, k and Total Base Price

According to the figure, if 800 helicopters are thought to be improved with using new technology, it can be easily seen that when the empty weight reduction is approximately 30%, then the total base price can get minimum value. It is also said that, at this point the R&D investment cost can get its minimum value.

At this point, for one helicopter the total base price value gets approximately 3 million dollars.

DL is another parameter that affects the gross weight value directly. In Figure 31, the relation between helicopter number, DL and total base price is presented. For example, DL is 9.5 and number of helicopter to be improved with new technology is 800, the total base price is very low. At this point, the R&D investment cost also gets its minimum value. If DL is increased, the number of helicopter should be between the number of 600 and 800. Thus, in this region, the technology development process can be cost effective.

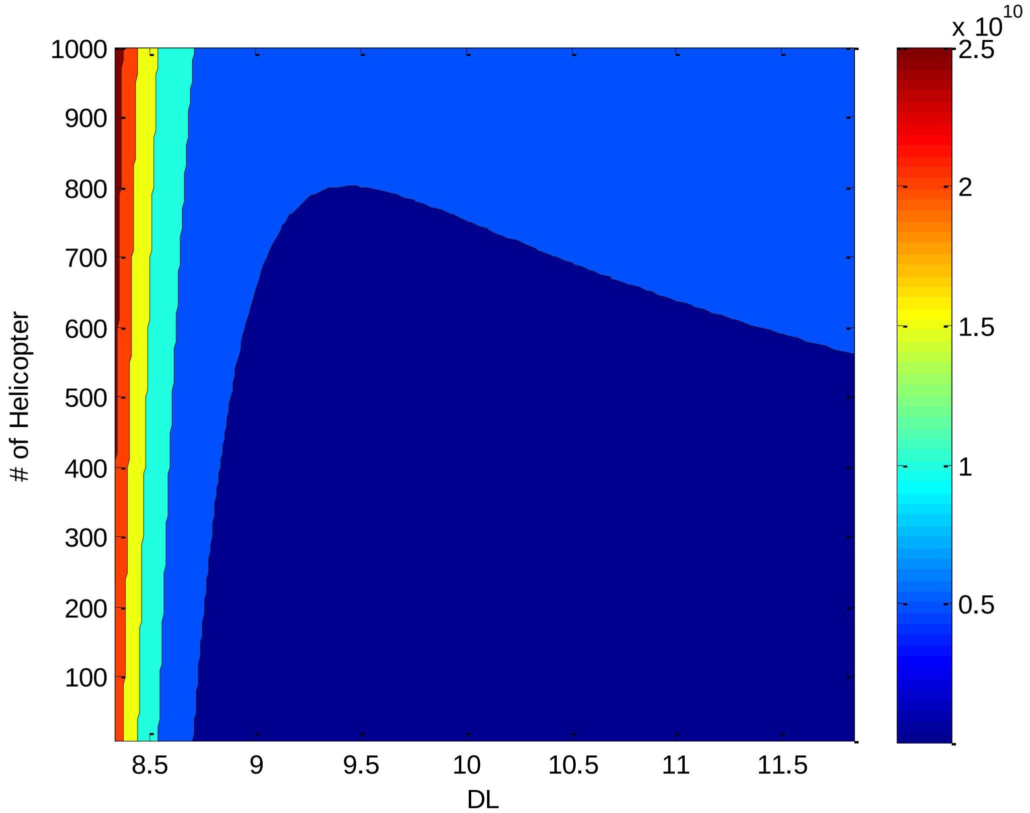

Figure 31 The Relation Between Number of Helicopter, DL and Total Base Price

Again at this point, for one helicopter the total base price value gets approximately 3 million dollars. Thus, it can be said that, for minimum R&D investment cost and total base price values, one helicopter base price should be minimum 3 million dollar.

3.3 Decision Making Methodology

Methodology proposed in this study has four basic steps. It starts with identification of technology development area together with the related R&D investment cost.

Then the new technology is examined to decide if and how much the empty weight is reduced (k). On the other hand, the technology may improve the airfoil or planform design of the blades related to FM parameter.

In the third step, helicopter base price is calculated with the implementation of new technology using the equation (2.2.3.1).

Finally, the total base price of the helicopter is evaluated using the equation (3.2.1).

As a result, the decision is made. If the total base price of the helicopter with new technology is greater than the current value, then it is wise not to invest in the new technology development activity. Otherwise, some qualitative parameters such as restrictive regulations or government foundations which can encourage decision makers to develop the technology can be used to decide continuing.

On the other hand, if the total base price of the helicopter with new technology is less than the current value, then decision makers easily decide to continue. The all process of the methodology can be seen in Figure 32.

Together with the evaluation of other factors, the decision on the investment of the R&D activities for the development of the new technology can be made.

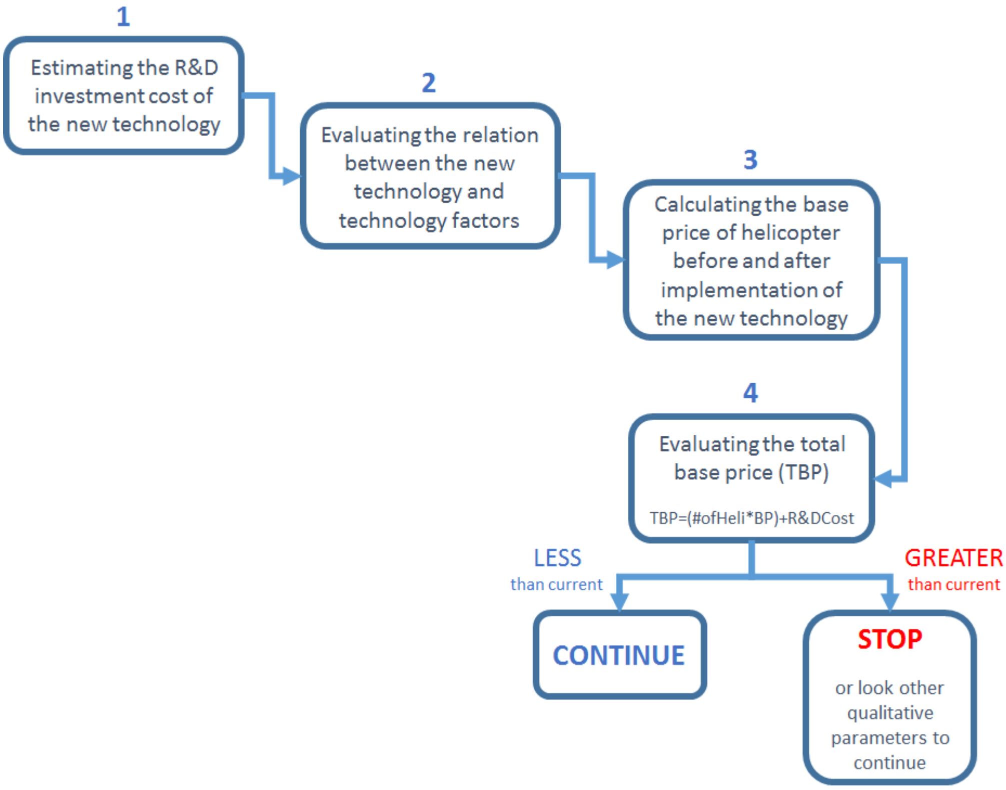

Figure 32 Methodology Flow

CHAPTER 4

APPLICATION OF THE METHODOLOGY

In this chapter, in order to see how methodology may be useful for decision makers during technology development decisions, two case studies are given below. The first one examines composite shaft technology development for the BELL429 helicopter and the second one addresses composite tail cone technology development for the Sikorsky UH-60 helicopter.

4.1 Bell 429 Composite Shaft

Composite shaft system is taken as a new technology implementation example. BELL429 helicopter, which can be seen in Figure 33, was chosen because several parameters can be found more easily than other helicopters. Once developed 110 helicopters are assumed to use this new technology.

Figure 33 BELL429 Helicopter

At this period, performance and economic metric data are supplied by TAI's Helicopter Department.

According to a study published in 2013 and supported by Boeing Company [16], it was shown that when a shaft system is produced with composite material, its weight reduction is approximately be 33% as seen in Figure 34.

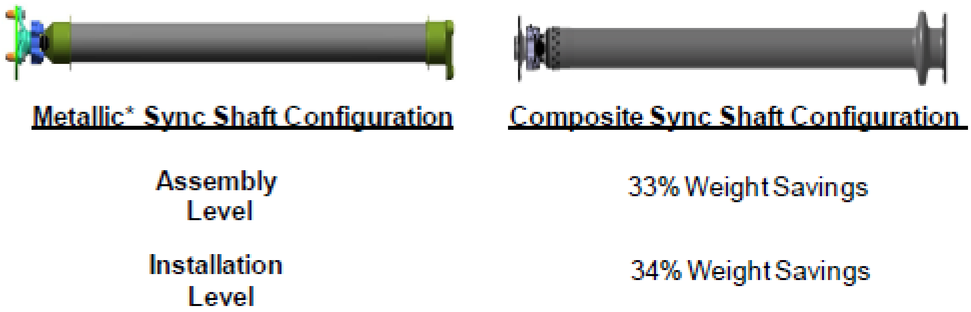

Figure 34 Metallic and Composite Shaft Weight Differences [16]

The basic geometry sizing and performance parameters of BELL429 can be seen in Table 3.

Table 3 Basic Specifications of BELL429

BELL 429 Spesifications	
WG	7500 lb
WE	4455 lb
D	36 ft
Range	761 km
V^{CURISE}	150 knot
Hover Altitute	13540 ft
Max Altitute	20000 ft
FM	0,72
DL	7,36 lb/ft^2
Number of blades	4
Base Price (Program)	5000000 $

Using the information, the weight reduction of BELL429 helicopter's empty weight is calculated by using the data from Table 3. Then the reduction of shaft weight and % reduction of helicopter empty was calculated as seen in Table 4.

Table 4 Reduction of Weights

Total Weights of Shaft	32 lb
Reduced Weight of Shaft (33%)	10,56 lb
% Reduction on W_E	0,0024

The R&D investment cost which is required to develop the new technology is then estimated. R&D investment cost includes infrastructure investments, test costs, material costs and other costs. The total R&D investment cost is thought to be approximately $900000.

After that, the base price of the helicopter which improved by using new technology was evaluated by using equation (2.2.3.1).

After at all, the total base price for 110 helicopter was calculated using equation (2.2.3.1) and compared with current base price value of BELL429 helicopter.

In Table 5, the differences between current base price and calculated total base price of BELL429 helicopters and the investment cost can be seen.

Table 5 Total Base Price Differences and Investment Cost

Total Base Price Difference	~990000 dollar
Investment Cost	~900000 dollar

Because of the total base price of 110 BELL429 helicopters with new composite shaft technology is less than current base price value; it can be said that it will be a cost effective investment project. If the calculation shows that the difference is negative value, then decision makers may use Figure 30 and Figure 31 in order to find ideal helicopter number which provides cost effective solution.

4.2 Sikorsky UH-60 Composite Tail Cone

The second case study is the composite tail cone for the UH-60 helicopter. Data for Sikorsky UH-60 helicopter is supplied by TAI. A batch of 220 helicopters is assumed to use this new technology. Sikorsky UH-60 helicopter and tail cone region can be seen in Figure 35.

Figure 35 Sikorsky UH-60 Tail Cone

According to TAI's experience on manufacturing, it can be said that the cost of composite parts are %20 less than the metallic parts of tail cone structural elements.

The basic geometry sizing and performance parameters of UH-60 helicopter can be seen in Table 6.

Table 6 Basic Specification of UH-60

UH-60 Spesifications	
WG	9979 lb
WE	4819 lb
D	53 ft
Range	511 km
V^{CURISE}	151 knot
Hover Altitute	10520 ft
Max Altitute	15180 ft
FM	0,72
DL	4,52 lb/ft^2
Number of blades	4
Base Price (Program)	5900000 $

Using the information, the weight reduction of Sikorsky UH-60 helicopter's empty weight is calculated by using data in the Table 6 and this Table 7 was obtained.

Table 7 Reduction of Weights

Total Weights of Tail Cone Parts	200 lb
Reduced Weight of Tail Cone (20%)	40 lb
% Reduction on W_E	0,8300

New base price of one helicopter is calculated using k technology factor with equation (3.1.1) and (3.2.2.1).

Then, the R&D investment cost required to develop new technology is estimated. This investment cost includes recurring costs as tooling, service costs as engineering, analysis costs as fatigue test, ground resonance test and vibration tests and also qualification cost of the helicopter. The total R&D investment cost was thought to be approximately $4000000.

After that, the total base price is calculated and compared with current total base price value of Sikorsky UH-60 helicopter. In Table 8, the differences of current and new total base prices for 220 of UH-60 helicopters and the investment cost are listed.

Table 8 Total Base Price Differences and Investment Cost

Total Base Price Difference	~6,5 million dollar
Investment Cost	~4 million dollar

The total base price of 220 Sikorsky UH-60 helicopters with new composite tail cone technology is substantially lower than current total base price value. Consequently the decision makers may decide in favor of the composite material utilization on tail cone.

According to the samples, BELL429 and Sikorsky UH-60, the differences between profits and R&D investment costs are quite different. It is caused from the gross weight difference of two helicopters. The gross weight of BELL429 is 7500 lb. and the gross weight of UH-60 is 9979 lb. The greatness of gross weight affects the total base price ratio.

CHAPTER 5

CONCLUSION

The aim of this thesis is to generate a methodology which can support helicopter developers for making more effective decisions for technology development activities using both performance and economic metrics.

Within the aim of thesis, the methodology was shown to work such a useful tool for decision making process. As seen in sample results, the methodology can demonstrate if an investment is profitable or not, with using technology factor effects.

Furthermore, the methodology uses performance parameters such as gross weight, DL and FM in order to evaluate basic price of a helicopter. This value is then used to obtain total basic price together with the number of helicopters and R&D investment cost. The equation developed helps to comment on base price, investment cost and number of helicopter together. It is possible that these variables can be used in order to obtain best cost effective technology development model.

The methodology also showed that, technology factors such as k or FM, is quite important for obtaining base price values and comment on investment costs. Thus, modernization projects of helicopters may also take advantage of the approach presented here to support decision-making.

At last, it is known that for military helicopter projects technology development process is quite related with reparability issue. But the base price estimation method does not seem to cover this approach.

In order to increase the accuracy from verification process topics mentioned below can be generated for future work:

- More and different kinds of helicopters should be used to increase the accuracy of the cost model.
- In addition to the weight reduction, FM and DL other technology factor types should be used.
- Sample number can be increased in order to show this methodology can be applied for broader area.
- Similar helicopters can be compared with using the methodology to see the technology effects.
- Reparability issue can be examined in order to improve the effectiveness of base price estimation method especially in military helicopter projects.

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APPENDICES

RF Method Code

In the appendix, the RF code [10] which was used to calculate base price estimation related to changes of gross weight, empty weight, DL and FM is given.

```
%% CODE FOR HELICOPTER SIZING AND BASE PRICE ESTIMATION


%%  Prior A/C Info BELL 429

phi =   4478/7500;      % weight ratio empty to gross
weight ratio
propeffic = 0.89;       % propulsive efficiency
L_over_D = 5.6;         % lift over drag
sld = 0.04;             % MR blade solidity
M = 0.72;               % Figure of Merit
hovereffic = 0.89;      % hover efficiency of system
dl = 7.37;              % disk loading of BELL429
numengines =1;


%% Assumed Info for All Aircraft

ed = 0.03;    % accounts for download (assumption)
k = 0.06;     % weight factor for non self-sealing tanks;
c = 0.63;     % Fuel consumption lb/hp/hour


%% Requirements

payload = 3022 ;        % weight of payload lbs (1760kg)
hoveralt = 12070;       % feet
hovertemp = 15;         % degrees F
hovertime = 10;         % min

vcruise = 148;          % knots
cruisealt = 20000;      % feet
Rclimb = 0.02925;       % f/s (Rate of climb)
cruisetemp = 125;       % degrees F
range = 403;            % required in nm (about 507km)
reserve = 240;          % reserve at cruise speed (min)
Re = range + vcruise*(reserve/60); % Range required in
nautical miles
```

```
%% Air Density Calculations

e = 2.718281828459046;             % exp (long format)
h = hoveralt*0.3048;               % meters
temp = hovertemp /1.8 + 255.37;    % degrees K
rho = 1.255* e^((-9.801/(287*temp))*h);
density = rho/1.225;      % density ratio to sea level



%% Gw Calculations

Ar = Re/(650*(propeffic/c)*L_over_D); % Range parameter

At = hovertime/(4560*sqrt(density)*(hovereffic/c)*((1-
ed)^1.5)*M);                               % Power parameter


weightguess = 4000; % initial guess for Wg before
iterations

deltaweight = 1000; % initial setting for Wmax

var1 = (1-Ar*(1+k))/(1+Ar*(1+k));

var2 = (At*(1+k)*sqrt(dl))/(1+Ar*(1+k));

count = 1;
while (deltaweight>0.001)
Wg(count) = weightguess(count) ;
Wgo =Wg(count)/1000;



% Section Weights

%% Installed Power Loading

if numengines==1
oei = 1;
else
oei = (numengines-1)/numengines;
end


powerload = oei*(38*hovereffic*sqrt(density)*M*((1-
ed)^1.5)*(1-0.195*(hoveralt/10000))*1-0.005*(hovertemp-
59))*(1+0.252*e^(-
```

```
0.0173*hovertime)))/(sqrt(dl)+0.069*sqrt(density)*Rclimb)
;   % eqn 5 OGE LAMDA=1

Wmr = (391*Wgo^1.13)/(dl^0.790);      % Main rotor weight
Wtr = (22.2*Wgo^1.26)/(dl^0.81);      % Tail rotor weight
Weng = (166*Wgo)/powerload;
Wps = 2.5*(Wgo^1.07)*(dl^0.54);
Wds = (525*Wgo^1.14)/((powerload^0.763)*(dl^0.381));
Wfc = 81.5*Wgo^0.712;
Wlg = 38.2*Wgo^0.975;
Wf  = (190*Wgo^1.07)/(dl^0.471);
Wav = 100;
Wmisc = 50;
Wtotal = Wmr+Wtr+Weng+Wps+Wds+Wfc+Wlg+Wf+Wav+Wmisc;
phi = Wtotal/Wg(count);

grossweight(count) = (payload)/(var1-
var2*(1+1.05*((1/(weightguess(count)/payload))+phi))^1.5-
phi);

weightguess(count+1) =
grossweight(count)+weightguess(count))/2;

deltaweight(count+1) = abs(grossweight(count)-
weightguess(count))/grossweight(count)*100;



%% Base Price Calculation

Engine_Type = 1.779 ;
Engine_No = 1.352 ;
Country = 1.000 ;
Rotors = 1.000 ;
Landing_Gear = 1.104 ;
Pressurize = 1.135 ;

H =
Engine_Type*Engine_No*Country*Rotors*Landing_Gear*Pressur
ize ;

emptyweight = grossweight(count)*phi ;
We = emptyweight ;

N_b = 4 ;           % Blade number
c = 0.37 ;          % chord lenght
den = 0.0026 ;            % density at 12000ft
DL(count) = Wg(count)/(2*3.14*(18^2)) ;   % disk loading
Vtip = 258 ;              % tip speed of blade
```

```
WeightCoeff(count) =
Wg(count)/(den*(2*(3.14)*(18^2))*(Vtip^2))

Solidity = (N_b*c)/(3.14*18)

FM(count) =
(1.08/(((0.0085*Solidity)/((4*(2^0.5))*(WeightCoeff(count
)^1.5)))+1.5)) ;

EngineRatedHP(count) =
(Wg(count)/(550*FM(count)))*((DL(count)/(2*den))^(0.5)) ;


base_price(count) =
236.77*H*((N_b)^0.2045)*(We^0.4854)*((EngineRatedHP(count
))^0.5843) ;

count = count+1;

end

final = count;


grossweight(final) = weightguess(final) ;
gw_value = grossweight(final) ;
emptyweight = grossweight(final)*phi ;
ew_value = emptyweight ;


%%
```