UNIVERSITY OF TURKISH AERONAUTICAL ASSOCIATION

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OPERATING AND MAINTENANCE COST ESTIMATION OF A FLIGHT SIMULATOR WITH SYSTEM DYNAMICS APPROACH

MASTER THESIS

Cengiz TELEME

Department of Engineering Management

Master of Science in Engineering Management Program

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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PREFACE

The thesis, *Operating and Maintenance Cost Estimation of a Flight Simulator with System Dynamics Approach*, aims to estimate the total operating and maintenance costs and breakdowns of components, subsystems of a flight simulator in its life cycle, at the beginning of the project/training. The study has been conducted to fulfil the graduation requirements of the Engineering Management graduate program at the University of Turkish Aeronautical Association. I have been engaged in researching and reporting the findings in this thesis since November 2016.

My simulation model was created with the help of my supervisor, Asst.Prof.Dr. Hasan Umut AKIN. In this research, it was a challenge to collect data from different databases. It was also a challenge to create the model and enter all necessary data as inputs. Fortunately, I was able to overcome the problems with the help of my supervisor especially on simulation modelling.

I would like to start my acknowledgement statements by thanking my supervisor for his guidance, patience and excellent help during this process to complete my thesis. I would like to thank jury members for their guidance. I am grateful to my family for all the values they have given to me, for their great support for my education and the sacrifices they have made for me. My wife, Ceyda Gizem Teleme, deserves the greatest thanks because of her extra patience, motivation and great sacrifices during this period.

I dedicate this thesis to my wife and our son who died when he was 14 days old, for the moments we couldn’t live together.

Cengiz TELEME

November, 2019

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LIST OF SYMBOLS/ABBREVIATIONS

CBS	Cost Breakdown Structure
EASA	European Union Aviation Security Agency
FAA	Federal Aviation Administration
FFS	Full Flight Simulator
FMECA	Failure Modes and Critically Analysis
FTD	Flight Training Device
FNPT	Flight Navigation Procedures Trainer
FSTD	Flight Simulation Training Device
LCC	Life Cycle Cost
MTBF	Mean Time between Failures
MTTR	Mean Time to Repair
OECD	Organisation for Economic Co-operation & Development
OFT	Operational Flight Trainer
SIGMA	Support for Improvement in Governance and Management
USSR	Union of Soviet Socialist Republics

ABSTRACT

OPERATING AND MAINTENANCE COST ESTIMATION OF A FLIGHT SIMULATOR WITH SYSTEM DYNAMICS APPROACH

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With the development of technology, flight simulators are taking an important place for flight training since the reality level is improving and it is very near to real platforms. Especially Full Flight Simulators (FFS) make almost same feeling as real platforms in the meaning of motion, vibration, vision and sensation. Flight simulators are cost effective flight training alternative and cost effectiveness of flight simulators were proven with several researches. But they have very high prices near to the real platforms and they have also other costs after purchasing and installing them. In some cases, these costs may exceed the cost of purchase. It is very important to know life cycle cost of a simulator in order to make accurate budget planning, to make better offers for tenders, to choose the best alternative and to plan spare parts in advance.

This study intends to develop a model to estimate operating and maintenance costs of a flight simulator in order to analyse the life cycle cost of a flight simulator using appropriate analysis methods. Another purpose is to estimate the breakdowns of the subsystems and components and to understand their effects to the system. It is assessed that the results and the method helps analysing and estimation of life cycle costs and breakdowns of components, subsystems of a flight simulator.

Keywords: Flight Simulator Life Cycle Cost Analysis, Life Cycle Cost, Cost Estimation, Flight Simulator

ÖZ

BİR UÇUŞ SİMÜLATÖRÜ İÇİN İŞLETME VE İDAME MALİYETLERİ TAHMİN MODELİNİN SİSTEM DİNAMİKLERİ YAKLAŞIMI İLE GELİŞTİRİLMESİ

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Kasım 2019, 104 sayfa

Teknolojinin gelişmesi ile birlikte, Uçuş Simülatörlerinin gerçeklik seviyesinin artması, Uçuş Simülatörlerini uçuş eğitimlerinin önemli bir parçası haline getirmektedir. Özellikle Tam Görev Simülatörleri (TGS) gerçek platformlarla hareket, titreşim, görsel ve hissiyat anlamında yakın seviyededir. Uçuş simülatörleri maliyet-etkin eğitim araçlarıdır, maliyet-etkin bir alternatif oldukları çeşitli araştırmalarla kanıtlanmıştır. Ancak gerçek platforma yakın seviyede, yüksek satınalma maliyetlerinin yanısıra satınalma ve kurulumdan sonra oluşan başka maliyetleri de bulunmaktadır. Bu maliyetler bazı durumlarda satınalma maliyetinin üzerine çıkabilmektedir. Daha doğru bir bütçe planlaması yapabilmek, ihalelerde daha iyi fiyat teklifi verebilmek, alternatifler arasında doğru seçim yapabilmek, yedek parça planlamasını daha iyi yapabilmek için ömür devri boyunca ortaya çıkaracağı maliyetleri önceden bilmek veya tahmin edebilmek son derece önemlidir.

Bu çalışmanın amacı, uygun analiz metodlarını kullanarak uçuş simülatörünün ömür devri maliyet analizini yapabilmek amacıyla işletme idame maliyetlerini tahmin etmeye yarayan bir model geliştirmektir. Bir başka amacı da bileşenlerin, alt sistemlerin sisteme olan etkilerini anlamak ve sistemin tamamı olan simülatörlerin arızalarını önceden tahmin edebilmektir.

Anahtar Kelimeler: Uçuş Simülatörü Ömür Devri Maliyet Analizi, Ömür Devri Maliyeti, İşletme İdame Maliyet Tahmin Modeli, Arıza Tahminleme, Uçuş Simülatörü

CHAPTER ONE

1. INTRODUCTION

Simulation can be defined as imitation of a situation or process. It helps to solve problem of real-world safely and cost effectively. In most cases, the production of a computer model of something is needed to imitate the real-world process. It has a wide range of uses. One of these purposes is flight simulation.

The flight simulation is used for training pilots or technicians in a safe and cost effective way. It can be also used for design and development of the real platforms. A Flight simulator reproduce the aircraft / helicopters behaviours on the ground. It allows to train aviators in different kinds of weather conditions and in different kinds of emergency situations which are dangerous or impossible to train with real aircrafts. It has a very critical role for training civilian and military pilots. The training in real aircrafts in the past are now being performed on flight simulators. The reality level of simulators improved and simulators present a very similar degree of flying experience to the real world due to development of computer based technology.The training with flight simulators of course have cost advantages compared to real aircrafts. Fuel consumption, real aircraft component costs and maintenance costs, and accidental risks are eliminated with flight simulators. Although flight simulators have several advantages especially in terms of cost and safety, they have also some costs. One cannot simply look at the purchase cost of the flight simulator.

In this thesis, Lifecycle Costs especially Operating and Maintenance Costs of a Flight Simulator is analysed. All cost items of a turn-key purchased simulator which are expected to be realized during its life cycle will be identified. The user of the flight simulator, the manufacturer or operating companies (such as training centers, maintenance companies) should know that the total cost of flight simulator is not only purchasing cost. Variable costs such as corrective maintenance costs and the fixed costs such as the preventive maintenance costs, personnel costs, facility maintenance cost are also included to calculate the total lifecycle costs of a flight simulator.

It is expected that the results of the study helps budget planners and producers determining the lifecycle costs of a flight simulator to guide planning and tender offer preparing activities.

In the second chapter, definitions and the literature summary of the previous studies are given. In the third chapter, the materials and methods used in the study are explained. Analysis results are discussed in the fourth chapter. In the fifth and final chapter, the conclusion and recommendations are given.

CHAPTER TWO

2. LITERATURE REVIEW

2.1 Definitions and Previous Studies

2.1.1 Flight Simulator

A flight simulator is a virtual reality system in which the cockpit and instruments of an aircraft are imitated and the conditions of actual flight are simulated.

With the development of technology, various types of flight simulators have been designed and produced.

The development history of flight simulators has been started at 1900s. The aviation pioneers learned to fly by making short "hops", progressively increasing the length of the "hop" until actual flight was achieved (Turner, 1913). Training was mostly limited to advice, given on the ground. There are a few examples of early training devices, but these were designed to enable pilots to experience the effects of the controls. The Sanders Trainer (Haward, 1910) was developed in 1910, comprised a cockpit which could be turned into the prevailing wind; if the wind was sufficiently strong, the cockpit would move in response to the pilot's inputs. Similar devices were developed by Walters and Antionette (Adorian et al., 1979) in the same year, where motion of the cockpit was controlled by instructors, as shown in Figure-2.1.

Despite the rapid advances in the early years of aeronautics, the handling qualities of these aircraft were poor and many were unforgiving if flown badly. It is claimed that more lives were lost in training than in combat during the First World War (Winter, 1982)

Although the flight training syllabus had matured by the 1930s, throughout 1912-1920s period the aircraft was accepted as the natural classroom for flight training, including training for instrument with ground schools providing the theory to support flying training. (Allerton, 2009)

The 1930s were indeed the years of the Link Trainer and this device was produced in many versions and sold too many countries such as England, Japan, France, Germany and the Union of Soviet Socialist Republics (USSR). In 1937 American Airlines became the first world airline to purchase a Link Trainer (Figure 2.2) for their Pilot Training. (Page, 2000)

Figure 2.1:The Antionette Flight Training Simulator (Courtesy: The Library of Congress) (D.Allerton, 2009)

Figure 2.2: A Link Trainer (D.Allerton, 2009)

These flight simulators are the first milestones for the development of flight simulation. By using the first simulators, people understood the importance and efficiency of flight simulators for pilots instead of using real aircrafts. That's why Link Trainer has sold too many. Flight simulation technology has made incredibly progress in the last 100 years. At the beginning of 21^{st} century, flight with a simulator can give almost the same feeling as the real aircraft.

These flight simulators, which are produced with advanced technology to give the same feeling as the real aircraft, also revealed complex simulators. This complex and high-tech simulators raise important issues such as maintenance and troubleshooting in order to use them with high reliability and high performance. One of the most important issues is the maintenance of the new generation simulators produced with high technology. The fact that the simulators are ready and running for their training allows the training to be carried out without interruption.

The new generation flight simulators have complex structure and have several high-tech and expensive sub-systems and components (Figure 2.3). To meet the requirements that pilots demand and need to realize the training realistic and at highest efficiency, simulator producers use latest technologies and expensive components.

Figure 2.3: Full Flight Simulator

Because the technical complexity of Flight Simulator types, it is very important to use the correct terminology. Flight Simulator Training Devices (FSTD) was grouped by European Aviation Safety Agency (EASA) as below:

"Flight simulation training device (FSTD) means a training device which is in the case of airplanes, a full flight simulator (FFS), a flight training device (FTD), a flight navigation procedures trainer (FNPT), or a basic instrument training device (BITD). In the case of helicopters, a full flight simulator (FFS), a flight training device (FTD) or a flight navigation procedures trainer (FNPT)."

EASA defined Full Flight Simulator (FFS) as a full size replica of a specific aircraft including all equipment and computer programs necessary to represent the airplane in ground. They have a visual system providing the outside of cockpit view and a force queuing motion system. Flight Training Device (FTD) means a full size replica of real aircraft, which has instruments, panels, equipment, and software but does not require motion systems or visual system (European Aviation Safety Agency (EASA), 2018).

Operational Flight Trainer (OFT) can be defined as a full size replica of the specific aircraft which has instruments, panels, equipment and software. They always have a visual system but they have no forced queuing motion system.

2.1.2 Effectiveness of a Flight Simulator

There are lots of studies conducted on training effectiveness and cost effectiveness of flight simulator. Some of these studies were focused on comparing the real aircraft and flight simulator for training effectiveness and some of them were focused on calculating the cost of flight training, hourly training cost and comparing them with real aircraft. Some of these studies are given below.

Orlansky and String (1977) has studied on Cost Effectiveness of Flight Simulators for Military Training. According to their study, it is concerned particularly with a review of the methods and data needed to predict the costs of flight training in simulators and in aircraft. They designed forms (Table 2.1) to calculate the costs of flight simulators and aircraft. The reporting results have been used to fill these forms for the purpose of making calculations. Annual flight time, number of staff trained, available seat number etc. are used to calculate the cost of hourly training cost. However they formulated all the inputs for calculating the cost, they also mentioned difficulty of data collection. It is also emphasized that the data set may not be accurate due to errors that may occur during recording, reporting and calculating the data. They mentioned the cost elements for procuring and operating simulators.

Table 2.1: Representative Cost Elements (Orlansky & String, Cost of Effectiveness of Flight Simulators for Military Training - Volume II Estimating Costs of Training in Simulators and Aircraft, 1977)

Academic Training	Notes
Operations	
• Pay & Allowances	
○ Instructors	1
○ instructional Support Personnel	2
• Training Device Maintenance	2
• Training Materials	2
Investment	
• Training Device Procurement	2
Flying Training Operations	
• Instructor Pay & Allowances	1
• Munitions Expended	
• Variable Aircraft Flying Costs	
○ Base Maintenance Labor	
○ Base Maintenance Materials	3
○ Depot Maintenance & Modification	
Investment	
• Aircraft Attrition & Procurement	4
Student Pay & Allowances	
Training Support	
Operations	
• Pay & Allowances	
○ Unit Command/Admin./Operations	5
○ Base Oper./Medical Support Pers.	6
Facilities Maintenance Material	
Investment	
• Training Program Development	

Notes:

1. Where instructor personnel engage in more than one typing of training (academic and flight) a basis for allocation, e.g., time spent between them, is required.
2. All instructional support personnel and training devices (other than aircraft) are assumed to be associated only with school-house training.

3. Consist of aircraft replenishment spares, other aircraft maintenance materials and POL. Costs of these requirements are considered wholly a function of flying hours.
4. Applicable only to new (yet to be procured) aircraft. Either, but not both, procurement or attrition would be applicable.
5. To the extent that a portion of unit command / operations personnel is identifiable with training.
6. BOS support required for incremental personnel associated with the training function (including students).

Operating costs of a simulator are comprised into two parts. The first, variable operating costs such as utilities, maintenance materials etc. which varies directly with the simulator operating hours. The second is the fixed costs which does not change with operating hours of simulator, such as staff salaries and preventive maintenance. Simulator training cost consist of variable costs and fixed costs. Operating costs and utilization data for one or two year has been collected from related department. The man-year information, utilization, materials and utilities costs have been recorded according to models of simulators by Management Analysis Department of Training Center. By using this data simulator utilization, variable and fixed costs, simulator training cost can be determined after utilization for some time (Orlansky & String, Cost of Effectiveness of Flight Simulators for Military Training - Volume II Estimating Costs of Training in Simulators and Aircraft, 1977).

Mayer (1981) has compared the aircraft costs and flight simulator costs regarding the flight training. The cost data has been collected from 2 different airlines companies. Total cost to realize the training on real aircraft has been shown in Table 2.2 and total cost for same type of flight simulator has been compared with aircraft training costs. In this study, it is highlighted that cost of training with flight simulators are about %9, 9 of training with real aircraft. The cost data were supplied from present information of costs recorded and calculated costs per hour by airline companies.

In this study different types of comparisons about costs and effectiveness between flight simulators and aircraft have been made with using the data collected from airlines (Table 2.2). Effectiveness and cost advantage of flight simulators have been indicated as conclusion of the study.

Table 2.2: Cost Comparison of Aircraft Training Versus Simulator Training Versus Simulator Training (Source Delta Airlines) (Mayer, 1981)

Cost Per Hour for Aircraft	DC-9	DC-8	B-727	L-1011
Fuel, Oil, and Taxes	$ 987	$2050	$1603	$2547
Direct Maintenance	130	205	110	385
Maintenance Burden	81	143	64	193
Total Aircraft Cost	$1198	$2398	$1777	$3125
Simulator Cost Per Hour				
Maintenance	$ 85	$ 85	$ 85	$ 85
Net Aircraft Cost	$1113	$2313	$1692	$3040

The average procurement cost of new simulators including major improvements to simulators acquired previously, fuel and other supplies required to operate aircraft, and cost of simulators has been analyzed. 42 pairs of simulators and aircrafts have been compared for fiscal years 1980 and 1981 (Figure 2.4).

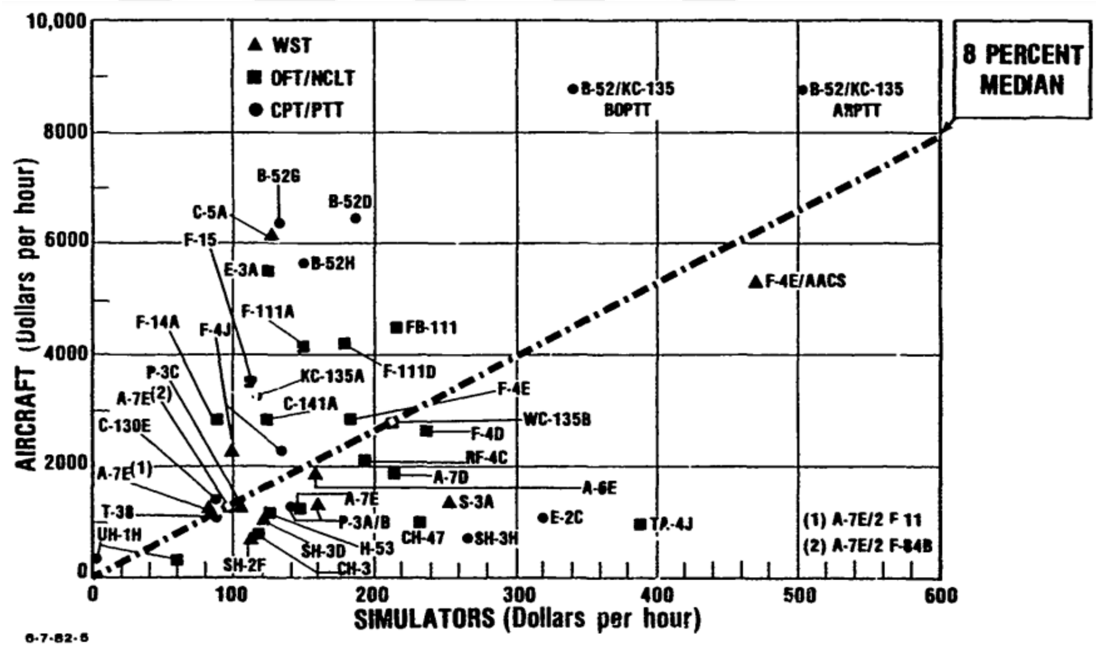

Figure 2.4: Full Flight Simulator Variable Operating Costs Per Hour for 42 Flight Simulators and Aircraft FY 1980 and 1981. (Orlansky, String, & Chatelier, The Cost Effectiveness of Military Training , 1982)

Variable operating costs are for fuel, oil, spare parts consumed as a function of use, the costs of pay and amortization are not included in these amounts. They found the median ratio of operating costs for simulator/aircraft is 0, 08 however it was 0, 12 in fiscal years 1975-1976

For example, F-4E type aircraft has a cost of approximately 2800 Dollars per hour and same type simulator has a cost of approximately 180 Dollars per hour. For F4-E type, simulator's operating cost ratio compared to the real aircraft is 0,064.

Based on the study of String and Orlansky (1977) they studied to analyze the effectiveness of training and they asked three key questions:

- Do Simulator really train the pilots?
- Do the skills learned in flight simulators transfer readily to aircraft?
- Are flight simulators worth what they cost?

To find the answers of these 3 important questions, they analyzed statistical data. It is also important to analyze effectiveness of training with flight simulators comparing with real aircraft. They made variable studies to measure the effectiveness of training with flight simulators. As a result of this study they prepared a summary of findings table. In this table Flight Simulators, Computer-Based Instruction, Maintenance simulators were compared with real aircrafts.

According to the results of this study, the effectiveness of simulator training and real platform training are about the same. The acquisition cost of a flight simulator is about 30% - 65%, operating cost is about 10%, life cycle cost is about 65% of an aircraft and its amortization period is about 2 years (Figure 2.5)

Orlansky, Knapp and String (1984) used Transfer Effectiveness Ratio to compare operating a Simulator and flying a military aircraft. They found that the cost to operate a simulator was about %10 percent of operating a military aircraft. The cost and effectiveness has been analyzed to help selection between alternative training solutions. The effectiveness of the training method and its investment cost has been discussed in their study.

EFFECTIVENESS	FACTOR	SAVINGS OR COST		
		FLIGHT SIMULATORS	COMPUTER-BASED INSTRUCTION	MAIN-TENANCE SIMULATORS
ABOUT THE SAME	STUDENT TIME	50% OF SIMULATOR TIME	30%	20-50%
	ACQUISITION COST	30-65%	?	20-60%
	OPERATING COST	10%	?	50%
	LIFE-CYCLE COST	65%	?	40%
	AMORTIZA-TION	2 YEARS	?	4 YEARS

Figure 2.5: Effectiveness of Flight Simulator Comparing to Real Aircraft (Orlansky, String, & Chatelier, The Cost Effectiveness of Military Training , 1982)

Lee (2005) has stated that between fiscal years 1993 and 1996, 42% decrease in Federal Aviation Administration (FAA) overall budget has reduced the training budget and FAA had to take action to realize technical training program more efficient. FAA has realized they have to limit the expensive real platform flight and technical trainings and organize computer based and simulator trainings. It is indicated that the high cost of flight simulators still remains a major obstacle to their widespread use in aviation. Not only the purchase cost, but also cost of maintenance, facility and necessary upgrades significant financial burden for organizations. Pilot training is indirect cost for companies or organizations to complete a mission so it is always subject to cost cutting efforts. Training simulators justify their costs with reducing the training time on operational aircraft. On the other hand, they reduce the rate of accidents and incidents to improve operational efficiency. The benefits of flight simulators are far outweigh the costs of purchasing and operating them and operational aircrafts are more expensive to purchase and operate.

For example, at 2005, a Full Flight Simulator costs approximately 10% of an operational aircraft but the price of a Full Flight Simulator may be more than 10 Million Dollars. For small airline companies and organizations it is hard to purchase a flight simulator because of its high prices, operating costs and difficulty to reach simulation technology in order to operate and maintain them. For example, the general aviation Flight Training Device (FTD) is typically about one-half the cost of the aircraft it replaces. The operating costs of smaller propeller-driven aircraft are also much less than large, turbo-jet aircraft, so defraying these costs with ground-based simulator training is less important. With the development of technology, the costs of purchasing FFSs and FTDs have reduced. (Lee, 2005)

2.1.3 Life Cycle Cost Analysis

The process starting with the conceptual (idea) development of the systems and until the system is removed from the inventory is defined as the life cycle of the system (Özkil, 2002). Although there is no unity in terms of application and terminology regarding the life cycle structure of the systems, life cycle generally consists of the following stages (Clevand & King, 1975):

- Concept development stage
    - Identification of existing needs or skills shortages
    - Defining the concept of "system" as a strategic guide
    - Technical, economic and environmental feasibility investigation for at initial level of system
    - Examination of alternative ways to achieve the purpose of the system
    - Seeking answers for the following questions. What is the cost of system? When will the system be ready? How to adapt to existing systems?
    - Identification of personnel and other needs needed for system support
    - Selection of initial designs to provide system objectives
    - Determining the organization of the system
- Project identification phase
    - Precise determination of human and other resources
    - Determination of final system performance characteristics
    - Detailed planning of the resources needed to support the system
    - Determination of realistic cost time and performance values

- Determination of risk and uncertainty areas
    - Identification of in-system and inter-system compatibility
    - Identification of needed support systems
    - Initial preparation of documents needed to support the system
- Production and marketing stage
    - Updating the detailed plans prepared in previous stages
    - Supplying spare parts stocks, raw materials, labor, financing
    - Allocation and management of resources required by production processes
    - Testing the production properties of the system
    - Start of production, construction and settlement
    - Preparation and publication of final documents on policies and processes
    - Performing the final tests to see that the system features are met
    - Preparation of plans for the support that will be needed during use
- Operational - maintenance phase
    - Activation of system by users
    - Consuming / using the outputs of the system
    - Assessment of technical, social and economic satisfaction to ensure real operating conditions
    - Provide feedback for other projects and planners under development
    - Maintenance of the system at necessary intervals
    - Evaluation of the validity of support systems
- Liquidation phase of the system
    - Completion of the technical and economic life of the system
    - Planning for the transfer of responsibilities to supporting organizations
    - Allocating resources to other systems
    - Creation of a database of lessons learned
    - Determining how the system is removed from the inventory
    - Determination of the scrap valuation method for the system

Elmakis & Lisnianski (2006) defined Life Cycle phases as Desing & Development, Production, Operation & Support and Disposal phases. Trends of Life Cycle Cost items over time is shown in Figure 2.6.

According to this graph, Design & Development costs start at the beginning of design phase and it continue until the middle of Operation & Support phase since Design & Development works continue with production and Operation & Support phase for a certain time. Production costs starts with maturation of design of product and it continue until the middle of Operation & Support phase since the development & design works of the product continue. Design of the product may be updated throughout the Production and Operation & Support phases. Operation & Support costs start some time after the start of the production. Life Cycle ends with Disposal of the product.

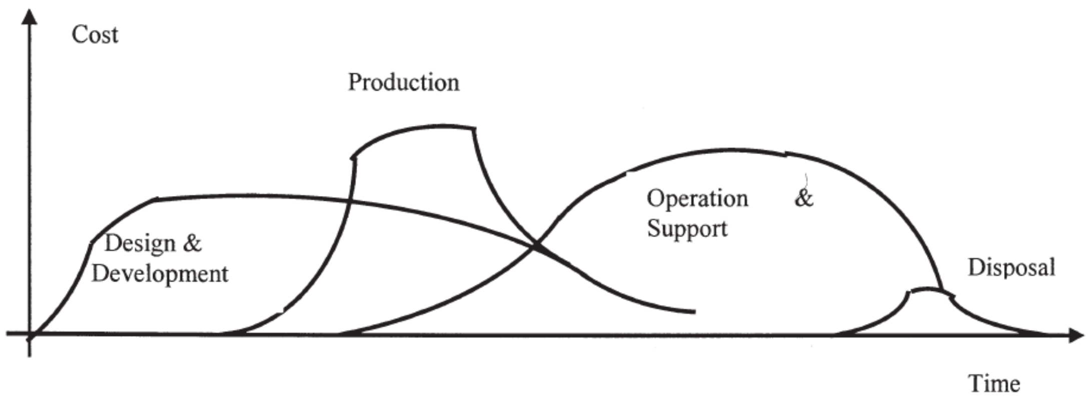

Figure 2.6: Different Types of Costs in Life Cycle (Elmakis & Lisnianski, 2006)

There are lots of work about Life Cycle Cost (LCC) Analysis in literature. There are various definitions of LCC and various calculation methods compatible with the sectors and their specifications.

Fleischer et al (2007) examined machine life cycle cost estimation via Monte-Carlo simulation. They studied deterministic and stochastic cost elements of a machine working in automotive industry. Thus they intend to suggest a method for estimation of life cycle costs and to decrease the financial risk of machine building companies due to life cycle cost of machines. They mentioned that the customers demand more extensive warranties for machines from manufacturers, therefore life cycle cost estimation should be done in order to eliminate penalties which can be reach up to %30 of machine price. The suggested methodology was consists of three stage; at the first step calculation of failure rate was done, at the second step deterministic life cycle cost elements are calculated and finally at the third step Monte-Carlo simulation to combine stochastic and deterministic life cycle cost elements were combined. Weibull data distribution is applied to estimate the failure rate of machine. Mean Time between Failures (MTBF) data and Mean Time to Repair (MTTR) data is used as inputs for Monte Carlo simulation. The life cycle cost elements related with machine reliability are stochastically modeled and the rest cost elements are assumed deterministic. For analysis of data Weibull method whose reasonable calculation starts with 10 about failure records is proposed. If no data is available, an adapted Failure Modes and Critically Analysis (FMECA) can be applied alternatively (Fleischer, Wawerla, & Niggeschmidt, 2007).

The Major Lifecycle Costs of a Flight Simulator are defined by Allerton (2009). There is a strong case that flight simulation has enabled budget airlines to grow and that, without simulation, they would not be able to operate.

The major costs of flight training include:

- The cost of purchasing flight simulator
- The cost of building the simulator facility
- The running costs of the simulator of the simulator facility (electricity, air conditioning, computer maintenance, spares provision, etc.)
- The staff costs to provide flight training and maintenance of the simulator (instructors, maintenance engineers, administrators etc.)

Allerton has investigated advantages of the flight simulation technology in his Principals of Flight Simulation book. In this study, the importance of using flight simulators and the necessity of flight simulators for flight training, maintenance training, design and developments of new parts or systems are highlighted. The cost of flight training with real aircraft is at least 10 times the cost of simulator training. Simulator training allows to manage the training operations at low cost compared to airborne training operations. Purchase price of a simulator and its sub-systems are mentioned. According to his study, visual system has been as high as %20 of overall cost of the simulator and motion system have been approximately %10 of total simulator price. With the development of technology, subsystems that have been very expensive in the past can now be purchased at a lower cost. Three factors which have improved the reliability of simulator has been indicated; much more reliable simulator sub-systems, the modular structure of simulator components which enable fast detection of faulty components and swapping it out quickly and finally monitoring of simulator systems continually and checking for variation of performance which allows preventative maintenance. In this study, the operational costs depended on the reliability and availability of simulator.

In 2013, another study was conducted by C. Best, G. Galanis, J. Kerry and R. Sottilare examining the issue of cost. According to researchers, it is important to analyse costs , benefits and effectiveness of real aviation platform and flight simulator of same model of platform in order to give decision of purchasing a real platform or simulator for training requirement. To analyse cost of simulator training they emphasized the importance of building a cost model. It is important to define the cost elements well because specifity and explicitness of the model helps cost analyzers and decision makers to understand the model themselves. Four categories in most cost models are: Research and Development, Inıtial Investment, Operations and Support and Disposal and Salvage (Mishan and Quah, 2007). The researchers defined all four categories of cost model, and Operations and Support Cost were de (Mishan & Quah, 2007)fined as costs which include costs for managing, operating, and maintaining the instruction after it has been implemented.

S.O.L.Zijp (2014) studied the Development of a Life Cycle Cost Model for Conventional and Unconventional Aircraft. Zijp mentioned in his study that in order to prove that a design is cost efficient the Life Cycle Cost (LCC) needs to be analyzed and should be done as early in the design phase as possible. The latter is due to the fact that 70% of the total Life Cycle Cost (LCC) is already fixed after the conceptual design phase. At the conceptual design phase it is difficult to give an absolute cost estimate, hence the focus of this research is to develop a model that estimates the relative cost and therefore allows for design trade-off.

2.1.4 System Dynamics

The system dynamics approach was developed in 1961 by Jay Forester at the Massachutes Institute of Technology, where he developed the programming language DYNAMO, the system dynamics, and published the book Industrial

Dynamics, which deals with the dynamic behavior of a manufacturing company. (Forester, Urban Dynamics, 1961)

Later on, he continued his researches on the subject with the "Urban Dynamics" book for the dynamics of North American cities, and the "World Dynamics" book for dynamics of modern economic systems. (Forester, World Dynamics, 1971)

DYNAMO does not have a very user-friendly interface, so it is used by a limited user. In 1980, High Performance Systems developed the first system-friendly system dynamics software called iThink. This software was developed for computers with Macintosh operating system and was later adapted by other companies to the Windows operating system. Powersim, developed by Norwegian Powersim, and Vensim, developed by Ventana, are the most frequently used software in this field. (Özkil, 2002)

Since Vensim has indexing properties, it can be used in large-scale modeling. Vensim was used in this thesis.

CHAPTER THREE

3. MATERIALS AND METHODS

3.1 Definitions

3.1.1 Life Cycle Cost

SIGMA (Support for Improvement in Governance and Management) which is a joint initiative of OECD (The Organization for Economic Co-operation and Development) and the European Union (EU) describes LCC as below:

“Life-cycle costing (LLC) is a methodology to evaluate all of the costs over the life cycle of works, supplies or services. LCC represent all of the costs resulting from the use of goods, services or works during their entire life span. The LCC methodology is an instrument for assessing these costs over time.”

It is also underlined that not only the procurement cost but also further costs such as operational and maintenance costs are important to select the truly “least expensive” alternative while procurement process.

There are lots of benefits of using a LCC methodology such as;

- Saving money, optimization of future costs, ensuring better forecast of total cost
- Acquisition of better products,
- Support sustainable development. (SIGMA, 2006)

Life cycle costs include the design, development, production, operation, maintenance, support, and final disposition costs of a product / system over its anticipated useful lifetime. (Department of Energy (DOE), 1995)

Life Cycle Cost is defined as summation of cost estimates from inception to disposal, determined by analytical study and which is estimation of total costs during their life. LCC analysis helps product/process selection with using total cost instead of initial purchase price. Life Cycle Cost is summation of Acquisition Costs and Sustaining Costs as shown in Figure 3.1. Acquisition Costs consist of Research and Development Costs, Non-Recurring Investment Costs and Recurring Investment Costs. All cost items related with Acquisition Costs is given in Figure 3.2 (Barringer, 1996)

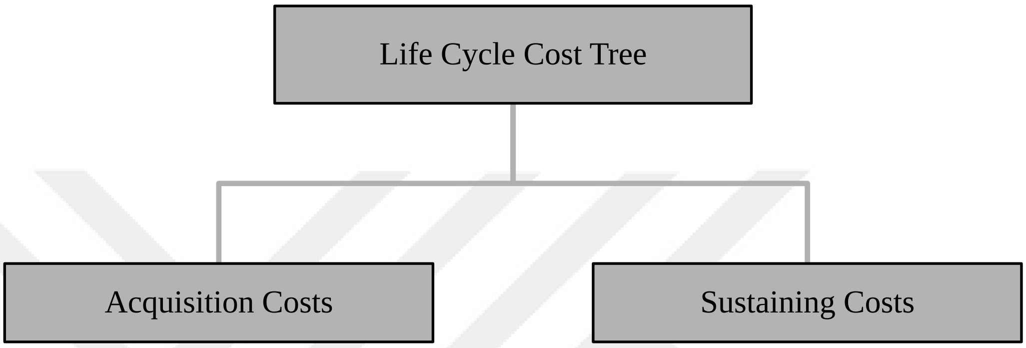

Figure 3.1: Top Levels of LCC Tree (Barringer, 1996)

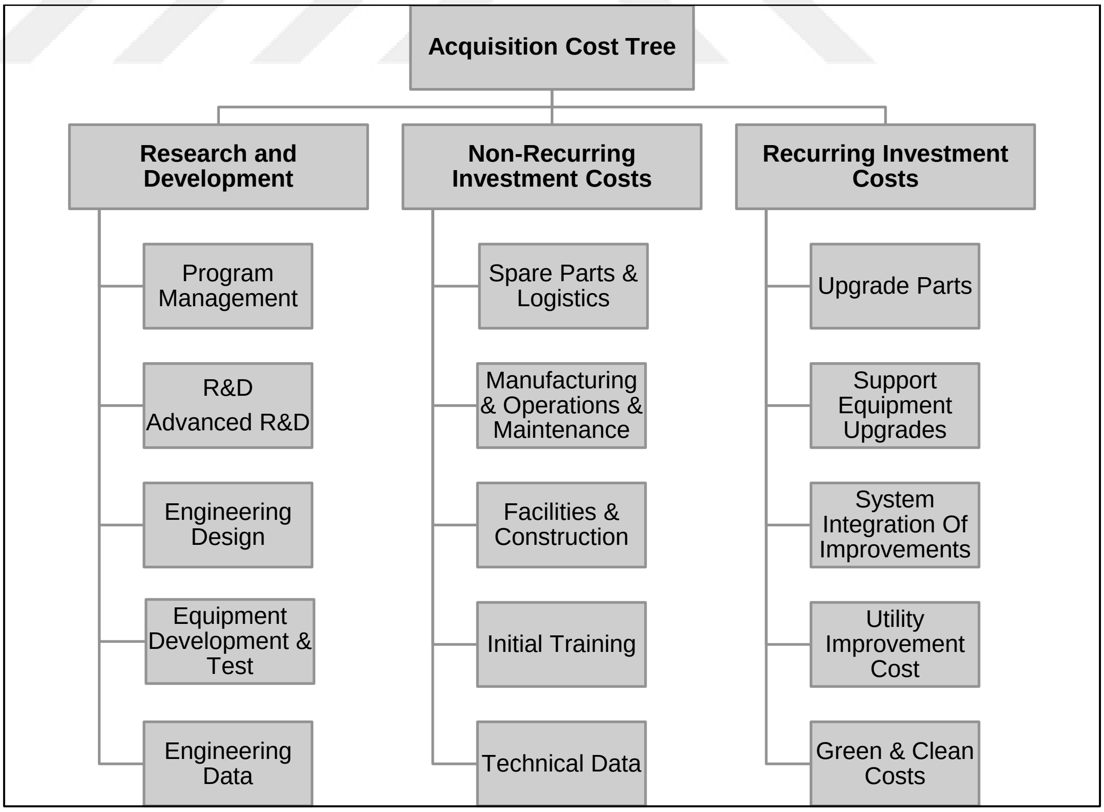

Figure 3.2: Acquisition Cost Tree (Barringer, 1996)

Sustaining Costs include Scheduled and Unscheduled Maintenance Costs, Facility Usage Costs and Disposal Costs. Labor, Materials and Overhead, Replacement or Renewal Costs, Transportation and Technical Documentation are some items of Maintenance Costs. Facility Usage Costs consist of Energy and Facility Usage Costs, Support and Supply Costs, Operations Costs etc. Disposal Costs include cost items as obligatory official permissions, correspondence, and documentation and physical disposal process. All cost items related with sustainment are given in Figure 3.3 (Barringer, 1996).

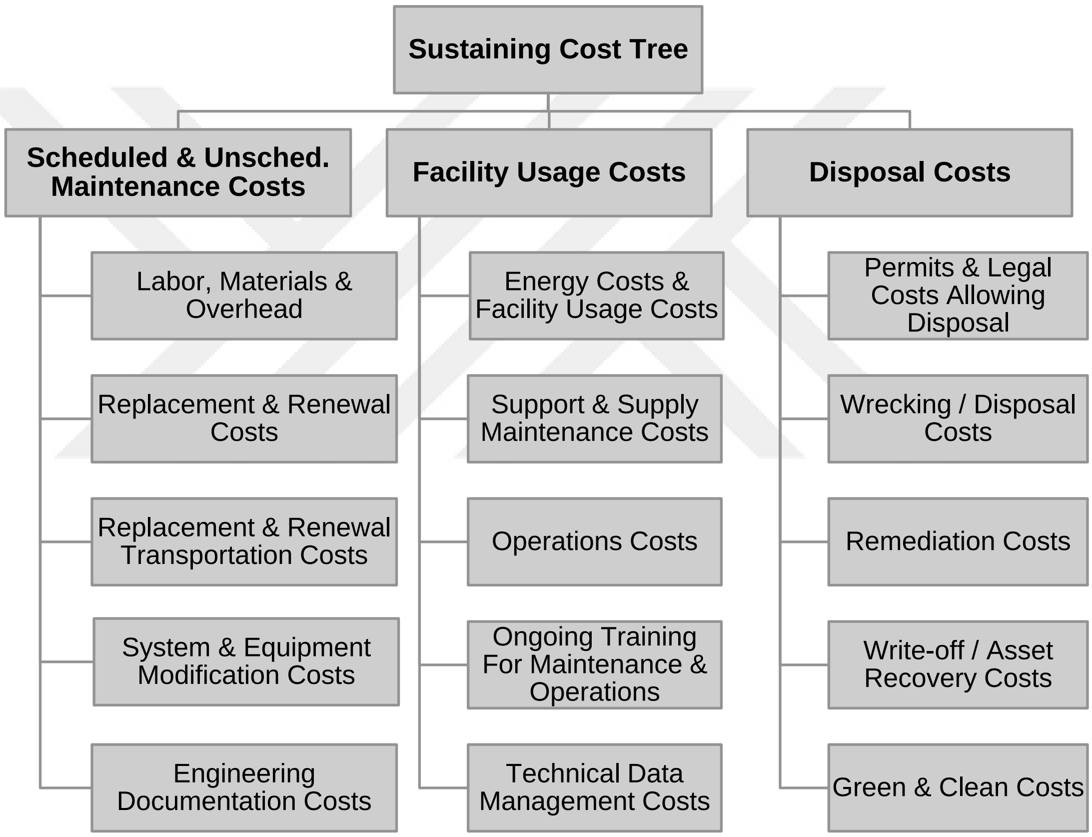

Figure 3.3: Sustaining Cost Tree (Barringer, 1996)

Life Cycle Cost of a system or product is defined as total cost of procurement (acquiring) and ownership. LCC includes all costs starting from the purchasing decision and continues until the disposal of the system (product). Total LCC is simply expressed as below (Elmakis & Lisnianski, 2006):

$$LCC = AC + SUC$$

Where;

AC: Acquisition Cost

SUC: System Utilization Cost

LCC Methodology is divided into two categories (Conventional and Environmental) by SIGMA. According to conventional LCC methodology, following "internal" cost categories can be evaluated in LCC (SIGMA, 2006);

- Investment Costs (purchase price, installation, commissioning, initial training of users)
- Operating Costs (Consumption of energy, consumables and other resources to use the system/product)
- Maintenance Costs (Service charges, spare parts)
- End of Life Costs (Decommissioning, disposal)

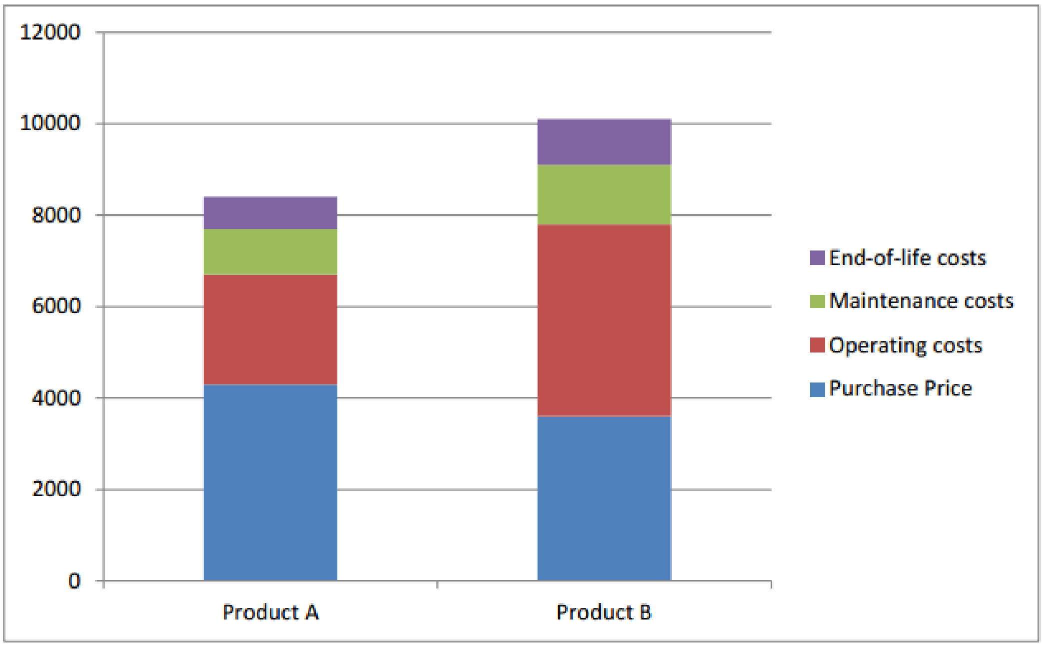

Figure 3.4: Illustration of Importance of Life Cycle Cost Analysis by Evaluation of Two Alternative Products (SIGMA, 2006)

According to the Figure 3.4, when only purchase prices are taken into account, Product B is least expensive however LCC approach shows product A is the least expensive product from a long-term perspective.

Environmental approach of LCC also takes into account also external environmental costs (environmental impacts which may negatively affect the human health, availability of resources, soil erosion etc.) An exhaustive LCC methodology should consist of all costs during lifespan of product / system as shown in Figure 3.5.

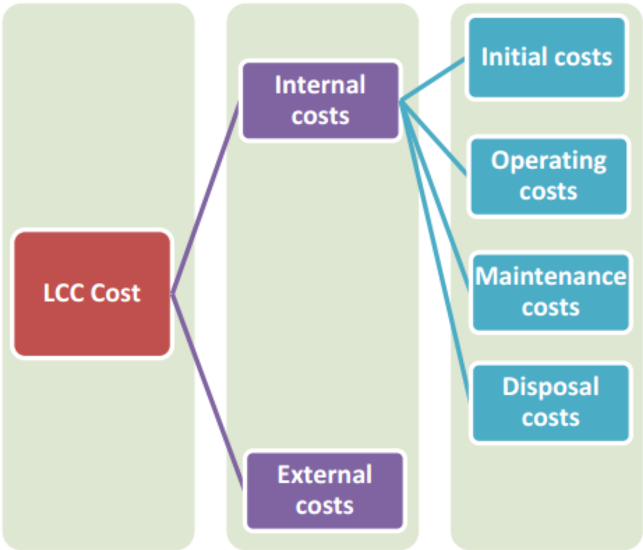

Figure 3.5: Life Cycle Cost Items (SIGMA, 2006)

3.1.2 An Overview of Life Cycle Cost Analysis Approaches

Life Cycle Cost Estimation is calculation of all cost items before they occur. There are various Cost Estimation technics. They can be categorized in three main group (Özkil, 2002);

i. Analogical techniques
ii. Parametric technique
iii. Engineering techniques

Another categorization was made by Niazi, Dai, Balabani, & Seneviratne (2006). The cost analysis techniques are shown as in Figure 3.6.

Qualitative techniques compare the existing product and new product. It is divided into two main groups; Intuitive and Analogical Techniques. Quantitative Techniques are based on a detailed analysis of product, specifications and manufacturing process. It is divided into two main groups; Parametric and Detailed Techniques.

Intuitive techniques are based on the previous experiences. The primary input of the analysis is expert opinions. It consist of two main groups; Case-Based and Decision Support Techniques. Case-Based or Case-Based Reasoning (CBR) uses existing products and it compare differences between existing product and new products. Changes are being applied and difference between two products are examined. Thus analysis can be done fast.

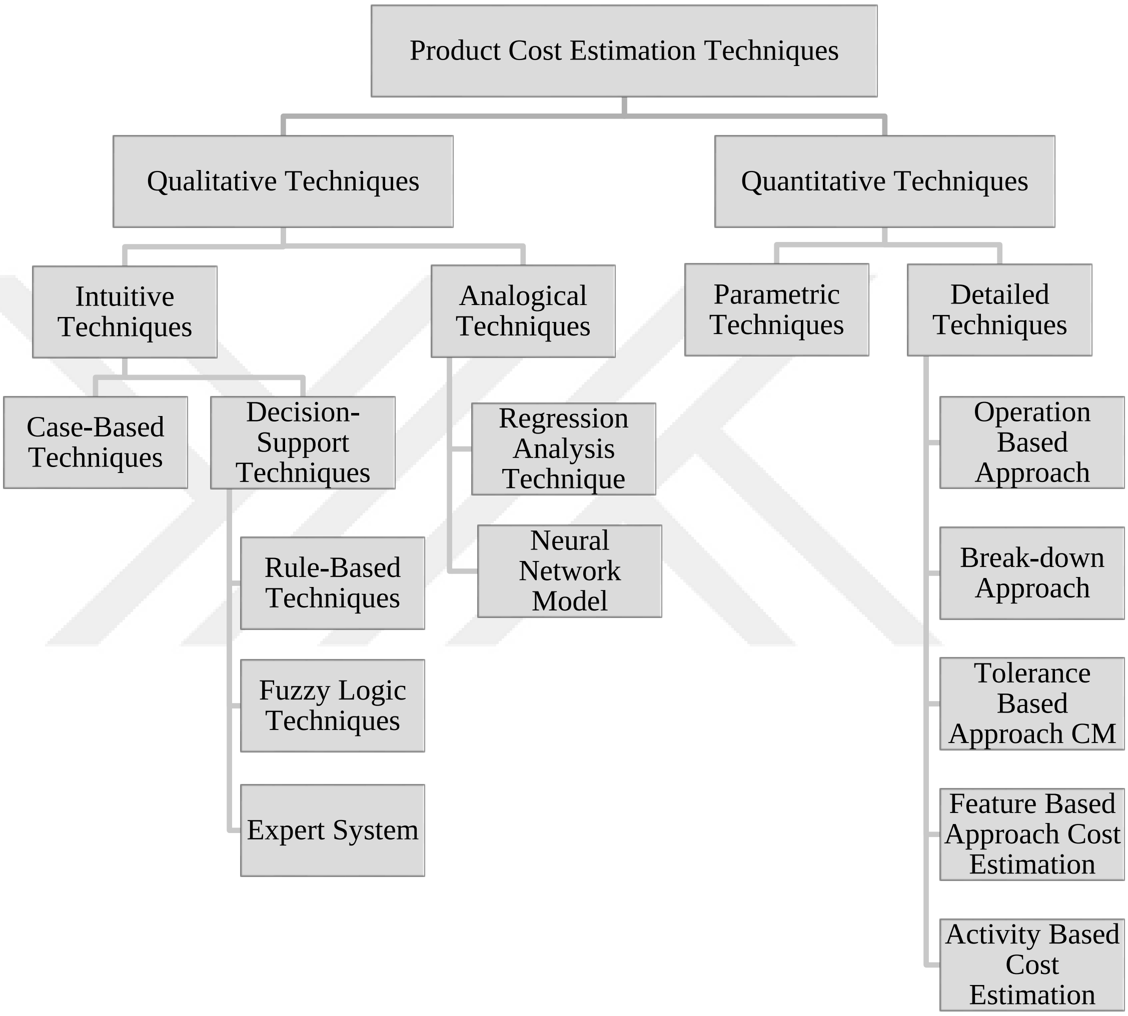

Figure 3.6: Product Cost Estimation Techniques (Niazi, Dai, Balabani, & Seneviratne, 2006)

Decision Support System is not used for only cost estimation, it has a wide usage range such as comparing two design. It is necessary to store the expert knowledge within the model for next decisions.

The second main type of qualitative techniques; Analogical Techniques uses previous cost estimations for past projects. This type of technique is not bases on human knowledge, it is based on the previous cost data. This type of cost estimation technique is a little bit quantitative.

Quantitative Techniques can be listed as Parametric (Top-Down) Approach which uses parameters such as weight, performance etc. and Analytical (Bottom-Up) Approach which uses labor time, rates (combined with material quantities), prices etc. to estimate the cost of product/activity.

In this study, Analogical and Engineering Techniques will be both used to make a total cost estimation. Cost Breakdown Structure (CBS) and Bill of Material (BOM) structure will be detailed with using top-down method. Operating cost will be calculated with using Analogical Technique and Maintenance Costs will be estimated with using Engineering Technique (Figure 3.7).

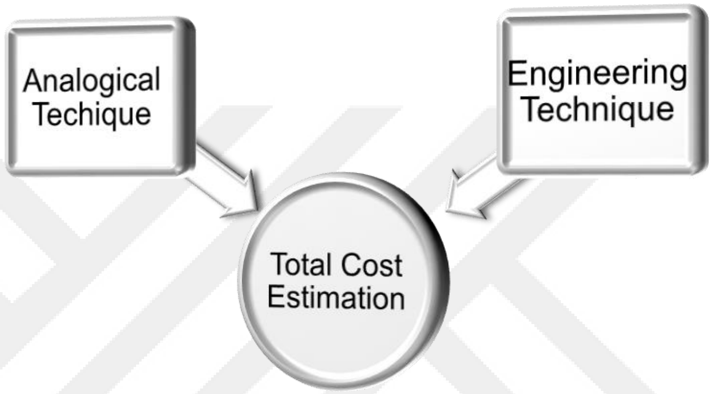

Figure 3.7: Operating and Maint. Cost Estimation Techniques Used in This Study

3.1.3 Life Cycle Cost Estimation

All costs incurred during the life cycle of products are called Life Cycle Cost (LCC). It always consist of Purchase and Initial Investment Costs, Preventive (periodic) Maintenance Costs, Corrective Maintenance Costs, Operating Costs. The manufacturers or users have to analyze all these costs to validate and plan the investment and budget correctly.

Life Cycle Cost Estimation aims to predict total cost of product / project during its life time. In order to do this, some detailed analysis, deterministic and/or stochastic techniques may be used. A detailed Work Breakdown Structure (WBS) for projects, a detailed Cost Breakdown Structure (CBS) is one of the most important part of Cost Analysis / Estimation studies. In this study, Operating and Maintenance Cost of a Flight Simulator will be tried to be estimated which helps Total Life Cycle Cost Estimation. Therefore a CBS will be analyzed.

3.1.4 Cost Breakdown Structure (CBS)

It is important to know all cost items related with product/project in order to make correct cost analysis. To be able to analyze Life Cycle Cost it is essential to use Work Breakdown Structure (WBS) for projects and Cost Breakdown Structure (CBS) for products.

A Cost Breakdown Structure (CBS) must be developed by the analyst in order to make an accurate life-cycle cost analysis. There is no set method to analyze cost breakdowns of different sectors but the method can be tailored according to cost structure of specific applications. However, there is no common method of variable applications, a cost breakdowns structure should contain the following basic characteristics;

- All cost elements of the system should be considered.
- The cost categories of the system should be well defined. Anyone interested in cost analysis should have understanding from the model and its categories.
- The categories and cost structure must be coded in order to allow for the analysis of some interested specific areas of the system such as system operation, energy consumption, spares, support and maintenance personnel, equipment and facility maintenance. (Blanchard, Verma, & Peterson, 1995)

All cost items should be well described to create the correct cost model and make the analysis correctly.

3.1.5 Cost Models

Life Cycle Cost (LCC) Models have been classified under various categories over the years. Life cycle cost models have been classified under three categories: conceptual models, analytical models, and heuristic models by Y.P.Gupta (Gupta & Skwirzyski, 1983) and (Sherif & Kolarik, 1981)

Life Cycle Cost models have been classified under two category as General Life Cycle Cost Models which have six different types and Specific Life Cycle Cost Models which have five different types (Dhillon, Life Cycle Costing for Engineers, 2009).

According to Dhillon, B.S, one of Life Cycle Cost Model (General Life Cycle Cost Model I) LCC can be expressed as follows:

$$LCC = RC + NRC$$

Where;

RC: Recurring Costs

NRC: Non Recurring Costs

$$RC = OC + IC + SC + MC + MTC$$

Where:

OC: Operating Cost

IC: Inventory Cost

SC: Support Cost

MC: Manpower Cost

MTC: Maintenance Cost

$$NRC = CP + CI + CQ + CR + CT + CRM + CS$$

Where;

CP: Procurement cost.

CI: Installation cost

CQ: Qualification approval cost

CR: Research and development cost

CT: Training cost

CRM: Reliability and maintainability improvement cost

CS: Support cost

A specific Life Cycle Cost Model has been expressed by Dhillon (1989). This model is concerned with estimating the life cycle cost of an early warning radar system. The expression of LCC Model of radar is expressed by;

$$LCC_r = C_p + C_o + C_s$$

Where;

C_p: Radar procurement cost

C_o: Radar operation cost

C_s : Radar logistic support cost

The radar procurement cost, Cp, is expressed by;

$$C_p = FC + ICC + DC + DOC$$

Where;

FC: Fabrication cost

ICC: Installation and Check-Out cost

DC: Design cost

DOC : Document cost

The radar operation cost, Co, is defined by;

$$C_o = C_1 + C_2 + C_3$$

Where;

C1: Fuel cost

C2: Cost of Personnel

C3: Cost of Power

The radar logistic support cost, Cs, is expressed by;

$$C_s = CRL + CRM + CIS + CRS + CIT + AC$$

Where;

CRL: Cost of repair labor.

CRM: Cost of repair material.

CIS: Cost of initial spares.

CRS: Cost of replacement spares.

CIT: Cost of initial training.

AC: Age cost.

Society of Automotive Engineers (SAE) also has a LCC model directed toward a manufacturing environment. The SAE model breaks down the costs as shown in Figure 3.8.

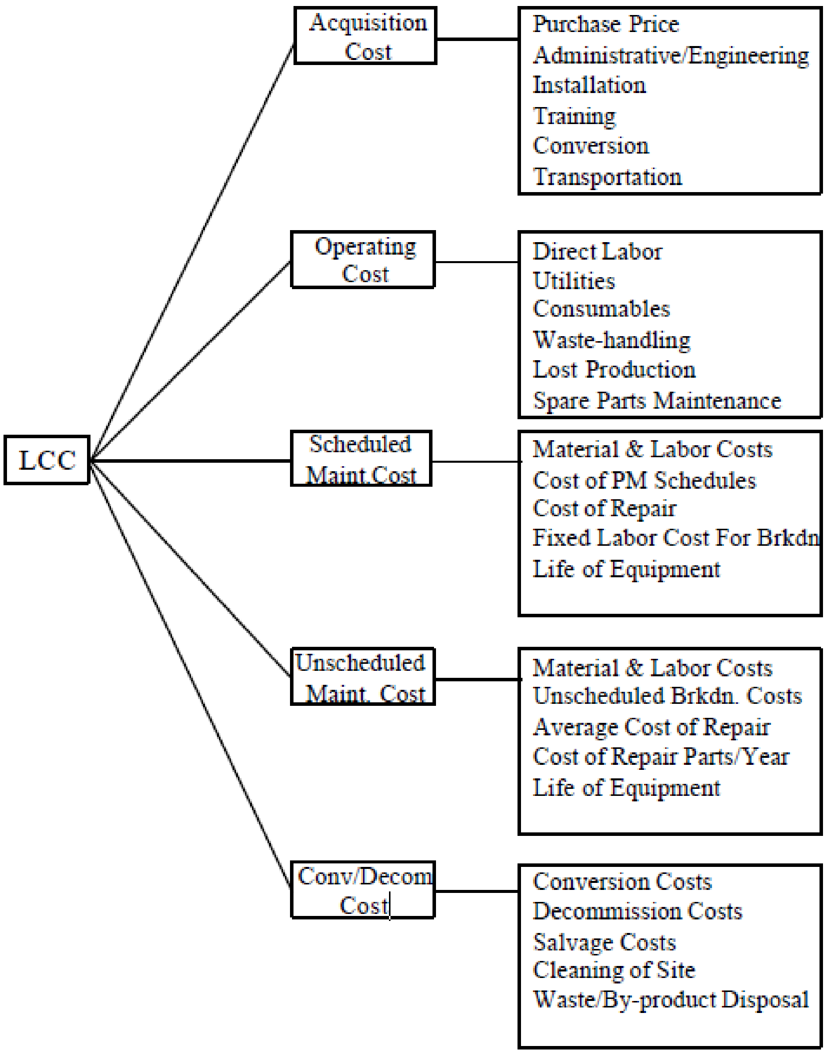

Figure 3.8: Life Cycle Cost Toward a Manufacturing Environment (SAE, 1993)

$$LCC = AC + OC + SMC + UMC + CDC$$

Where:

AC: Acquisition costs

OC: Operating costs

SMC: Scheduled maintenance costs

UMC: Unscheduled maintenance costs

CDC: Conversion/decommission costs.

Total System Cost (C) includes all future costs associated with the acquisition, utilization and subsequent disposal of system/equipment.

$$C = (C_R + C_I + C_O)$$

where;

$C_{R:}$ R and D Cost

C_I: Investment Cost

$C_{O:}$ Operations and Management Cost

Research and Development Cost (C_R) includes non-recurring all costs such as feasibility studies, basic and advanced research and development studies, engineering and design works, prototype modelling for hardware and related documentation, program management.

$$C_R = (C_{RM} + C_{RR} + C_{RE} + C_{RT} + C_{RD})$$

where;

C_{RM} : Program Management Cost

C_{RR} : Advanced R&D Cost

C_{RE} : Engineering Design Cost

C_{RT} : Equipment Development/Test Cost

C_{RD} : Engineering Data Cost

Investment Cost (C_I) includes all costs related with purchasing (acquisition) of the system/equipment. In this category, design and development costs are not included because they has been completed). It covers manufacturing, manufacturing management, system construction, and initial logistics support.

$$C_I = (C_{IM} + C_{IC} + C_{II})$$

where;

C_{IM} : System/equipment manufacturing cost

C_{IC} : System construction cost

C_{II} : Cost of initial logistic support cost

Operations and Management Cost (CO) includes all costs related with the operations and maintenance of the system in its life cycle. It covers system operations, maintenance, sustainment, modifications and disposal of the system (Blanchard, Verma, & Peterson, 1995).

$$C_O = C_{OO} + C_{OM} + C_{ON} + C_{OP}$$

where;

C_{OO} : Cost of system/equipment life-cycle operations

C_{OM} : Cost of system/equipment life-cycle maintenance

C_{ON} : Cost of system/equipment life-cycle modifications

C_{OP} : Cost of system/equipment life-cycle phase out and disposal

3.2 Introduction of the Flight Simulator (OFT)

There are various types of flight simulators. Since they are very expensive systems, manufacturers design and produce flight simulators according to the requirements of customers. Flight simulators have subsystems and these subsystems are composed of several components.

Robert F.Hodson (Hodson, 1985) divided the heart of Flight Simulation System into three main subsystems; Cockpit, Motion System and Visual system. Rehmann (1995) has divided flight simulators into ten subsystems; Cockpit, Audio, Motion, Control System, Math.Model, Environment, Ground Handling, Mission Equipment, System Latency and Visual. Type of flight simulator and number of subsystems may vary according to model of simulator.

In this study, Total Operating and Maintenance Costs of an Operational Flight Trainer (OFT) of a T-38 type aircraft flight simulator was investigated. As mentioned above, Operational Flight Trainer is a full replica of an aircraft and it has a visual system and it has no motion system. Typically, an OFT is divided into five main subsystems; Flight System, Mission System, Instructor Console, Visual System and Simulator Support System.

The OFT has been used by the customer in Turkey since 2013. The customer has purchased the system as a turn-key solution. After purchasing the OFT, operating and maintenance should be done by expert personnel of manufacturer or any other company. If the contract includes maintenance and operating costs for a certain period of time, it can be carried out by the manufacturer. Some customers may wish to select a company by tender after receiving the product or after the contractual maintenance and operation period has expired. In both cases, accurate estimation of Life Cycle Cost (maintenance costs, operating costs, etc.) is vital for the customer and Manufacturer / Maintenance Company in order to make an accurate budget planning, tender offer preparation and spare parts management.

In this study, Total Operating and Maintenance Costs of a flight simulator will attempted to be estimated. In order to estimate the total cost, Life Cycle Cost concept will be discussed. A methodology for the analysis of the problem will be described. By applying the necessary steps the Total Operating and Maintenance Cost of a flight simulator will attempted to be estimated.

Cost Breakdown Structure of flight simulator will be analyzed, a Cost Model will be defined and cost estimation technics will be used to be able to make analysis correctly. In order to estimate these costs, deterministic and stochastic methods will be used by using Random Poisson distributions due to lack of data for some components (subsystems). A simulation model will be used to calculate all fix and variable costs (preventive maintenance cost, cost of corrective maintenance, operating costs etc.) at earlier phases (design, purchasing or installation) of the project. This will allow us to estimate "Total Life Cycle Cost" of the flight simulator and we may be able to use these results for budget planning, feasibility works, determining the offer for tenders, spares and consumables management in the meaning of acquirement and stock.

3.2.1 Product Tree Analysis of OFT

Another very important point is to make an accurate Product Tree analysis. Since each component has its own characteristics and MTBF value, failure rate distributions should be designed for each one separately. Some third level part of OFT tree is shown in Figure 3.9.

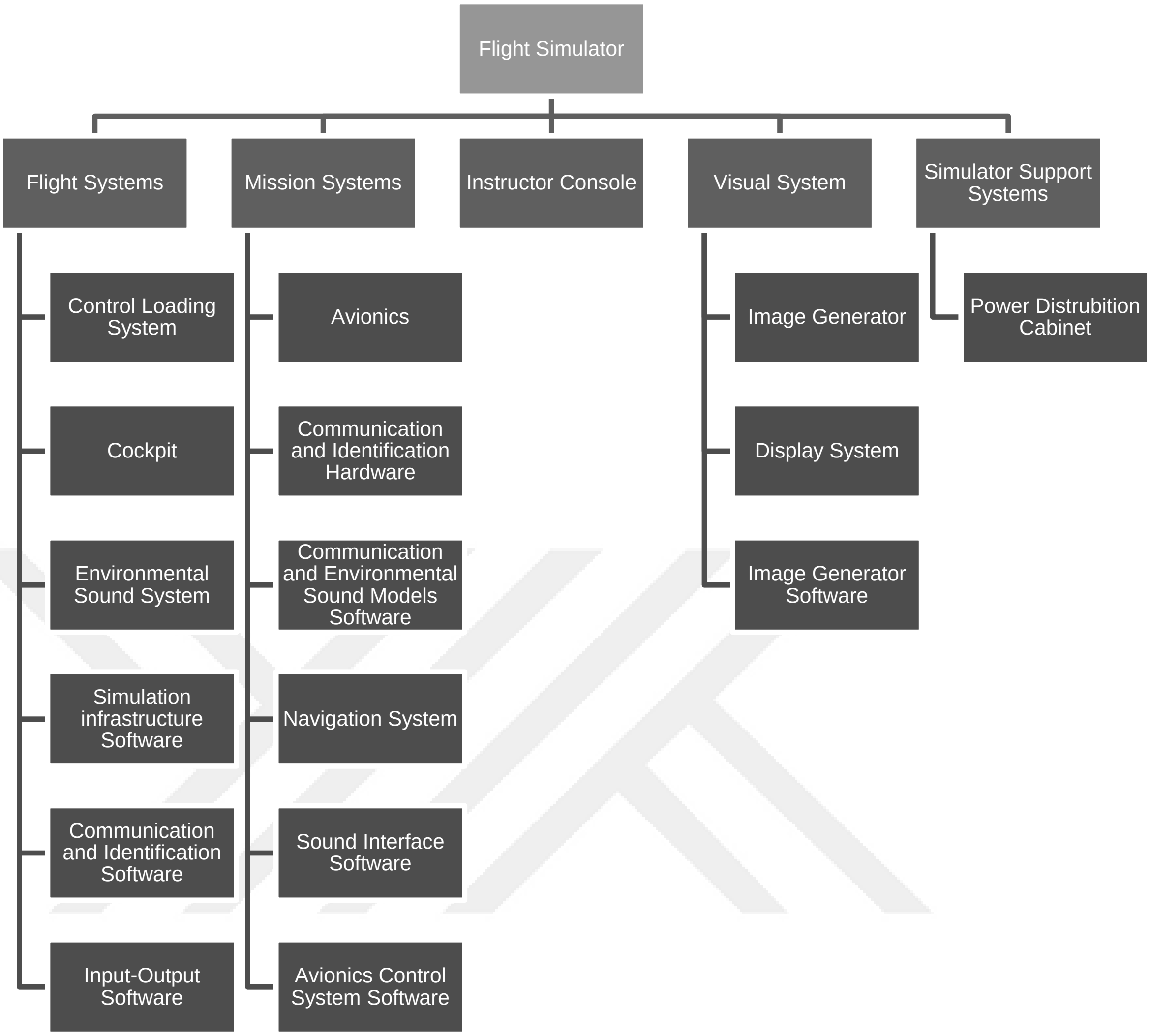

Figure 3.9: Third Level BOM of an OFT

Machines normally consist of a large number of components, but the statistic broadness of the field data for a precise analysis is only given for some components. So it is important to break down the machines bill of material (BOM) to a manageable detail scale by defining life cycle relevant machine components (Fleischer, Wawerla, & Niggeschmidt, 2007)

In this study, Flight Simulator (OFT), its subsystems and components under these subsystems have been detailed by creating a product tree. The first level is the main product; flight simulator, the second level consists of the main subsystems of flight simulator and the third level consists of subsystems or components of main subsystems.

3.2.2 Life Cycle of the OFT

It is assumed that flight simulator will be used 10 (ten) years after it has been sold and installed. After 10 years it will be resold as second-hand or scrap. In some cases they may be used after renovation but this may be a different subject of study. The scope of the study starts with installation and ends with the resell of OFT as shown in Figure 3.10.

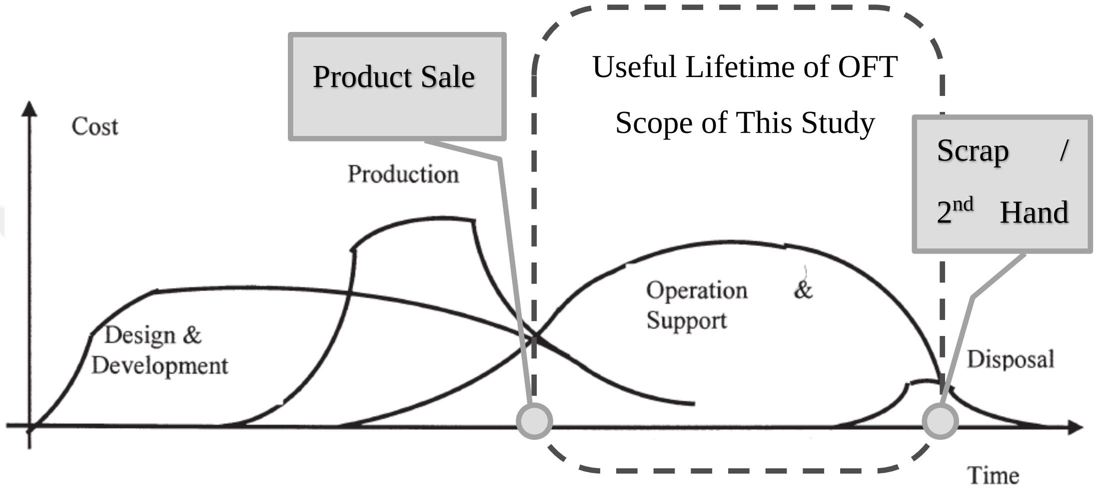

Figure 3.10: Different Types of Costs in Life Cycle (Elmakis & Lisnianski, 2006)

3.3 Methodology

To make LCC analysis, "Life Time" of the product should be well defined/known. After determination time period that will be analyzed, a Cost Breakdown Structure (CBS) should be prepared. In this study, to analyze LCC and to estimate operating and maintenance costs of OFT development of a simulation model is envisaged. All steps are defined in Figure 3.11.

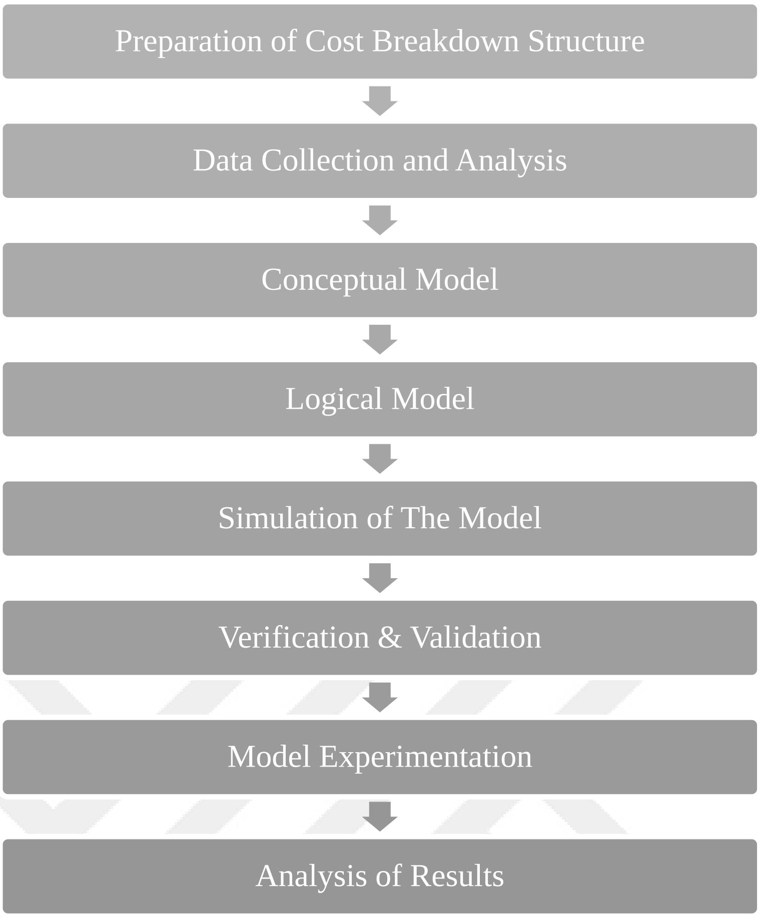

Figure 3.11: Methodology Diagram of the Study

3.3.1 Determining Cost Breakdown Structure (CBS)

Cost Breakdowns Structure (CBS) is one of the most essential part of this study. Preparing an accurate CBS is very important to analyze and calculate LCC correctly. Firstly, all items constituent CBS should be defined. After defining cost items, suitable cost model for each item can be applied to calculate or estimate these items.

To make the LCC estimation of the flight simulator, the most important subject is determining the cost items of the flight simulator. First of all, these cost items should be well defined for reliability of calculation. After defining items, every item will be analyzed separately. By using top-down cost modelling as shown in Figure 3.12, cost items need to be defined and the calculations for every item needs to be considered.

The main cost items of a flight simulator can be listed as below:

- Purchasing Cost
- Investment Cost (Facility etc.)
- Operational Cost (electricity consumption, personnel salaries etc.)
- Preventive Simulator Maintenance
- Corrective Maintenance (Failures)

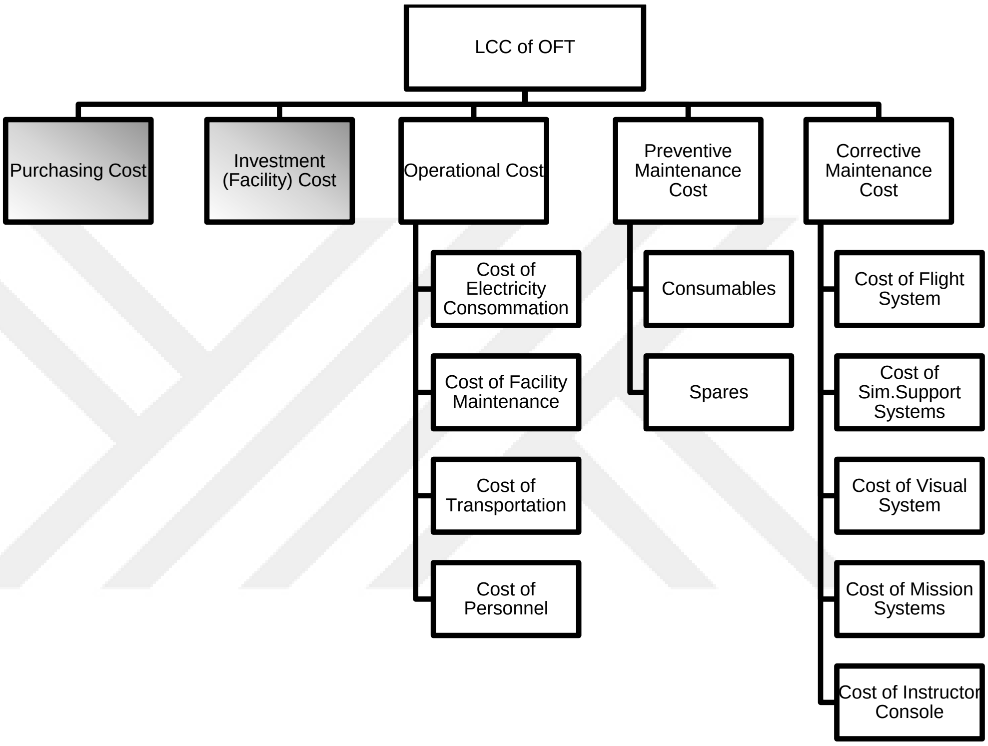

Figure 3.12: Life Cycle Cost Items of an Operational Flight Trainer

In scope of this study, OFT was purchased as a turn-key solution therefore Purchasing Cost and Investment (Facility) costs are fix costs. These costs can be directly added into CBS of study. Operational Costs, Preventative Costs and Corrective Maintenance Costs are subject to analyze and prediction to complete the cost model. All cost items in CBS of OFT will be examined in the following sections.

3.3.2 Cost Model

Main Life Cycle Cost Items diagram of an Operational Flight Trainer can be seen in Figure 3.12. The gray colored cost items (Purchasing Costs and Investment

Costs) can be obtained from market researches. Other cost items have been analyzed, calculated and estimated in this study.

In order to calculate the total operating and maintenance cost of a flight simulator both deterministic and stochastic methods will be used. In this study, operating costs will be analyzed, purchasing cost and building cost are fix cost items. At the beginning of the project, purchasing cost of the flight simulator, building construction and preventive simulator maintenance costs may be known because they are fixed costs, but operating costs and corrective maintenance cost are variable. It is necessary to analyze and predict cost of operations and number of breakdowns to calculate the Total Operating and Maintenance Cost of the flight simulator. To be able to simulate stochastic cost items especially Corrective Maintenance Cost which belongs to unexpected failures all costs are converted to daily basis. Failure database used in this study contains daily failure information. Thus, if a component fails, it means that component has a failure in related day, two or more failures for same component in same day are discarded (it is an extreme condition). To simulate the system, all costs are converted to daily basis.

In this study, the cost breakdown structure (CBS) is generated as follows:

Total Life Cycle Cost of System (LCC):

$$LCC = (C_I + C_{OM} - P_S)$$

Where;

C_I : Investment Cost

C_{OM} : Operations and Maintenance Cost

P_S : Selling price of Used Product

Investment Cost (C_I) is composed of acquisition cost of the system as turn-key solution. It includes all costs associated with the system design, R&D, production and initial logistics support costs which are covered by the manufacturer. It also includes the profit of the manufacturer.

Operations and Management Cost (C_{OM}) is composed of all costs related with the operations and maintenance of the system in its life cycle. It covers system operations, maintenance, sustainment, modifications.

Selling price of Used Product (P_S) is the money that will be gained by selling the system after usage. In this study, the life cycle of the flight simulator will be accepted as 10 years. After 10 years it can be re-used by modifications and renovation of some parts of the system or it can be directly sold as scrap.

Investment Cost (C_I) is consist of all cost items occurring until the system is ready to operation. It means initial investment costs such as purchasing cost and building constructing cost.

$$C_I = (C_P + C_B)$$

Where;

C_I : Investment Cost

C_P : Purchasing Cost

C_B : Building Construction Cost

Thus, Total System Cost can be defined as;

Total Life Cycle Cost of System (C):

$$LCC = (C_P + C_B + C_O - P_S)$$

3.3.1.1 Purchasing cost

With the development of technology, the prices of flight simulators fall down. It is much easier to reach the technology and with the help of competition between the producers, each one try to make best offers for the customers. Technological development and globalization allowed to reach high technology with lower prices.

However the prices are much lower than before, a full flight simulator can be easily reach at the prices of 30-40 Million USD. Purchasing price can be used directly into the Life Cycle Cost calculation.

According to market research conducted in 2019 in Turkey, purchasing cost of a T-38 Model OFT is approximately 6, 5 - 7, 5 Million USD.

3.3.1.2 Facility (Building) investment cost

Flight simulators are produced with high technology. There are lots of electronic or mechanical sub-systems and components which are very important for operating the simulator. These special high-tech product should be operated in a special building. The temperature of the building, humidity, clean air flow should always be controlled and have to be kept in suitable range. For Full Flight Simulator (FFS) a special floor is needed in order to operate the flight simulator safely because of vibration and motion system forces that are applied to ground. There has to be Uninterruptible Power Supply (UPS) system to keep the system on power and prevent system failures against unexpected power failures. Building construction cost is consist of structure cost and infrastructure costs. The cost of building changes according to the size and design of building.

3.3.1.3 Operational cost

Operational cost is total amount of cost that occurs to realize training. It has mixed cost structure which consist of fix and variable parts. Electricity consumption, cost of facility maintenance, cost of transportation, cost of personnel are the general items of total operational cost.

Electricity consumption can be divided into two main group. The first one is consumption of building of facility and the other one is consumption of flight simulator. Building lightings, air conditioning, office devices (computer, printer etc.) consume electricity to fulfil the operational requirements of the flight simulator facility. Total consumption of electricity of building does not vary in a wide range, it is approximately the same value at same time period. Thus we may accept this value as fixed after calculating the average consumption per time period that will be used.

To realize flight training, flight simulators should have been setup in a suitable building of facility. Facility building maintenance is a requirement to keep the building in good shape and operational performance at the high level. Electricity infrastructure, air conditioning, UPS of building and other items should be maintained in defined periods. Performing this maintenance keeps infrastructure of building at high level but at the same time it adds cost for flight training.

Another item that constitutes operational cost is transportation. Daily transportation of personnel from their houses to simulator facility and from simulator facility to their houses create cost. The type of transportation changes, in this study while calculating this item, car rental option is considered. Thus transportation cost is consist of car rental cost and fuel consumption cost.

Personnel costs consist of salaries, compensation, meals, premiums, insurance and taxes. To operate the flight simulator at least two personnel must be assigned, as one technician and one instructor console operator. In most cases, this number is three at minimum. When one personnel should leave for annual holiday or in case of emergency the other two personnel be able to operate the systems. Personnel number must be multiplied by shifts of work day. If flight training is being performed for 16 hours a day, there must be 2 shifts in order to operate it. In this study, 16 hours of training per day is assumed.

Operational Costs can be modelled as below;

$$C_{OP}: C_E + C_{FM} + C_T + C_{PE}$$

Where;

C_E: Cost of Electricity Consumption

C_{FM}: Cost of Facility Maintenance

C_T: Cost of Transportation

C_{PE}: Cost of Personnel

3.3.1.3.1 Cost of electricity consumption

Cost of Electricity Consumption (C_E) is consist of electricity consumption of Facility such as lighting, electricity consumption of air conditioners, computers, other office devices of personnel etc. and consumption of the OFT.

Electricity consumption of facility is related with working days and hours. It is not directly affected by flight hours of the OFT. Daily Cost of Electricity Consumption of Facility can be formulated as follows:

$$C_{EF}: P_E * H_D$$

Where;

C_{EF}: Daily Cost of Electricity Consumption of Facility.

P_E: Price of Electricity (USD/kWh)
H_D: Operating Hours (Hour /Day)

Electricity consumption of OFT is directly affected by flight (operating of system) hours. Therefore, formulation of related cost item is as follows:

$$C_{ES}: P_E * F_D$$

Where;
C_{ES}: Daily Cost of Electricity Consumption of Flight Simulator
P_E: Price of Electricity (USD/kWh)
F_D: Flight Hours -Operating Hours of OFT (Hour /Day)

3.3.1.3.2 Cost of facility maintenance

As mentioned in the previous sections, Flight Simulators are high-tech and expensive products. They have complicated structures and they have sensitive electronic subsystems and components. To operate this high-tech and sensitive products, it is necessary to operate a building with special conditions. Temperature and humidity conditions, cleaning are vital requirements. Operating such a special facility have different kinds of cost items. Facility maintenance cost (C_{FM}) can be modelled as follows:

$$C_{FM} = C_{UPS} + C_{ACM} + C_{FCM}$$

Where;
C_{UPS}: Cost of UPS Maintenance
C_{ACM}: Cost of Air Condition Maintenance
C_{FCM}: Cost of Facility Cleaning and Maintenance

Maintenance of UPS and Air Conditioners are requiring expertise and special devices and in general, service is usually purchased from specialist companies. In this study, this services are purchased. These cost items are calculated by converting daily basis by using “cost of service” and “time period”. For example, UPS Maintenance cost is calculated as below:

C_{UPS}: Cost / Time Period (Days)

C_{UPS} = 2250 USD / 90 Days

C_{UPS} = 25 USD / Day

Costs of Air Conditioners Maintenance and Facility Cleaning/Maintenance are calculated with using same method.

3.3.1.3.3 Cost of transportation

Personnel working at Training Facility which OFT was established, use car rental to go to work and return to home. 16 hours working site consist of 2 shifts. Therefore, 2 different rental cars are used. Cost of Transportation consist of Car Rental Fee and Fuel Consumption.

Cost of Transportation (C_T)

$$C_T = C_{CR} + C_{FC}$$

Where;

C_{CR}: Cost of Car Rental

C_{FC}: Cost of Fuel Consumption

3.3.1.3.4 Cost of personnel

In this study, OFT is operated 16 Hours/Day with 2 shifts. An OFT requires 2 technical personnel; one Technician and one Console Operator to operate the system. To meet the needs of staff such as tea, coffee, catering and simple cleaning of offices, one more personnel is necessary. Thus 3 (three) personnel per shift is required. A 2-shift system must have a total of 6 (six) personnel.

Cost of Personnel (C_{PE}) can be expressed as below:

$$C_{PE} = C_{SAL} + C_{COMP} + C_{MF} + C_{BON} + C_{IT}$$

Where:

C_{SAL}: Cost of Salaries

C_{COMP}: Cost of Compensation

C_{MF}: Cost of Meal Fee

C_{BON}: Cost of Bonus Paid to Personnel

C_{IT}: Cost of Insurance and Taxes

3.3.1.4 Cost of maintenance

Other important cost item of Operational and Maintenance Costs (C_{OM}) is Cost of Maintenance. It can be divided into two main groups; Operational Costs and Maintenance Costs. Maintenance costs consist of two main items; preventive maintenance cost and corrective maintenance cost. It can be formulated as follows:

$$C_{OM} = C_{OP} + C_{PMC} + C_{CMC}$$

Where;

C_{OP} : Operational Cost

C_{PMC}: Cost of Preventive Maintenance of Simulator

C_{CMC}: Cost of Corrective Maintenance of Simulator

Thus, the main cost model can be expressed as follows:

Total Life Cycle Cost of System (C):

$$LCC = (C_P + C_B + C_{OP} + C_{PMC} + C_{CMC} - P_S)$$

3.3.1.4.1 Cost of preventive simulator maintenance

With the development of technology, flight simulators reached at a high level of reality. But this situation also caused the flight simulators became very complex and expensive systems. Visual system, motion system, avionics and other sub-systems and components are being used to improve the reality level. Most of these systems are expensive, sensitive and most of them are electronic, mechanic or electro-mechanic. Therefore the usage and preventive maintenance of components and sub-systems are very critical issues to prevent unwanted breakdowns or loss any part of system (this means money and time loss). The preventive maintenance should be well defined and should be done on time. Preventive maintenance also creates costs because of consumables and spare parts change.

The purpose of preventive maintenance is to prevent or minimize malfunctions that may occur in system. Hence it can be called as preventative maintenance. It can be planned in different periods such as weekly, monthly or annually. The periodic maintenance cost per day can be calculated by dividing the total cost of period to number of days in a specific time period and considered in the model. It includes consumables and spare parts costs. Controls of electronic, mechanical and hydraulic systems, cleaning and disinfecting of some parts (O_2 masks, headphones etc.) are made. Some of components such as lamps of projector of visual system should be changed in this preventive maintenance faithful to the period of change. All components subject to change with preventative maintenance are listed as shown in Table 3.1 and Table 3.2.

Table 3.1: Cost of Consumables per Day

Component	Unit Price	Quantity	Total	Period (Day)	Cost Per Day
Projector Lamp	900	10	9000	125	72
Printer Cartridge	75	3	225	180	1.25
Screen Cleaning	400	1	400	90	4.44
Oxygen Masks	100	2	200	180	1.11
Air Filter	160	2	320	90	3.56
Cleaners	120	1	120	30	4.00
TOTAL					**86.36**

Preventative maintenance activities are designed to increase the effectiveness of flight simulator and extend the life of the device. (ETC Integrated Logistics Support, 2019)

Table: 3.2: Cost of Spares per Day

Component	Unit Price	Quantity	Total	Period (Day)	Cost Per Day
Keyboard	50	1	50	730	0.07
Mouse	20	1	20	730	0.03
Headphones	250	3	750	365	2.05
Seat Cover	100	2	200	365	0.55
Various Lamps				730	5.5
Various Spares				730	13
TOTAL					**21.20**

The number of each item and unit prices can be collected from product tree (BOM) of the system. Change periods of each item should be determined by the manufacturer. According to changing periods (useful life) of each item, change periods can be converted to daily basis. In this study, all items subject to change during preventative maintenance with different periods were obtained from manufacturer. Changing periods are converted into daily basis and daily cost total preventative maintenance is calculated.

On the other hand, spares are other cost item for preventative maintenance. In this study, spares cost is calculated as 21.20 USD/day as shown in Table 3.2.

Cost of Preventive Maintenance can be expressed as follows:

$$C_{PMC} = C_{CON} + C_{SPA}$$

Where;

C_{CON}: Cost of Consumables

C_{SPA}: Cost of Spares

Preventive maintenance cost may change according to amount, price, and specifications of components which are subject to change periodically. In this study, cost items and costs were obtained from the manufacturer. Total preventative cost may change according to cost of components, model of simulator, specifications and preventative maintenance period.

3.3.1.4.2 Cost of corrective maintenance

One of the most important cost item is cost of corrective maintenance due to failures/breakdowns. As previously mentioned flight simulators are high-tech and complex systems. There are a large number of sensitive electronic and mechanical subsystems. Unexpected failures can occur in these complex systems consisting of hundreds of components. These failures are sometimes remedied by rebooting, sometimes disassembly and reassembly, sometimes by repairing, and sometimes by replacing the part with a new one. Rebooting, disassembly and reassembly and repairing by crew may not incur additional costs because cost of personnel is fixed and the salaries and other payments must be made to employed personnel every month. Repairing outside the organization by another company, and replacing the part with a new one (except out-of-warranty) create additional cost.

The multiplication of the cost of the component and number of breakdowns of related component during the life cycle gives total cost of corrective maintenance. Previous studies on this subject focused on calculating the cost of training after the working period. All cost items are recording on a form or in a database and after training finishes, the results are collected from these forms or database. Total cost is being divided by training hours realized and finally cost of flight training per hour is calculated.

Calculating the hourly training cost is very important in order to calculate correctly the budget, determining the sales of training hours, giving offers to tenders of military or civil organizations for Integrated Logistics Support (ILS) of same type of flight simulator produced before. It can be used as an input for other calculations. But for some purposes it may be so late to calculate the cost of flight training or life cycle cost of flight simulator at the end of working period / its life cycle. If the flight simulator is the first produced product of its type we also need to calculate (as estimation) the total cost of flight simulator in its life cycle. To achieve this goal, the fixed costs must be calculated and the variable cost should be tried to predict.

Between cost items, the hardest item to calculate is cost of corrective maintenances. Because breakdowns cannot be planned and they occur unexpectedly. It is hard to expect the total number of breakdowns in total life cycle of simulator.

The breakdown information has been collected from the failure database that has been recorded since 2013 by manufacturer. It was hardest part of the study since it takes much time to collect data and normalization of data which was entered by different personnel with using different terminology.

Corrective Maintenance Cost can be calculated by using failure information and costs of components. To calculate the total cost, Product Tree (BOM) should be well defined and MTBF data should be used to calculate/simulate the failures. Cost of each component and total number of failure of each component in defined life time (life cycle) period is vital information to calculate corrective maintenance cost.

In this study, Flight Simulator (OFT) consist of 5 (five) main subsystems. Therefore the main cost model of daily cost of corrective maintenance can be expressed as follows:

$$C_{CMC} = C_{FS} + C_{MS} + C_{IC} + C_{VS} + C_{SSS}$$

Where;

C_{FS}: Cost of Corrective Maintenance of Flight System

C_{MS}: Cost of Corrective Maintenance of Mission System

C_{IC}: Cost of Corrective Maintenance of Instructor Console

C_{VS}: Cost of Corrective Maintenance of Visual System

C_{SSS}: Cost of Corrective Maintenance of Simulator Support System

All components under these subsystems are formulated with same method by using Bill of Material (BOM) of OFT. Corrective Maintenance of each component is calculated as follows:

$$C_{CMC-X} = N_{TF-X} * C_X$$

Where;

N_{TF}: Number of Total Failure of X Component.

C_X: Cost of replacement of X Component.

While calculating Corrective Maintenance Cost, BOM is analyzed with using Top-Down technique and cost of corrective maintenance of subsystems and system are calculated with using Bottom-Up technique.

In this study, to obtain MTBF value, two different method are used. A failure database created by user is used to calculate MTBF value and to fit a data distribution function in order to estimate the possible failures in the future with using simulation software. And another MTBF value database is used with using Electronic Parts Reliability Database (EPRD) and Non-Electronic Parts Reliability Database (NPRD). Two different MTBF database are used and two scenario are designed to calculate total cost. Detail information about scenarios will be discussed in following chapter.

3.3.2 Conceptual Model

Conceptual model of the system consist of Inputs, System Structure and Outputs. Inputs of the system are Pilots, Maintenance Staff and Engineers working on design and R&D. System consists of an Operational Flight Trainer (OFT), personnel, facility and other resources required for flight training and design works. The outputs of the system are Flight and Maintenance Training and R&D works. Conceptual model of the system is shown in Figure 3.13.

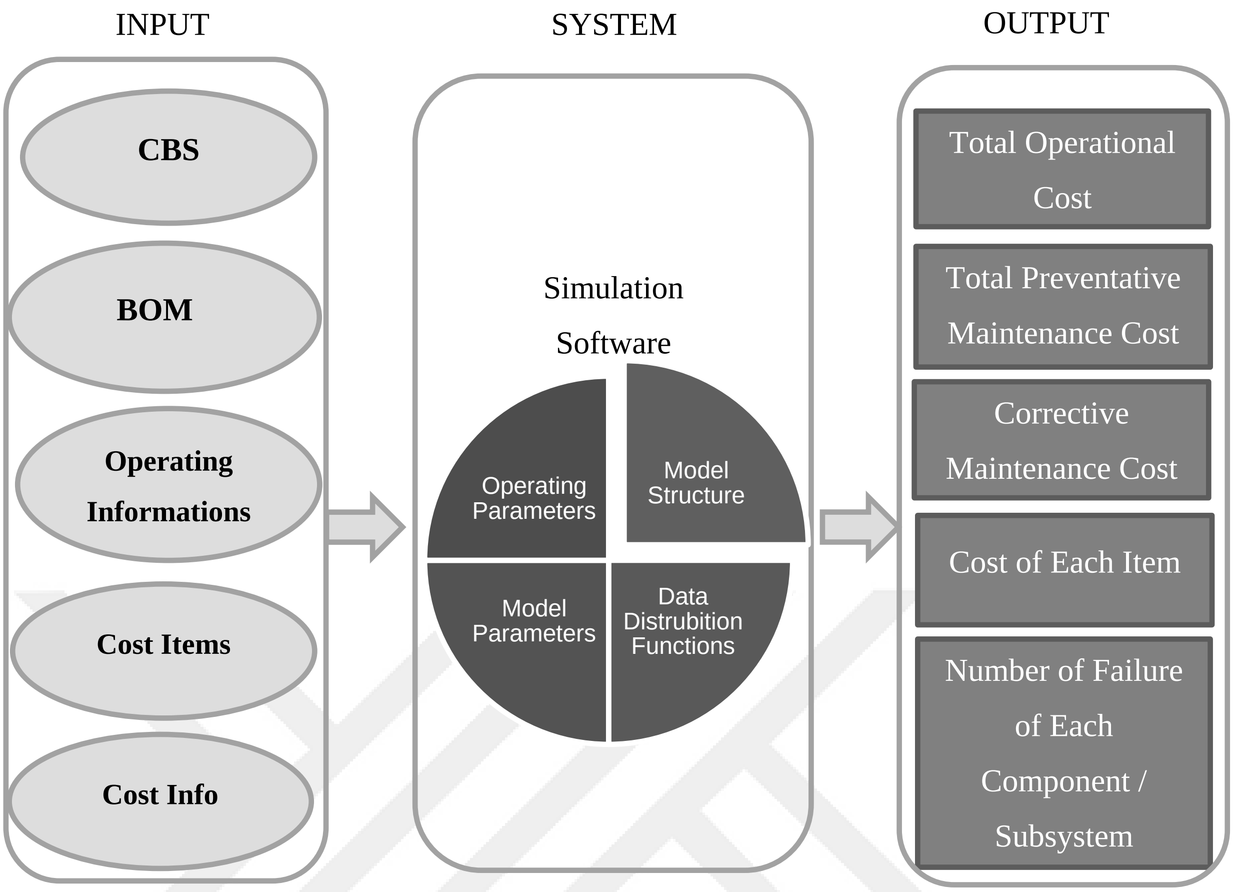

Figure 3.13: Conceptual Model of the System

3.3.3 Logical Model Flow Chart

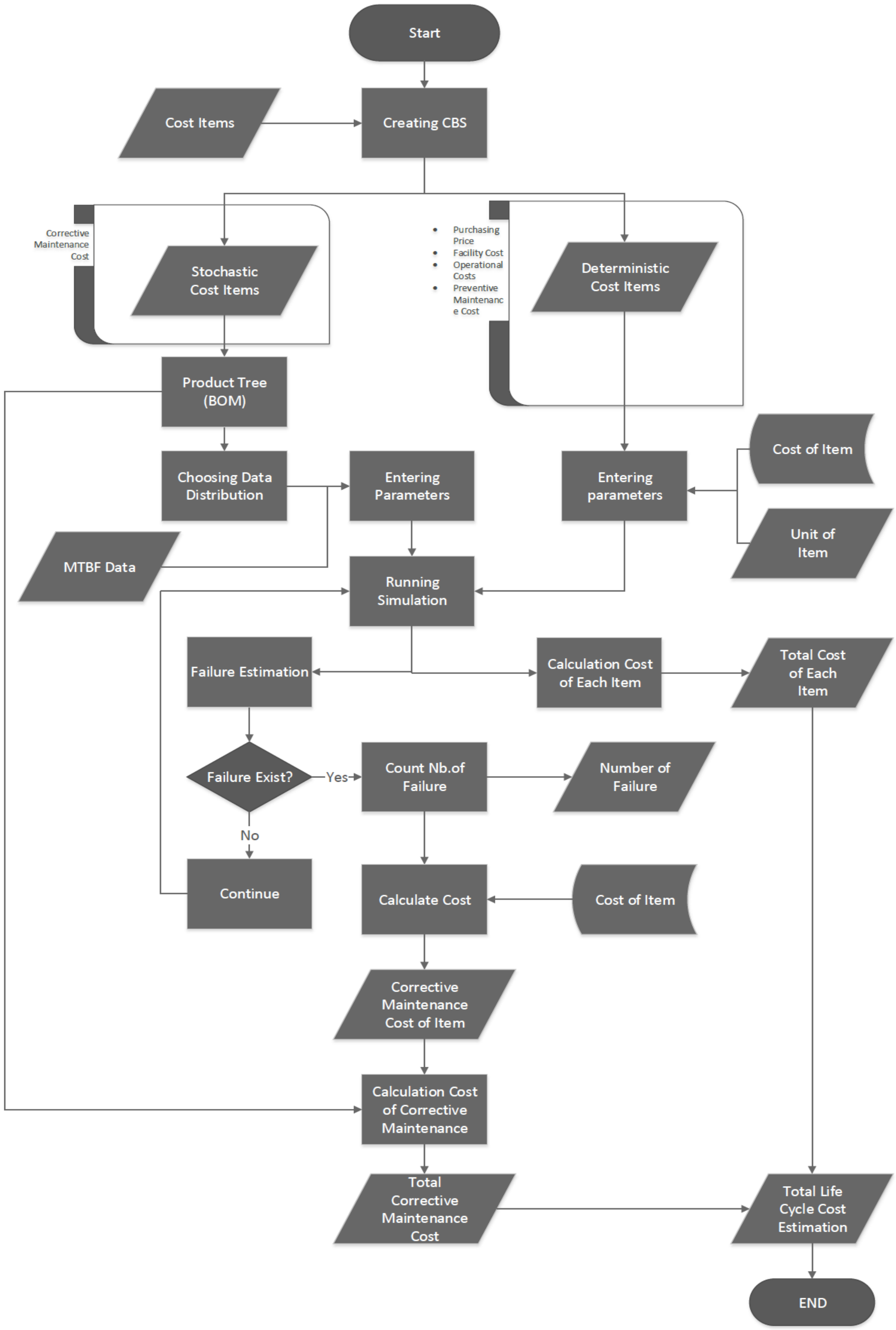

Figure: 3.14: Logical Model Flow-Chart Diagram

According to Logical Model, after creating CBS with using all cost items related with product, cost items are identified as stochastic or deterministic. Deterministic costs (daily costs of items) are simulated with using daily fix costs information and they are simply calculated. Stochastic cost item(s) are estimated with using simulation parameters and data functions entered into simulation software and results are generated by simulation software as shown in Figure 3.14. Deterministic and stochastic cost items have different processes and different data flow as shown in Logical Model.

3.3.4 Input Data Analysis

To calculate/predict the total number of breakdowns Mean Time between Failures (MTBF) can be used. It is the average time between two failures, which is sometimes very hard to calculate due to insufficient data. In general, the producers calculate this value by applying tests on products for a long time and they record statistical data. They calculate the total number of failure in one million hours (FPMH) working period.

MTBF value can also be calculated with the data recorded previously (Table 3.3). Recording breakdown data with the part information (as part name, part number etc.) and failure date allows to calculate the average failure time. In this study, MTBF value is used in both type. If there is failure(s) of related component in database MTBF value is calculated and used in simulation model. If there is no failures of related component, MTBF value is obtained from the database of Windchill Quality Solutions software which is used to manage the life cycle of products. It contains a large MTBF data library with millions of components and dozens of test environment types. For every part, there are MTBF values for different test environments such as Ground Fixed (GF), Naval (N), Naval-Submarine (NSB), Airborne (A) etc.

For example, to calculate MTBF of Mission Computer (MC), we need to know failure dates. According to database, MC failed at 393^{rd}, 449^{th} and 456^{th} days.

Table 3.3: Calculating MTBF values from Existing Failure Database.

Action Taken-2	(Birden Çok Öğe)	19.12.2012	
Satır Etiketleri	**Say Incident Identifi**	Failure Day	MTBF (Records)
OFT01	**92**		
Görev Sistemleri	**3**		
MISSION COMPUTER	3		
100-655011-000	**3**		
15.01.2014 17:00	1	392.7083333	392.7083333
12.03.2014 14:40	1	448.6111111	55.90277778
19.03.2014 16:00	1	455.666794	7.05568287
Görsel Sistem	**49**		
ADAPTÖR 5V 3A	2		
593500-9893	**2**		
09.07.2014 08:00	1	567.3333333	567.3333333
07.01.2015 12:20	1	749.5144097	182.1810764

It is very important to estimate the failure date of components. With a reliable estimation, manufacturer and user be able to predict the dates of breakdowns, prepare their maintenance plans, control the level of spare parts stock, estimate the total cost of corrective maintenance, estimate the cost of corrective maintenance in specified time period, conduct the budget etc. In this study, MTBF values calculated or taken from database will be used in failure rate distribution functions. Failure Rate Distributions will provide generating random failures for simulation model.

To calculate MTBF value, ARENA Input Analyzer was used. Input data has been prepared in Microsoft Excel by entering "0" for non-failure days and "1" for failure days as shown in Table 3.4.

Table 3.4: Daily Breakdown Information of Components

5	**Day**	**3.1.2.1**	**3.1.2.7**	**3.1.2.8**	**3.3.8**	**3.3.9**	**3.4.1**	**3.4.2.2**
6	1	0	0	0	0	0	0	0
7	2	0	0	0	0	0	0	0
8	3	0	0	0	0	0	0	0
9	4	0	0	0	0	0	0	0
10	5	0	0	0	0	0	0	0
11	6	0	0	0	0	0	0	0
381	376	0	0	0	0	0	0	0
382	377	0	0	0	0	0	0	0
383	378	0	0	0	0	0	0	0
384	379	0	0	0	0	0	0	0
385	380	0	0	1	0	0	0	0
386	381	0	0	0	0	0	0	0
387	382	0	0	0	0	0	0	0
388	383	0	0	0	0	0	0	0
389	384	0	0	0	0	0	0	0
390	385	0	0	0	0	0	0	0
391	386	0	0	0	0	0	0	0

Sayfa1 Sayfa2

By using daily breakdown information of components prepared for the whole working period, the best fitting data distribution type and parameters can be calculated in ARENA Input Analyzer. Firstly, daily breakdown information file is converted to a “notepad” file. With using “Data File” and “Use Existing” functions data file is selected. “Fit All” command finds the best fitting distribution to the dataset. It also gives the distribution function expression in Distribution Summary window. The expressions that ARENA Input Analyzer calculated are given in Table 3.5.

Table 3.5: Results of Input Data Analysis

Component	Result	MTBF
3.1.2.1	POIS(0.00978)	102.2494888
3.1.2.7	POIS(0.000889)	1124.859393
3.1.2.8	POIS(0.00133)	751.8796992
3.3.8	POIS(0.00133)	751.8796992
3.3.9	POIS(0.000889)	1124.859393
3.4.1	POIS(0.00667)	149.9250375
3.4.2.2	POIS(0.0142)	70.42253521

Components that have sufficient number of failures to create a failure data distribution and MTBF values can be used in the model. In this study, more than one failure was accepted to calculate failure data distribution and MTBF value. Other MTBF values of components which have one or zero failure were obtained from Windchill database.

If there is not accurate data in the database, data in library of Windchill or an alternative lifetime management software can be used. Failure per Million Hour data should be converted to MTBF in order to prepare the data in an appropriate form to use in the model. For example;

FMPH = 15,9 Failures / Million Hour

MTBF = 1.000.000 / 15,9 = 62.893,08 Hours

MTBF = 2620, 55 Days (converted to suitable unit for model)

3.3.5 Simulation of Total Operating and Maintenance Cost Estimation

The main purpose of this study is to provide a method by which we can estimate the total operating and maintenance costs of a flight simulator in its life cycle. It will help us to calculate/estimate the total life cycle cost of it. Total life cycle cost of a flight simulator consists of fixed and variable costs as mentioned previously. In this study, a simulation model is created and all cost types is tried to be estimated to calculate the total cost. While estimating fixed costs, information based on experiences and expert opinions were used.

3.3.5.1 Modelling tool

System Dynamics which was developed by Jay Forester in 1961 can be thought as a computer-aided approach to policy analysis and design. The first system dynamics programming language was DYNAMO which was not very user-friendly. After being converted to Windows-based systems, Powersim and Vensim were developed. The system dynamics approach consist of defining the problem (such as complex social, managerial, economic, or ecological systems—literally any dynamic systems) dynamically, mapping and modelling stages until to the steps for building confidence in the model and policy implications. The three salient features of system dynamics are the ability to model feedback, delays and transient behavior. These modelling features are useful in understanding the dynamics of complex systems. (System Dynamics Society, 2019)

In order to calculate failure costs which are variable costs, randomly generated numbers were taken as a basis in accordance with this distribution by using statistical distribution model. Total failure costs will be calculated by multiplying these randomly generated breakdowns by the costs of the parts. This calculation will be made with the simulation model to be run in the VENSİM simulation software. VENSIM is a simulation software created by VENTANA Systems Inc. which can be used to solve a variety of problems.

3.3.5.2 Model assumptions

In this study, to analyze total life cycle of flight simulator, assumptions were made for some situations and for some variables. The life cycle of simulator was assumed as 10 years and model settings were made according to this value. Product tree may be different for various models of flight simulators. Since the model that we analyze is an operational flight trainer, it has no motion system. Another flight simulator may have motion system or other additional subsystems. In this case, they should be added into the product tree and the model.

It is also assumed that there is 16 hours of flight training with this flight simulator. All calculations were made according to this value. It may be changed according to flight hours of flight simulator. Consumables that need to be replaced periodically such as projector lamps, keyboard-mouse set of instructor, pilots headset etc. were added into preventive simulator maintenance.

Mean Time To Repair (MTTR) values since all failures has been solved in 24 hours according to failure database and breakdowns of some mechanical parts were discarded since there is not any MTBF value neither in EPRD/NPRD databases nor in failure database and impossible to estimate the failure.

3.3.5.3 Model structure

To find the Total Cost, simulation model is formed as top-down fractures. Since breakdown records are recorded daily and working for 16 hours in a day, the model is set to run on a daily basis. For 3650 days since life cycle of simulator is assumed as 10 years without any update/revision. Time step is set as 1 day. Of course, these settings can be set to best suit the organization's working times and life cycle of simulator. It can be set as hourly, daily, weekly, monthly or annually (Figure 3.15).

Firstly, the main cost items; Preventive Maintenance of Simulator, Operational Costs, Cost of Corrective Maintenance (Breakdowns) were determined as input for the model. The Building of Facility Cost and Purchasing Cost of Flight Simulator are not included to model.

Daily costs of Preventive Simulator Maintenance, Operational Costs and Cost of Corrective Maintenance are added daily to Total Cost. To create the model correctly, all items are numerated respectively. Simulation model is constructed on this numerical base.

Each cost item is managed in different sheets of the simulation model. Thus it is much easy to create, control, find and update if necessary. Periodic Simulator Maintenance, Operating Costs and Total Cost of Corrective Maintenance are numerated as 1,2 and 3 respectively . Than, lower levels are numerated compatible with these numbers. For example, Cost of Corrective Maintenance of Flight System is numerated as 3.1 since it is the first subsystem of simulator on BOM (Figure 3.15). At lower levels, it is much harder to find the correct component, therefore numerating is necessary. The model structure is composed compatible with numerating BOM.

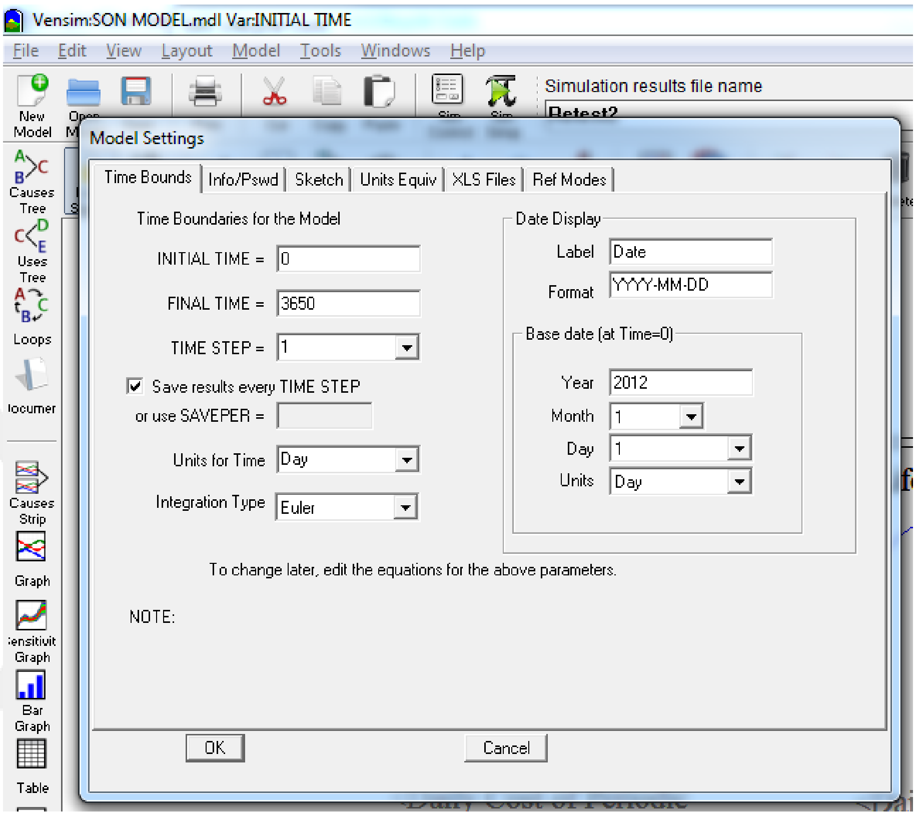

Figure 3.15: Settings of Model in Vensim Simulation Software

All variables of model are calculated in small model parts and in different sheets of the model compatible with product tree (BOM). Model is divided into small model pieces and at the end of construction the total value is tried to be found with combining small pieces as shown in Figure 3.16.

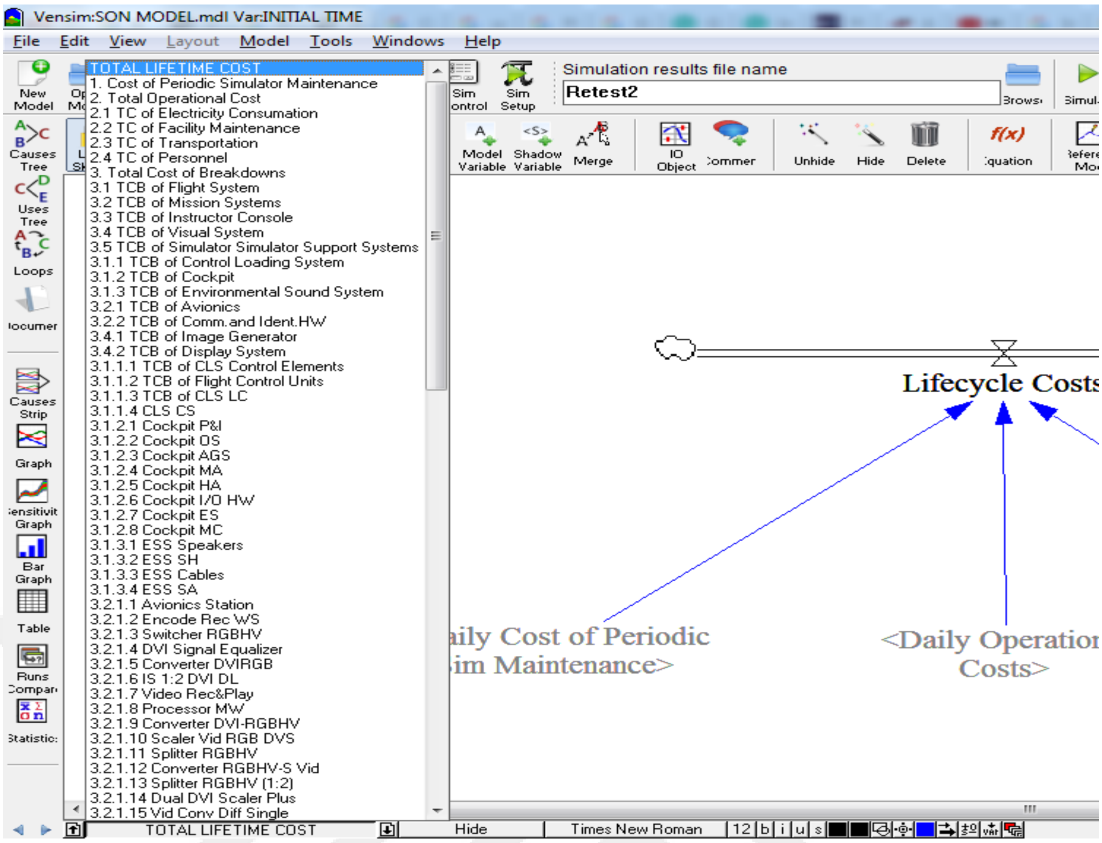

Figure 3.16: A View of Model Structure in VENSIM Simulation Software

For example, Daily Cost of Preventive (Periodic) Simulator Maintenance the calculation formula is as follows:

$$C_{PMC} = C_{CONS} + C_{SPA}$$

Where;

C_{PMC}: Cost of Preventive (Periodic) Simulator Maintenance

C_{CONS}: Cost of Consumables used in Preventive Maintenance of Simulator

C_{SP}: Cost of Spares used in Preventive Maintenance of Simulator

$$\sum C_{PMC} = (C_{CONS} + C_{SP}) * Day$$

Simulation Model calculates Daily Preventive Maintenance Cost using the formula above and calculates the total cost incurred during the period of operation according to the entered parameters of the model as shown in Figure 3.17.

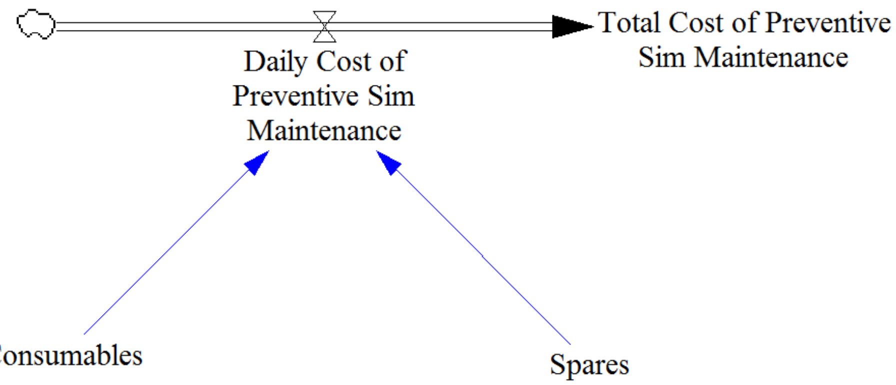

Figure 3.17: Details of Cost of Preventive Maintenance of Simulator

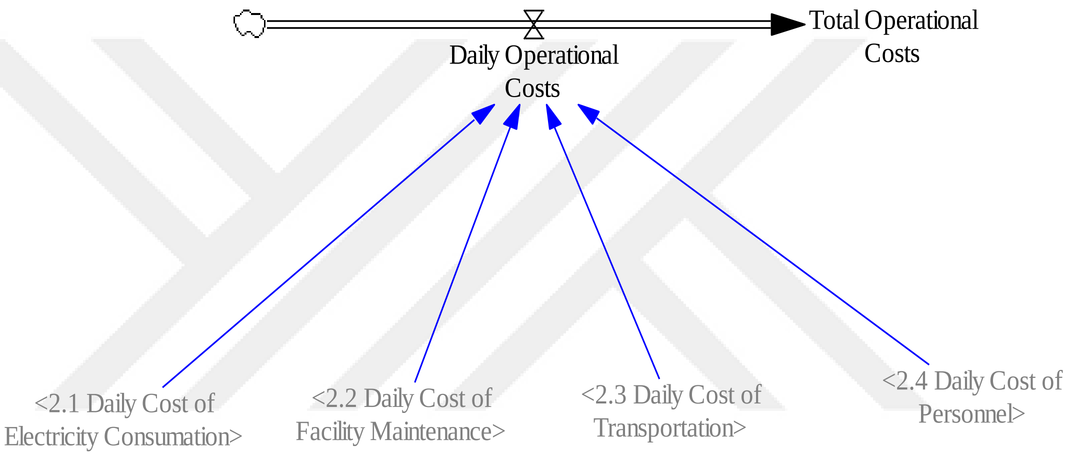

Figure 3.18: Daily Operational Costs of a Flight Simulator

Daily Operational Costs is calculated as follows:

$$C_O: C_E + C_{FM} + C_T + C_{PE}$$

Where;

C_E: Cost of Electricity Consumption

C_{FM}: Cost of Facility Maintenance

C_T: Cost of Transportation

C_{PE}: Cost of Personnel

Total Operational Cost is calculated the total cost incurred during the period of operation according to the entered parameters of the model as shown in Figure 3.18

Since the model settings is set as daily working, all parameters and data are converted to daily values (Figure 3.17, Figure 3.18 and Figure 3.19). All cost items that affects Total Life Cycle Cost were included into model as shown in Figure 3.20.

$$C_{CMC} = C_{FS} + C_{MS} + C_{IC} + C_{VS} + C_{SSS}$$

Where;

C_{FS}: Cost of Corrective Maintenance of Flight System

C_{MS}: Cost of Corrective Maintenance of Mission System

C_{IC}: Cost of Corrective Maintenance of Instructor Console

C_{VS}: Cost of Corrective Maintenance of Visual System

C_{SSS}: Cost of Corrective Maintenance of Simulator Support System

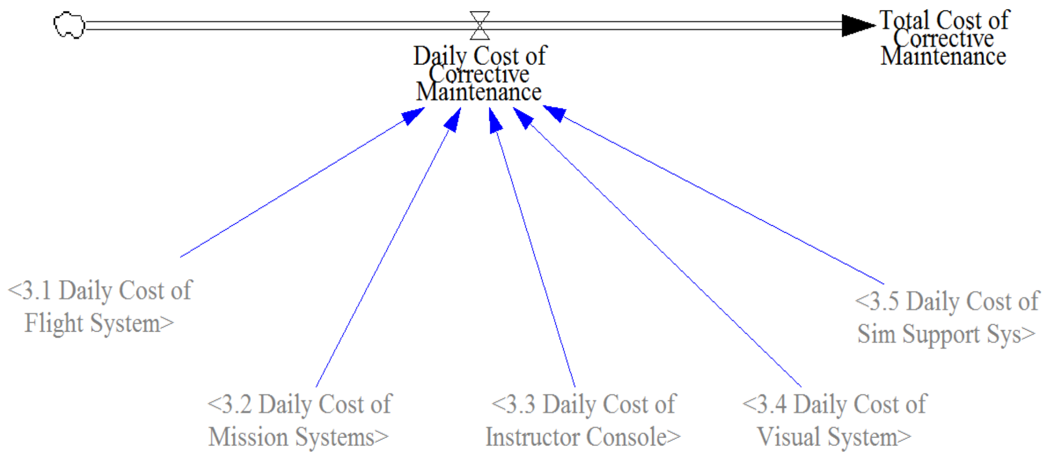

Figure 3.19: Simulation Model for Calculation Total Cost of Corrective Maintenance of Subsystems

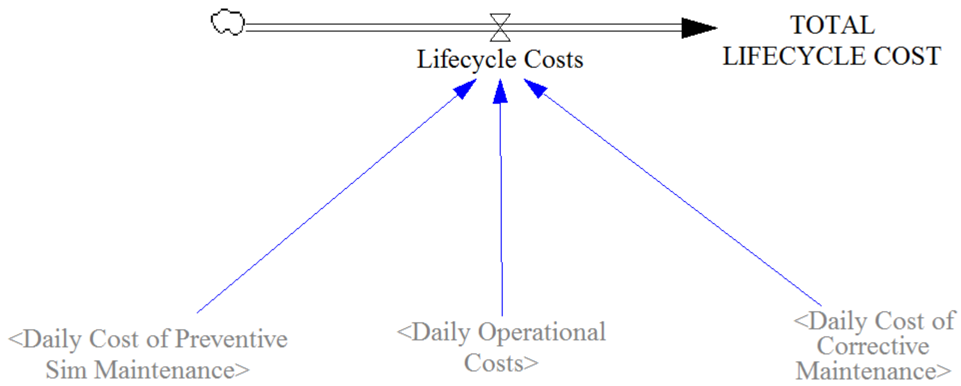

Figure 3.20: Variable and Fixed Costs of a Flight Simulator

3.3.5.4 Determining the variables

In the simulation model, equations of variables were defined to create values to get results of simulation. In order to calculate corrective maintenance costs, component cost information is also required to be used in the model of each part.

Another example is electricity consumption cost. To be able to calculate the cost of electricity, cost of electricity per hour and total working hours should be known. In this study, the electricity consumption cost of facility and flight simulator and its subsystems are separated. Electricity cost of facility is not effected by flight training hours of simulator, hence it is constant per day. To calculate the daily electricity cost of building, total daily working hours should be multiplied by electricity consumption and cost per KW/h. On the other side, to calculate the electricity consumption cost of flight simulator, training hours should be known and it must be multiplied by electricity consumption per hour and cost of electricity cost of KW/h.

3.3.5.5 Mean time between failures (MTBF)

Estimation of breakdowns was the hardest part of the model. To get an accurate result, data that we use must be correct, reliable and complete. To estimate the breakdowns; history of breakdowns, MTBF library of a life cycle management software such as Windchill as mentioned before, and some other prediction technics could be used. In this study, the failure database which was collected for 7 years was used. If there is failures of component and there is enough data to calculate the MTBF, that it was used. If there is not any failure or there is not enough data to calculate MTBF of related component, MTBF library of Windchill software is used.

To generate another scenario with using MTBF value of components Failure Database, a Data Distribution Function is used. To determine the correct distribution function which will be used in the simulation model, ARENA Input Analyser was used. For example, Cockpit Panels and Indicators which have 25 failures in 2250 days working period in the Failure Database was analyzed. The failures information was set as “0” for days without failure and “1” for days which failure occurred. The results of fitting data is shown in Figure 3.21;

```
        Distribution Summary

Distribution:   Poisson
Expression:     POIS(0.00978)
Square Error:   0.000000

Chi Square Test
  Number of intervals   = 2
  Degrees of freedom    = 0
  Test Statistic        = 0.00211
  Corresponding p-value < 0.005

        Data Summary

Number of Data Points   = 2250
Min Data Value          = 0
Max Data Value          = 1
Sample Mean             = 0.00978
Sample Std Dev          = 0.0984
```

Figure 3.21: ARENA Input Analyzer Results

3.3.5.6 Estimation of breakdowns

To generate data for estimation of breakdowns a Failure Rate Distribution (FRD) should be used in the model. Each component (according to lowest level of BOM as in the model) has its own equation. MTBF data was used as an input for related equations of failure rate. An example of FRD is shown in Figure 3.22.

Failure Rate Distribution function of each component is below:

$$FRD = integer\ (Random\ Poisson\left(0\ ,1\ ,\frac{1}{MTBF},0\ ,1\ ,Noise\ Seed\right))$$

The parameters in the equation come from the type of Random Poisson Number Function of software. To generate random number to acting as breakdowns in equations the random number function should be used. In this study, random Poisson distribution function is used. FRD was modelled with Poisson distribution since it fits best to model occurring independently from each other over a period.

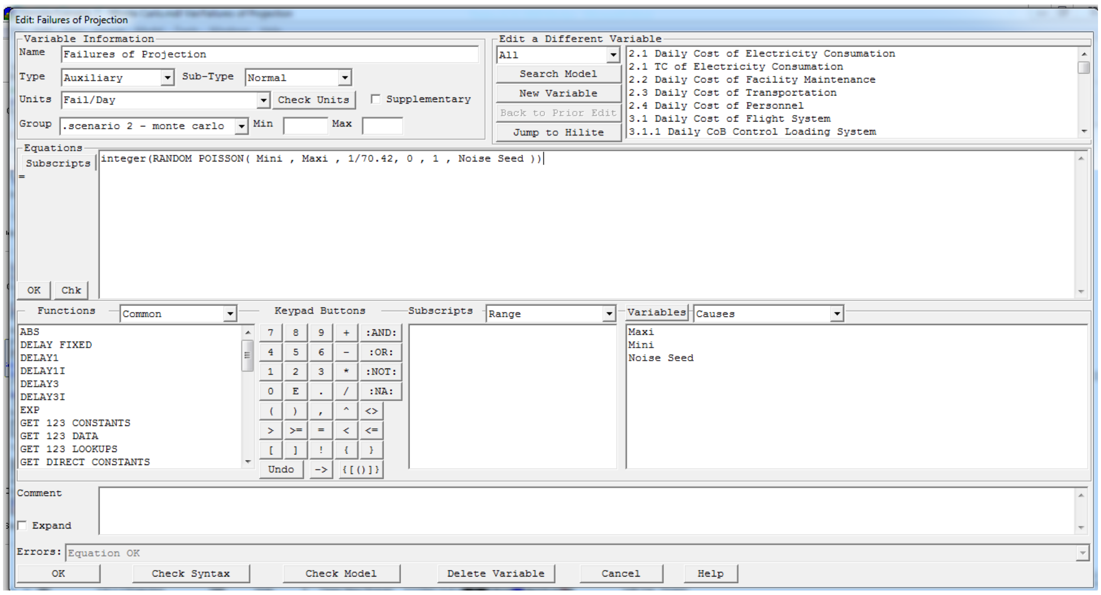

Figure 3.22: Estimation Formula of Failures for a Component

The function used in model is as below:

RANDOM POISSON (m,x,M,h,r,s)

"m" is the minimum and "x" is the maximum value that the function will return. Where necessary the distributions will be truncated to return values above this. Truncation occurs after the output has been stretched and shifted. If the number drawn is below this value it will be discarded and another number drawn.

"h" is a shift parameter that indicates how much the distribution will be shifted to the right after it has been stretched (but before being truncated).

"r" is a stretch parameter that indicates how much the distribution will be stretched before it is shifted and truncated. Note that for the NORMAL distribution h and r correspond to the mean and standard deviation.

"s" is a stream ID for the distribution to use. NOTE this is not only a noise seed. Please read carefully the definition of stream ID. In most cases the final argument should be 0!

In this study, since it is tried to generate random breakdown data, it is necessary to know whether there is a breakdown on a daily basis. For this reason, "mini" is set to 0 and "maxi" is set to 1 in order to access the information with or without breakdown on a daily basis. "0" means no fault for the relevant day, "1" means no fault for the relevant day. Therefore, "m" is set to "0" and "x" is set to "1".

M is calculated with MTBF data. To enter the correct parameter to “daily” function MTBF value must be converted to “daily” basis. MTBF was calculated daily in this study, thus it must be converted by 1/MTBF. This process convert it to daily breakdown number. As a result, “M” should be 1/MTBF.

“h” is set as 0 because there is no need to shift the data distribution to right side. “r” is set as “1”. This parameter is set by the help of VENSIM Help, as indicated for Random Poisson data distribution function.

In the equation of prediction of failures, Noise Seed is used as a parameter. When the Stream ID passed to the RANDOM functions is zero, they will use the default noise seed. You can control this by creating a variable in the model (usually a constant) called NOISE SEED. When this variable exists in the model its value is used to initialize the random number stream for any random function using Stream ID 0. Changing NOISE SEED will then generate alternative noise streams in multiple simulations. An integer should be used between 0 and 2^31 (about 2 billion), or less than 2^24 (about 16 million) in single precision.

After entering all necessary parameter to function, now it can be generate daily random breakdowns data. This function is able to generate daily breakdowns data but to be able to calculate the total cost of corrective maintenance all breakdowns during the life cycle should be counted. To do this, a special function is used as mentioned below:

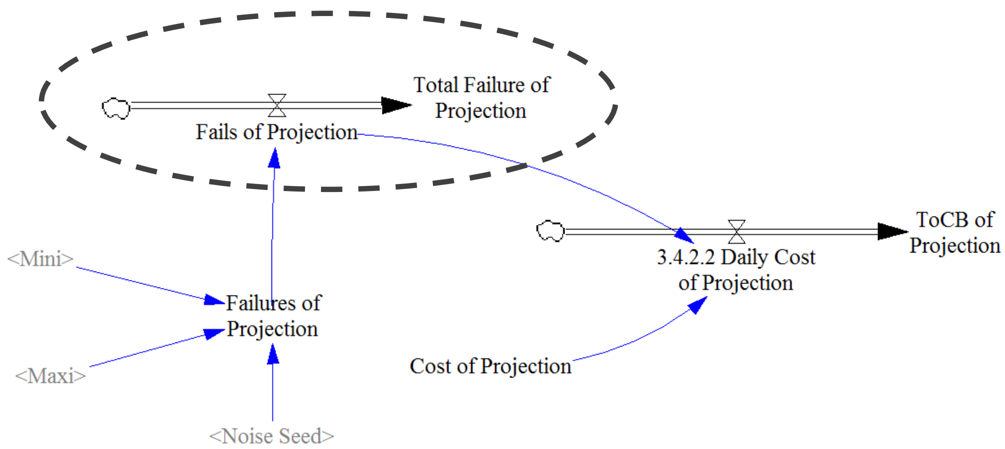

Figure 3.23: Function That Counts Breakdowns During The Life Cycle

Breakdowns are counted daily and total breakdowns are calculated in Level Function <Total Failure of “Related Component Name” > as shown Figure 3.23 above. The necessary function (Figure 3.24) should be entered to function field of <Fails of “Related Part Name”> is :

IF THEN ELSE (Failures of “Variable of Related Part”>0, 1, 0)

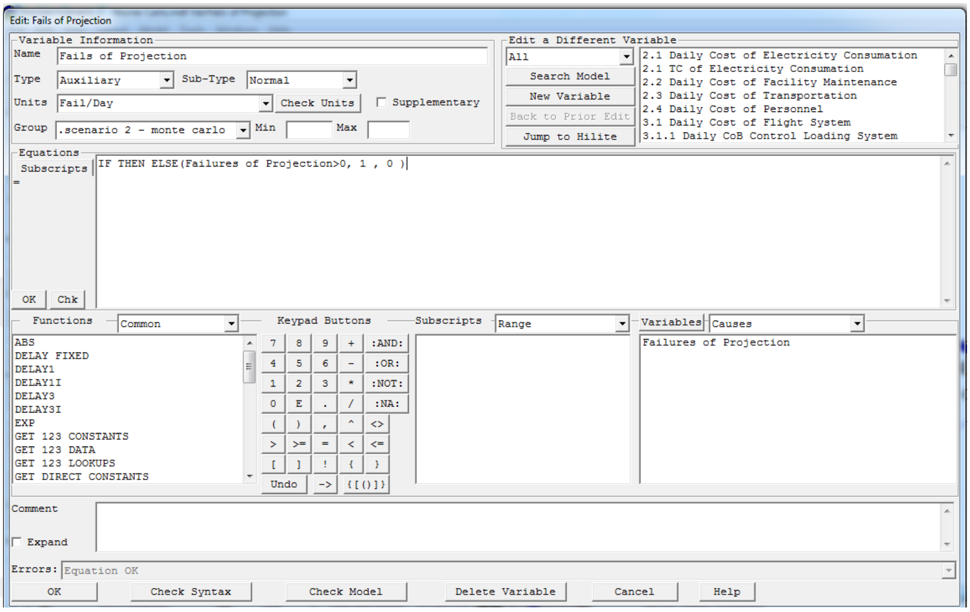

Figure 3.24: Data input form of VENSIM for Variables

Rate function of VENSIM, add one breakdown to total breakdowns if there is a breakdown on that thay. As mentioned previously this data come from random data generation function. Thus total breakdowns number can be counted during the working period of simulation.

When noise seed changes, different random breakdown data change. Thus the result of simulation changes. This allow to generate multiple simulation results compatible with the data distribution function. (Figure 3.25)

By generating random daily breakdowns for each component, calculating total cost of corrective maintenance of each component during life cycle of simulator is possible. By adding all components to related subsystem compatible with BOM, the total corrective maintenance cost of subsytems can also be calculated (Figure 3.26 , Figure 3.27). The same method can be applied to all BOM with bottom-up technique.

The sum of total corrective maintenance costs of subsystems gives the total cost of corrective maintenance (breakdowns) of flight simulator (Figure 3.28).

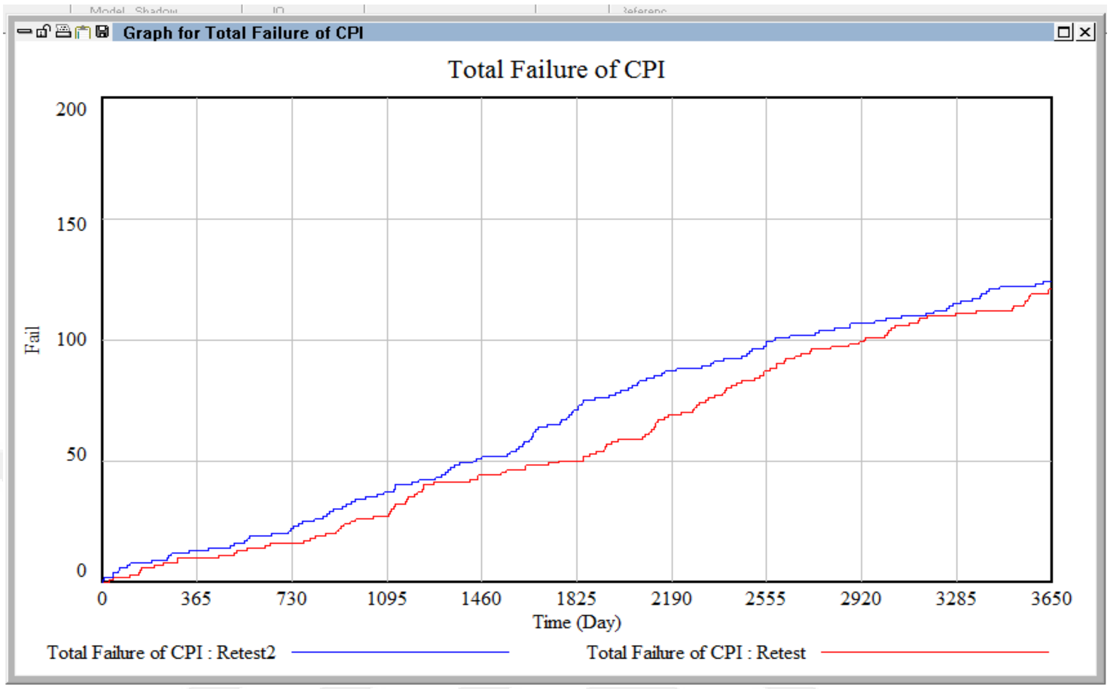

Figure 3.25: Different Results of Simulation for Number of Breakdowns with Using Different Noise Seeds

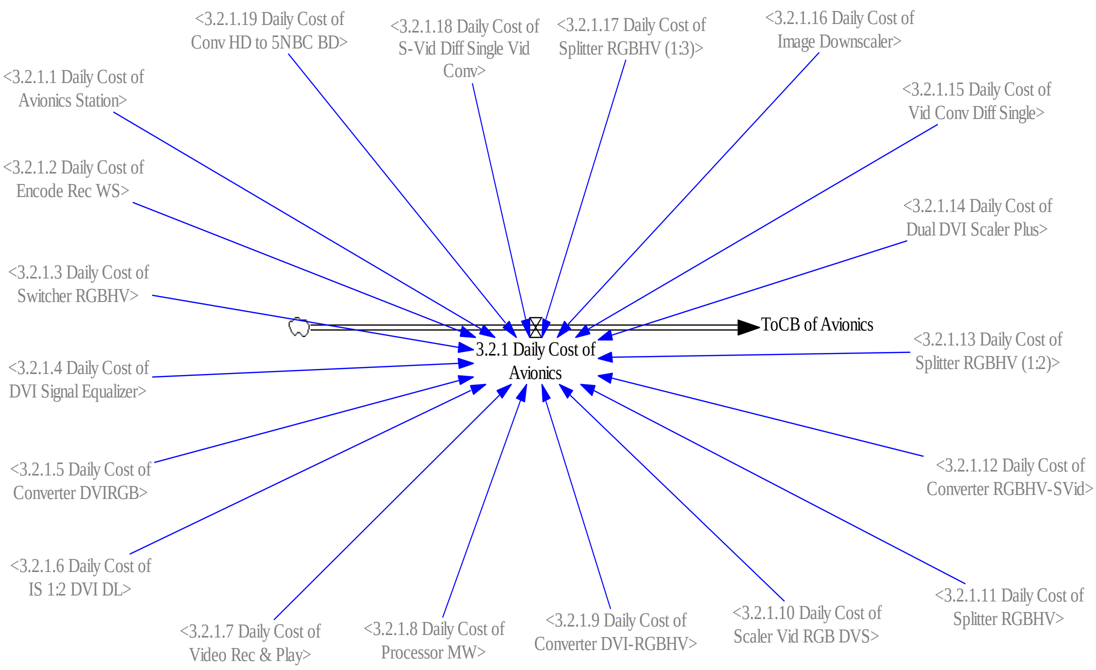

Figure 3.26: Level-3 Total Cost of Avionics Subsystem of a Flight Simulator

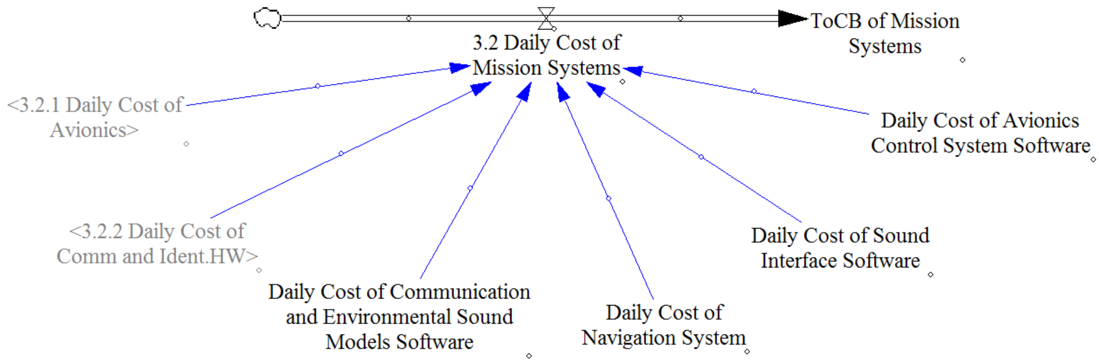

Figure 3.27: Level-2 Total Cost of Avionics Subsystem of a Flight Simulator

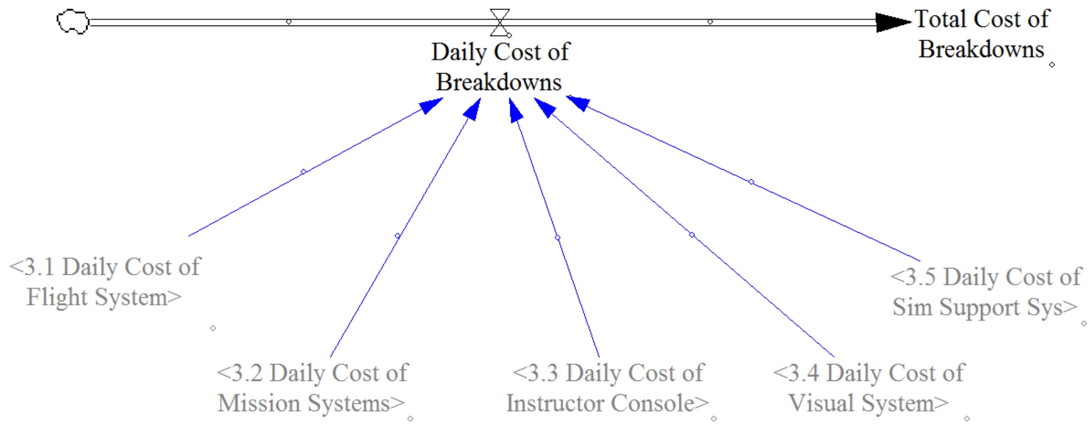

Figure 3.28: Level-1 Total Corrective Maintenance Cost of a Flight Simulator

3.3.5.7 Estimation of number of breakdowns

This part of model serves the purpose of calculating corrective maintenance cost of a component, subsystem or completely flight simulator. The purpose may be calculating only the number of breakdowns. It can be used in statistical studies, spare parts acquisition planning, stock management, research & development studies by engineers or any other purposes. To get outputs of total number of breakdowns, the total failures of components and subsystems should be used (Figure 3.29) and another part should be designed in simulation model (Figure 3.30)

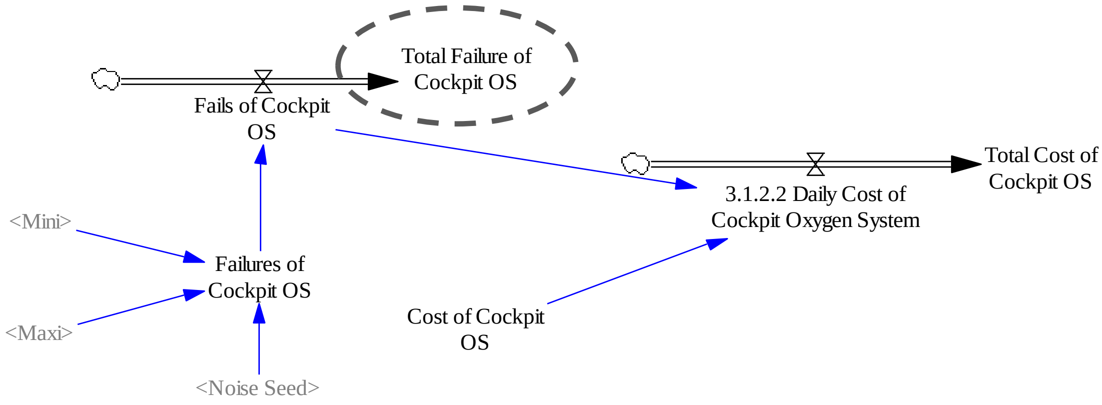

Figure 3.29: Simulation Model for Prediction of Failures of Cockpit-Oxygen System Component

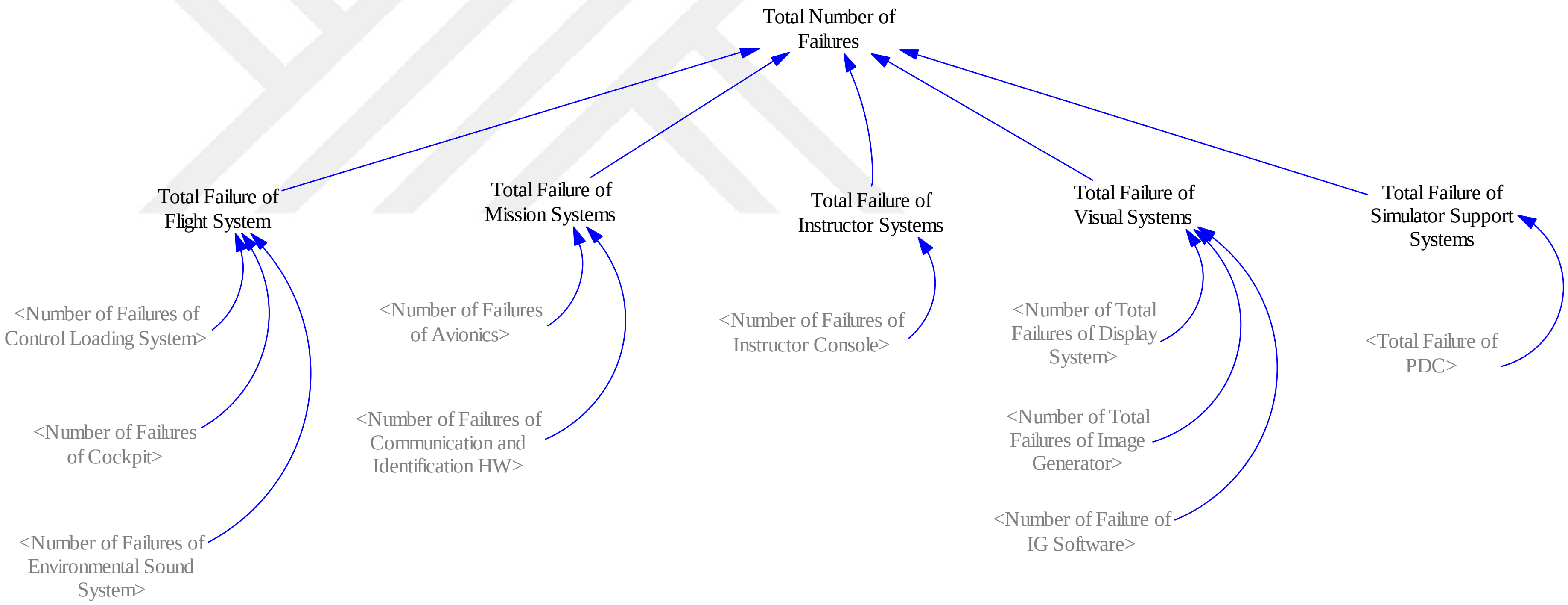

Figure 3.30: Simulation Model for Calculation of Total Number of Failures

3.3.6 Scenarios for Different MTBF Values

Windchill contains reliability data on both commercial and military electronic and non-electronic components in Electronic Parts Reliability Database (EPRD) and Non-Electronic Parts Reliability Database (NPRD). There are different values for reliability of components as Failure per Million Hour (FPMH) which were collected from different sources and under different kinds of conditions. There are several data which were collected from Commercial and Military sources such as Airborne, Airborne-Attack, Ground, Ground-Fixed, and Naval etc. On the other hand, there are also different values for the same component which were used under similar conditions of use. This difference may occur according to quality of (may vary according to manufacturer) of the component, conditions of use (environment) and user.

By using these different FMPH values, MTBF values are calculated by using conversion mentioned above. In this study, 2 (two) different scenarios are examined in order to analyze values of Total Maintenance Cost obtained by running the model with different MTBF values. Three of these MTBF values were used from Windchill. The minimum, median and the maximum FMPH values of latest versions of EPRD (2016) and NPRD (2016) of Windchill were used to calculate a weighted MTBF value and run one scenario.

The second scenario was prepared by using Failure Database of manufacturer (or user). Failure records in failure database have been analyzed and MTBFs (days) have been calculated by calculating the time between the failures for same components as mentioned in the previous sections.

MTBF values of two scenarios which were used in simulation model are given in Table 3.6. Three columns under Windchill Database contain MTBF data for three scenarios mentioned above. "Failure Database" column contains the MTBF data for fourth scenario. If there is not sufficient failure records and MTBF value could not calculated, average Windchill MTBF value was used for related component.

Table 3.6: MTBF Values used in Simulation Model according to Two Scenarios

(BOM)	WINDCHILL DATABASE				FAILURE DATABASE	
ID	MTBF Min	MTBF-Med	MTBF-Max	MTBF-Cal	MTBF Calc. (Failure Records)	Nb. of Failure
3.1.1.1	6,967.67	1,074.44	534.60	1,966.67	530.33	1
3.1.1.2	27,173.91	20,109.40	4,578.75	18,698.37	-	0
3.1.1.3	44,642.86	6,684.49	5,697.36	12,846.36	-	0
3.1.1.4	21,626.30	18,011.53	15,318.63	18,165.17	-	0
3.1.2.1	15,470.30	3,491.62	286.12	4,953.82	102.25	25
3.1.2.2	41,946.31	15,586.03	4,578.75	18,144.87	-	0
3.1.2.3	-	-	-		-	0
3.1.2.4	328,947.37	16,711.23	15,318.63	68,518.49	-	0
3.1.2.5	6,250,000.00	10,064.41	5,028.16	1,049,214.30	-	0
3.1.2.6	5,012.03	2,463.54	840.39	2,617.76	2,169.60	1
3.1.2.7	29,205.61	3,308.63	181.50	7,103.60	1,124.86	2
3.1.2.8	22,482.01	17,076.50	2,245.78	15,505.63	751.88	3
3.1.3.1	781,250.00	189,393.94	41,666.67	263,415.40	-	0
3.1.3.2	2,083,333.33	5,028.16	3,483.84	351,154.97	-	0
3.1.3.3	223,214.29	25,303.64	19,778.48	57,367.89	-	0
3.1.3.4	65,789.47	33,422.46	11,996.16	35,245.91	-	0
3.2.1.1	1,337.76	255.01	28.50	397.72	-	0
3.2.1.2	1,337.76	255.01	28.50	397.72	-	0
3.2.1.3	183,823.53	18,825.30	15,318.63	45,740.56	-	0
3.2.1.4	74,404.76	27,173.91	5,012.03	31,352.07	-	0
3.2.1.5	89,285.71	10,032.10	8,378.02	22,965.36	-	0
3.2.1.6	66,489.36	27,173.91	5,012.03	30,032.84	-	0
3.2.1.7	183,823.53	19,968.05	15,318.63	46,502.39	-	0
3.2.1.8	36,127.17	3,765.06	1,795.98	8,830.56	-	0
3.2.1.9	54,347.83	719.30	363.01	9,598.01	-	0
3.2.1.10	1,337.76	359.63	181.50	492.96	-	0
3.2.1.11	66,489.36	27,173.91	5,012.03	30,032.84	-	0
3.2.1.12	89,285.71	17,409.47	8,378.02	27,883.60	-	0
3.2.1.13	66,489.36	27,173.91	5,012.03	30,032.84	-	0
3.2.1.14	1,337.76	359.63	181.50	492.96	-	0
3.2.1.15	54,347.83	719.30	363.01	9,598.01	-	0
3.2.1.16	1,337.76	359.63	181.50	492.96	-	0
3.2.1.17	66,489.36	27,173.91	5,012.03	30,032.84	-	0
3.2.1.18	89,285.71	10,032.10	8,378.02	22,965.36	-	0
3.2.2.1	781,250.00	189,393.94	41,666.67	263,415.40	-	0

(BOM)	WINDCHILL DATABASE				FAILURE DATABASE	
ID	MTBF Min	MTBF-Med	MTBF-Max	MTBF-Cal	MTBF Calc. (Failure Records)	Nb. of Failure
3.2.2.2	223,214.29	25,303.64	19,778.48	57,367.89	-	0
3.2.2.3	10,486.58	359.63	181.50	2,017.77	-	0
3.2.2.4	223,214.29	25,303.64	19,778.48	57,367.89	-	0
3.2.2.5	223,214.29	25,303.64	19,778.48	57,367.89	-	0
3.2.2.6	223,214.29	25,303.64	19,778.48	57,367.89	-	0
3.2.2.7	367,647.06	39,808.92	30,637.25	92,920.00	-	0
3.2.2.8	7,118.45	3,426.54	1,231.77	3,676.06	-	0
3.2.2.9	183,823.53	19,841.27	15,318.63	46,417.87	-	0
3.2.2.10	183,823.53	19,841.27	15,318.63	46,417.87	-	0
3.2.2.11	183,823.53	19,841.27	15,318.63	46,417.87	-	0
3.2.2.12	781,250.00	189,393.94	41,666.67	263,415.40	-	0
3.2.2.13	1,257.04	359.63	181.50	479.51	-	0
3.2.2.14	14,602.80	1,681.46	1,318.29	3,774.49	-	0
3.2.2.15	223,214.29	25,303.64	19,778.48	57,367.89	-	0
3.2.2.16		29.50		29.50	-	0
3.3.1	94,696.97	50,403.23	20,161.29	52,745.19	-	0
3.3.2	148,809.52	27,173.91	5,012.03	43,752.87	-	0
3.3.3	27,173.91	10,382.06	5,016.05	12,286.37	-	0
3.3.4	18,115.94	6,921.37	3,344.03	8,190.91	-	0
3.3.5	7,118.45	3,426.54	1,231.77	3,676.06	-	0
3.3.6	22,321.43	4,688.67	251.16	6,887.88	1,414.58	1
3.3.7	54,347.83	20,764.12	10,032.10	24,572.73	-	0
3.3.8	54,347.83	20,764.12	10,032.10	24,572.73	751.88	3
3.3.9	27,173.91	3,960.71	2,024.62	7,506.90	1,124.86	2
3.3.10	1,337.76	255.01	28.50	397.72	-	0
3.3.11	89,285.71	35,714.29	10,032.10	40,362.49	-	0
3.3.12	54,347.83	20,764.12	10,032.10	24,572.73	-	0
3.3.13	19,349.85	1,654.31	285.01	4,375.35	-	0
3.3.14	625,000.00	41,946.31	9,484.07	133,711.55	-	0
3.3.15		29.50		29.50	-	0
3.3.16	215,517.24	15,060.24	10,162.60	47,653.47	1,331.46	1
3.4.1	148,809.52	27,173.91	5,012.03	43,752.87	149.93	15
3.4.2.1	15,060.24	7,200.46	2,847.38	7,784.91	-	0
3.4.2.2	1,337.76	211.51	181.50	394.21	70.42	34
3.4.3		29.50		29.50	-	0
3.5.1	297,619.05	36,337.21	20,096.46	77,177.39	713.52	1

MTBF data obtained from EPRD & NPRD database can be used as weighted value. To calculate weighted MTBF value, an equation which is used for unit cost forecasts with using weighted data can be adapted.

$$UC = A + 4B + C / 6$$

Where;

UC: Forecast Unit Cost

A: minimum unit cost of previous projects

B: average unit cost of previous projects

C: maximum unit cost of previous projects

With adapting this equation, MTBF value can be calculated as;

$$MTBF = MTBF_{min} + 4\ MTBF_{med} + MTBF_{max} / 6$$

For example, MTBF value for component numbered as 3.1.1.1 in BOM can be calculated as follows:

$$MTBF= 6{,}967.67 + 4*1{,}074.44 + 534.60 / 6$$

$$MTBF = 1{,}966.67$$

3.3.7 Monte Carlo Simulation

The Monte-Carlo method was already proposed by several authors for the calculation of the mean values of reliability key figures of systems (Fleischer, Wawerla, & Niggeschmidt, 2007).

In this study, stochastic cost calculations were made by Random Poisson data distrubition with using MTBF data of each component. In this random distribution function, Noise Seed is used to generate random breakdowns over 200 runs. To estimate the total cost distrubition of flight simulator corralated with noise seed, Monte Carlo analysis is the suggested method to see the probabilities.

In Figure 3.31 the probability of distrubition function of number of breakdowns can be seen. This graph helps to analyse the number of breakdowns will occur in which range with which probability. For this study, number of breakdowns occuring within ranges of 50%, 75%, 95% and 100% probabilities are shown in Figure 3.31.

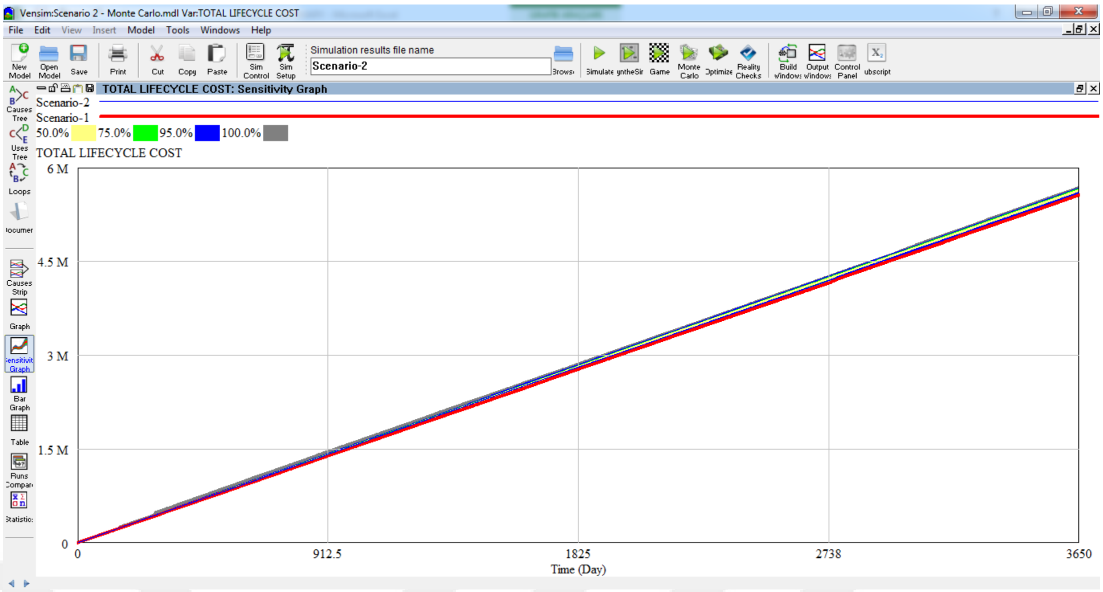

Figure 3.31: Sensitivity Analysis of Total Cost Estimations

The statistical distrubitions of total total cost is shown in Figure 3.31. The range of distubition with probabilities 50%, 75%, 95% and 100% can be analysed by examining this graph.

According to sensitivity analysis by using Noise Seed parameter, the range of distrubition of total cost estimation is narrow. This means, total cost estimation can be done very close to real numbers in a narrow range since noise seed does not change to result in a wide range.

3.3.8 Determining Number of Runs of Simulation Model

At first step, both two scenarios were run in the simulation model by entering the related MTBF data for all components. The model initially were run 10 times for two scenarios. After performing 10 runs the outputs of the simulation model have transferred to Microsoft Excel. By using Excel, descriptive statistics of results of 10 runs have been calculated. The results are shown in Table 3.7.

Table 3.7: Descriptive Statistics for 10 Runs of Four Scenarios

Descriptive Stats of 10 Runs	**Scenario 1**	**Scenario 2**
Mean	5561320	5640290
Standard Error	6448.725455	7233.708746
Median	5553860	5633100
Mode	#YOK	#YOK
Standard Deviation	20392.66044	22874.99557
Sample Variance	415860600	523265422.2
Kurtosis	4.358413567	1.732289237
Skewness	1.923107107	1.39080417
Range	70390	75980
Minimum	5541660	5614450
Maximum	5612050	5690430
Total	55613200	56402900
Count	10	10
Confidence Level (95.0%)	14588.03048	16363.78605

According to results of 10 runs, the confidence level (%95) values varies. In accordance with the purpose of this study, we want less varying results to improve the confidence level.

To get more accurate results, the simulation model must be run more than 10 times. The resulting results are analyzed statistically and tested to see if they have the desired reliability. Correct run number should be found in order to get accurate results at desired level of confidence.

$$\mathrm{n} = \frac{{z_1}^2 - \alpha}{2} * \frac{\mathrm{s}^2}{h^2}$$

Or

$$n = n_0 * \frac{{h_0}^2}{h^2}$$

n: Required number of runs for desired confidence level.

n_0 : Number of first run

h_0 : Confidence Level of first runs

h :Desired Confidence Level

The confidence level can be achieved by running the model at sufficient times. For example in this study, if maximum ± 5.000 USD is desired for the confidence interval, then to get the results at desired confidence level, required number of runs should be calculated by using the formulas above. By using this formula necessary runs for all scenarios were calculated and the results are given in Table 3.8:

Table 3.8: Calculation Necessary Runs for Desired Confidence Level

Necessary Runs for Conf.Level of 5.000 USD	**Scenario 1**	**Scenario 2**
Result	85.12	107.11
Nb of Runs Required	86.00	108.00

At last step, the model has been run at neccesary number which were calculated above. The result are transferred to Microsoft Excel and descriptive statistics were calculated again. The results are given in Table 3.9:

Table 3.9: Descriptive Statistics after Performing Required Number of Runs

Descriptive Stats After Performing Required Nb.of Runs	**Scenario 1**	**Scenario 2**
Mean	5561287.558	5637411.204
Standard Error	1857.315023	2050.736513
Median	5557735	5635665
Mode	5553550	5650250
Standard Deviation	17224.03095	21311.879
Sample Variance	296667242.2	454196186.4
Kurtosis	1.787926836	0.489536314
Skewness	1.176440475	0.262646547
Range	88390	119700
Minimum	5533450	5580460
Maximum	5621840	5700160
Total	478270730	608840410
Count	86	108
Confidence Level (95.0%)	3692.839855	4065.345959

CHAPTER FOUR

4. RESULTS AND DISCUSSION

In this thesis, the total operating and maintenance cost of a flight simulator which is important part of life cycle cost of the flight simulator was investigated. The main cost items of a flight simulator were identified. The building construction cost, flight simulator purchasing cost, preventive simulator maintenance cost, operating costs and corrective maintenance costs were identified as five main cost items. Building construction cost and flight simulator purchasing cost were excluded from the research since there are various researches on these subjects and these items can easily be added to model if they are necessary. The inflation effect has also been ignored since all calculations were made by USD and it has similar effect with inflation. If calculations are made in Turkish Curency and inflation effect is to be considered, it can be added into model. The main purpose of this study was to estimate the cost of flight simulator after its installation over its life cycle.

At first step, three of five main cost items were analyzed. All fixed and variable cost items that constitute LCC were identified. To calculate the periodic maintenance cost, two different cost items has been identified. A fixed amount was calculated by investigating the spare parts and consumables expenses that need to be replaced during periodic maintenance. In general, periodic maintenance costs are naturally fixed since it was added as a fixed cost item. If there are different types of periodic maintenance cost items at different amounts, they can be added to the model to generate separate inputs.

Secondly, the operating costs of a flight simulator were analyzed. All the costs that constitutes the operating costs were examined. There were various fixed and variable operating cost items such as electricity consumption, facility maintenance, transportation and personnel costs. Electricity cost is calculated by multiplying the price of electricity and the total consumption of facility or flight simulator seperately. If there are any changes in price of electricity or average daily flight hours of flight simulator, it can be easily changed in the model. Facility maintenance is average daily cost and it can be found by converting costs of a defined period to daily cost. Transportation cost is addition of car rental fee and fuel costs. Personnel cost consists of all direct and indirect costs that are arising from the employement of personnel. Salaries, compensation, meal fee, bonus, insurance and taxes are included into model as main cost items of personnel. If there are another cost item related with main cost items, of course it can be added into model.

Finally, and the most important part of this study is corrective maintenance cost. In order to estimate total corrective maintenance cost in life cycle of the flight simulator, bill of materials of the flight simulator was formed. All subsystems and components of flight simulator were identified. Cost of each item and estimation of breakdown of related component were added into model as input. Estimation of breakdowns were calculated by data distribution functions using Mean Time Between Failure (MTBF) values recorded by previous experiments or found in library of Windchill Quality Solutions software. The two scenarios have been prepared according to different MTBF data on Windchill and Failure Database of User/Manufacturer. In the first scenario, MTBF values were determined using Three-Point Estimate Method considering minimum, average and maximum of FMPH values in Windchill database. In the second scenario, MTBF values were determined using Failure Database.

4.1 Analysis of Outputs

Settings of the model were made compatible with the life cycle of flight simulator. The model was run. For each variable, it is possible to get the result as graph or table.

It is possible to get daily and total costs from the simulation model. Number of failures, preventive maintenance of flight simulator, operational and corrective maintenance costs and other variables can also be analyzed. Total life cycle cost of components, subsystems and the flight simulator can be viewed as graph or table. In this section, outputs of simulation are analysed.

Since preventive simulator maintenance is a fixed cost, total cost of periodic simulator maintenance results show a regularly increasing trend. This is an expected result since the periodic maintenance are done regularly and costs were converted to daily units as fixed costs. Daily preventive maintenance cost is calculated as approaximately 107,56 USD. Annual preventive simulator maintenance cost is 39.259,40 USD and the total preventive maintenance cost over a 10-year period is 392.594 USD.

Operational costs also show an increasing trend since operational costs are fixed costs. It was calculated monthly and converted to daily basis compatible with the model. Daily operational cost was calculated approximitely 1389 USD. Annual operational cost is 506.985 and the total operational cost over a 10-year period is 5.069.985 USD.

The number of breakdowns are multiplied by the cost of component to find the corrective maintenance cost. As mentioned before, this calculations were made stochastically. Annual corrective maintenance cost vary from year to year as shown in Figure 4.1. Therefore, the cumulative corrective maintenance cost shows an irregular behaviour since breakdowns suddenly appear on some days randomly.

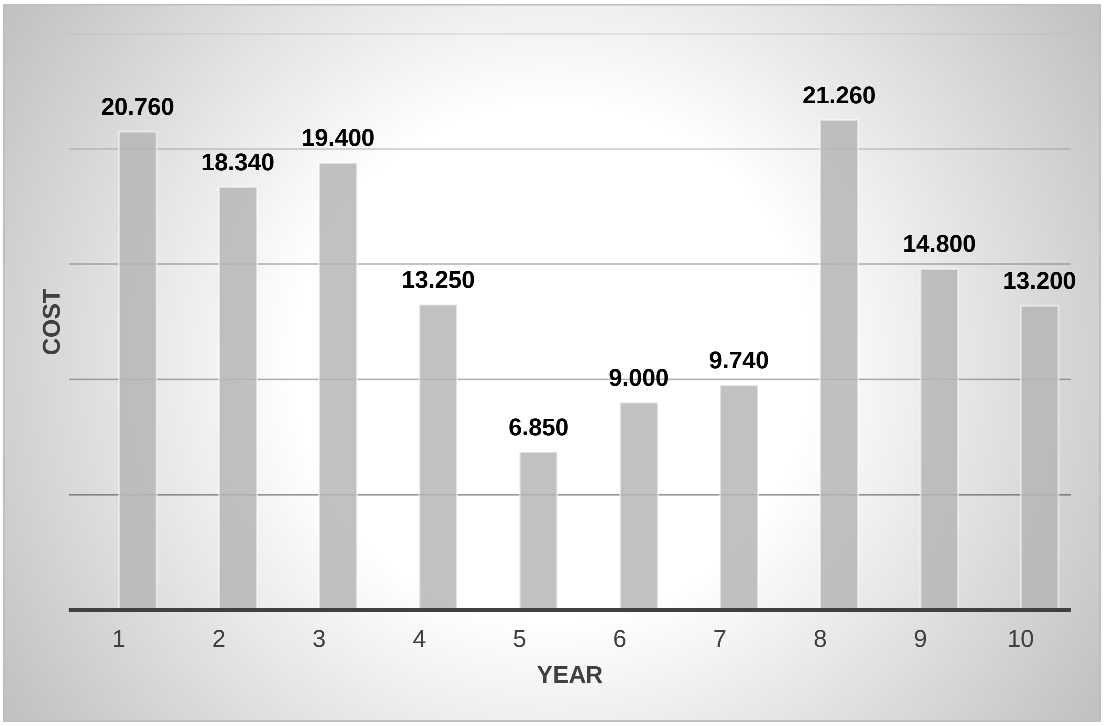

Figure 4.1: Annual Corrective Maintenance Cost of a Flight Simulator

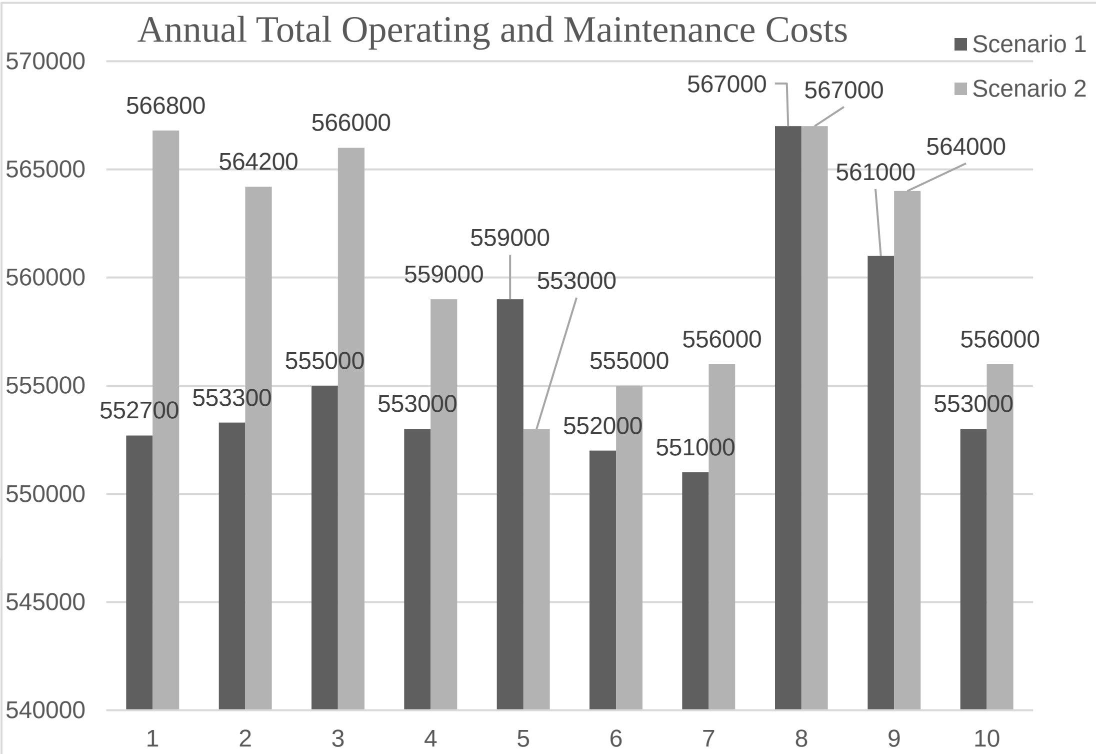

Figure 4.2: Annual and Total Operating and Maintenance of a Flight Simulator

Total life cycle cost of simulator has fixed and variable costs. Annual total cost of a flight simulator vary from year to year because of random failures. Thus cumulative total cost of flight simulator shows irregular increasing trend since corrective maintenance cost affect the regularity of total costs (Figure 4.2).

Statistical information about simulation can be seen on “statistics” mode of VENSIM Simulation software. This is small numerical brief about the results. Minimum, maximum and average daily cost can be seen as shown in Table 4.1.

Table 4.1: Statistical Analyses of Simulation of the Model

VARIABLE	COUNT	MIN	MAX	MEAN	MED.	STDEV	(NORM)
Scenario-1	3651	0	5.607 M	2.807 M	2.809 M	1.616	.5756
Scenario-2	3651	0	5.557 M	2.772 M	2.773 M	1.604	.5786

To analyse the number of breakdowns of subsystems, VENSIM gives numerical and graphical outputs. Numerical data can be used to analyze failures of component, subsystems and flight simulator by daily or for desired time intervals. For example, annual breakdowns of flight system are shown in Figure 4.3 for the two scenarios.

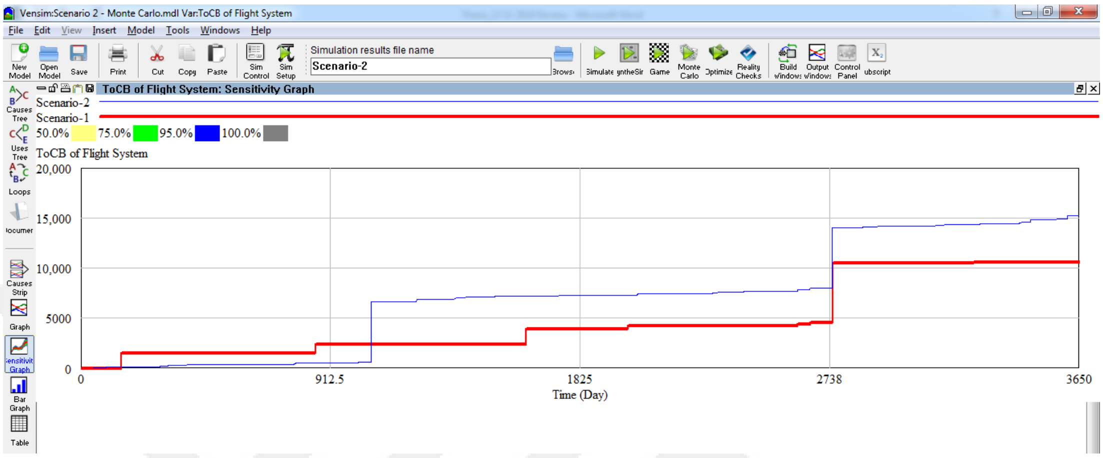

Figure 4.3: Total Number of Failures of Flight System

Simulation model allows us to generate such information for all components, subsystems and whole system. By using these information, graphs or statistical analysis can be prepared and analysed. VENSIM can generate graphical and statistical outputs. But if output type or information is insufficient, row ouput data can be exported to Microsoft Excel and output can be prepared manually.

It is useful to generate such graphs to examine in which subsystems breakdowns occur frequently. Timeline graphs show daily expected failures in each subsystem. Thus maintenance planning and research and development works can be done according to these information. On the other hand, total number of failures of flight simulator is shown in Figure 4.4 can be used for several purposes such as personnel employment planning compatible with breakdown numbers.

The number of total failures of a flight simulator can be viewed as graph over 10 years (Figure 4.4). In this graph it is possible to see annual accumulated number of breakdowns of flight simulator and total number of breakdowns over 10 years. By analyzing this graph, it is possible to see annual number of total failures of the system year by year. It may help to estimate annual number of failures for each component, subsystem and whole system.

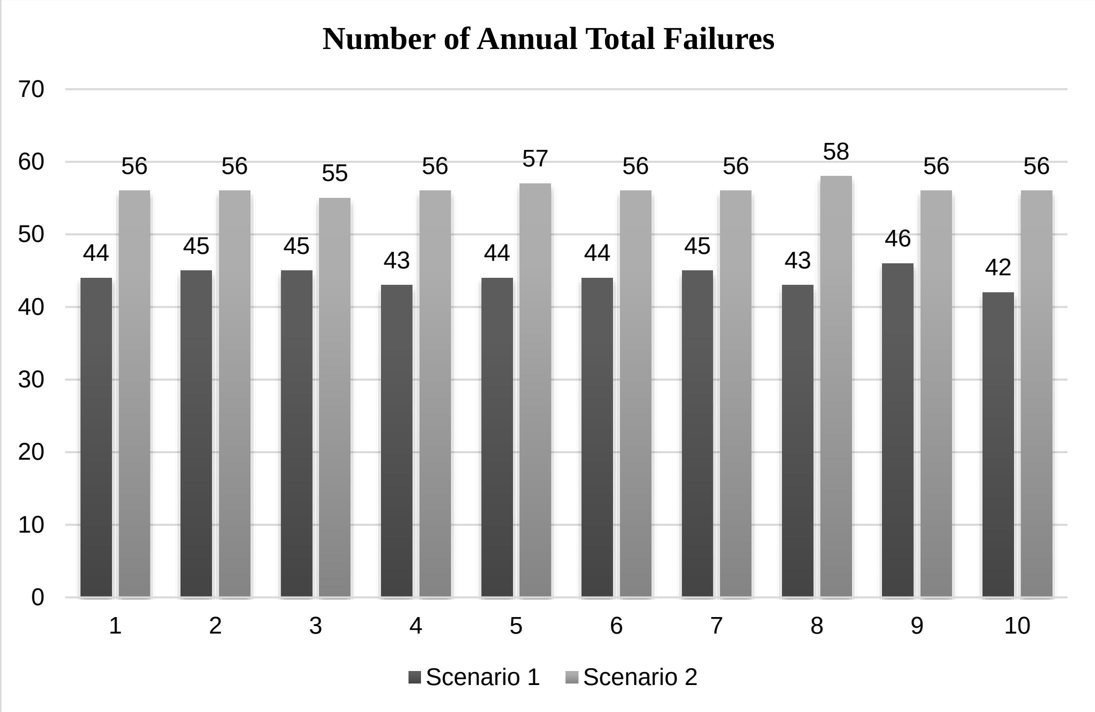

Figure 4.4: Number of Total Annual Failures of a Flight Simulator

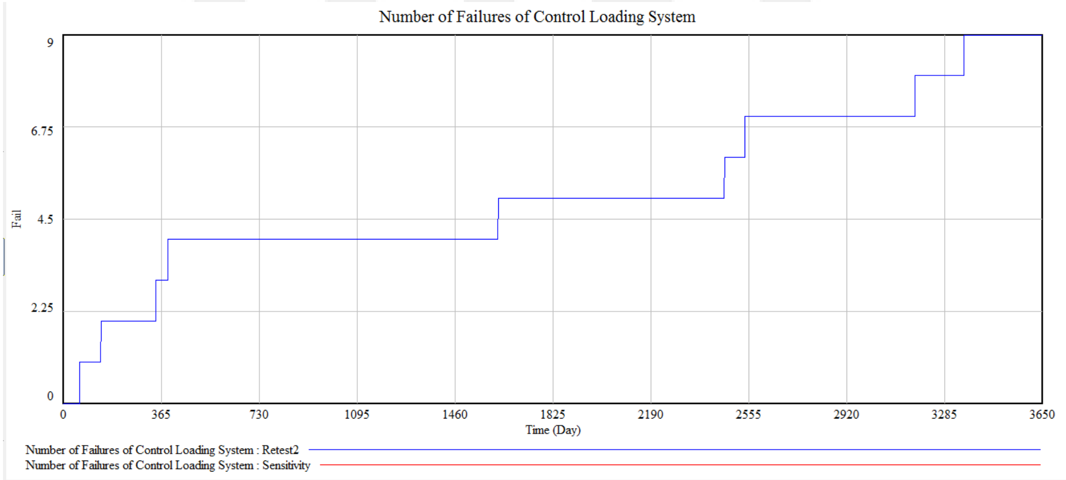

Figure 4.5: Total Cumulative Number of Failures of Control Loading System

VENSIM Simulation software allows creating outputs for all variables. If lower level analysis is needed, it can be created by selecting the variable and clicking on "graph" button on the left side of the program. To analyse breakdowns in more detail, lower levels (subsystems or components) should be selected and output should be created as shown in Figure 4.5.

To make what-if analysis on simulation model, "SynthSim" mode should be used. It allows to see effects of parameters change on the results. (Figure 4.6) For example, to see the effect of Final Time change, slider of Final Time parameter should be moved left or right side.

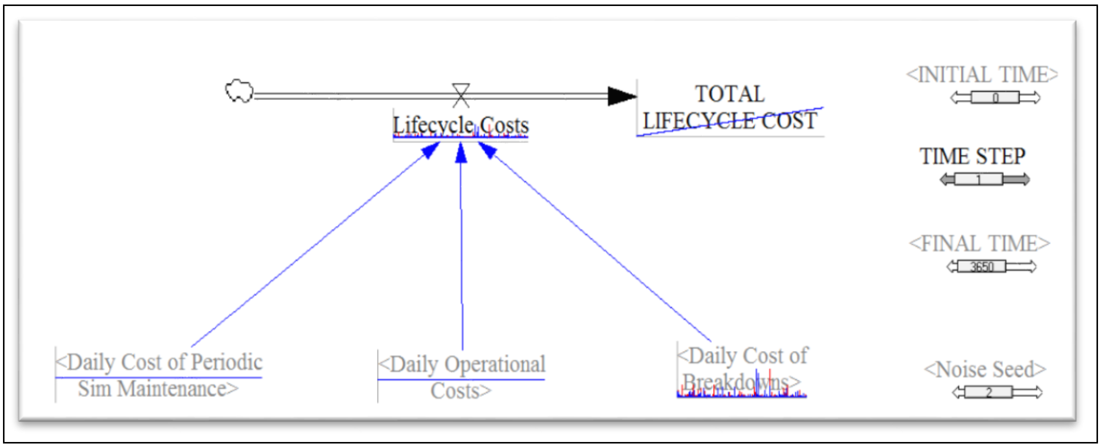

Figure 4.6: Reference Mode and SyntheSim View of the Model

VENSIM allows different analyses based on graphs with various kind of outputs. As an example, total cost shows increasing trend but for long time simulations it is hard to see the daily details. A graph which consist of accumulated total life cycle cost and daily basis cost help to do daily cost analysis better (Figure 4.7).

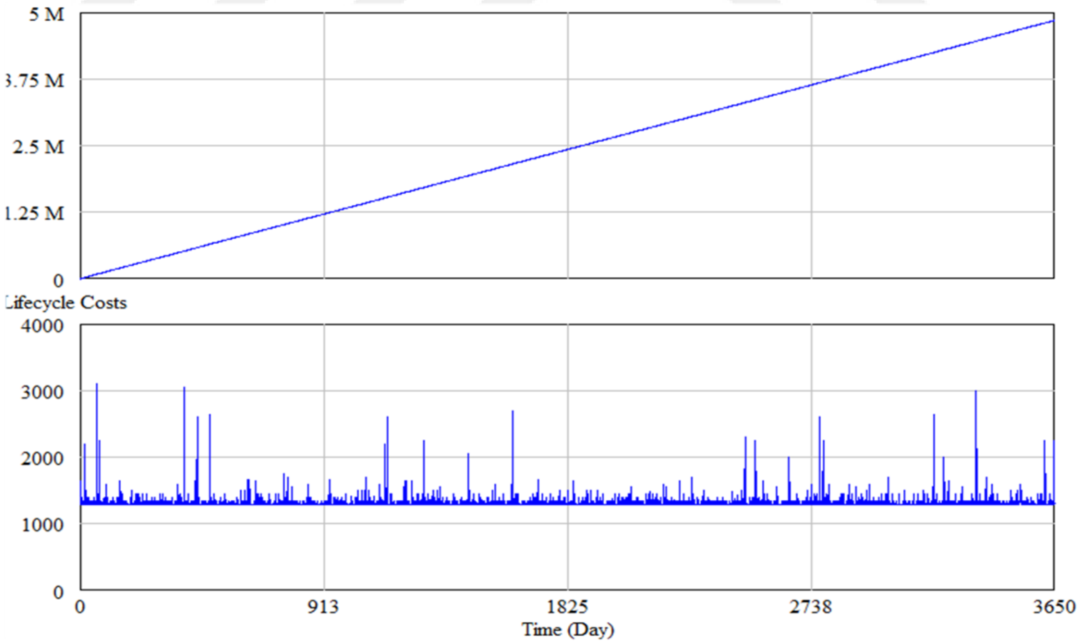

Figure 4.7: Reference Mode and SyntheSim View of the Model

It is also possible to see the results as numeric on table format (Figure 4.8). To do this “Table Time” button should be clicked. To use results in calculations or to understand value changes better it is a necessary output of the simulation. In this study, the total estimated operating and maintenance cost is estimated 5.561.287,56 and 5.637.411,20 Million USD respectively in the two different scenarios (except purchasing cost of simulator and building construction cost).

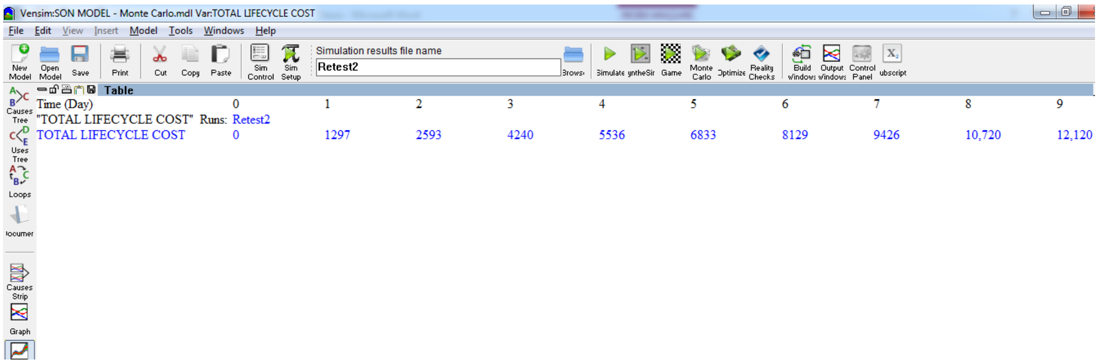

Figure 4.8: Table Form Output of Total Life Cycle Cost Data

Figure 4.9 shows the effects of subsystems and their subsystems to number of breakdowns occurred. This causes tree allows to see trend characteristics of breakdowns of each subsystems, their subsystems and whole system.

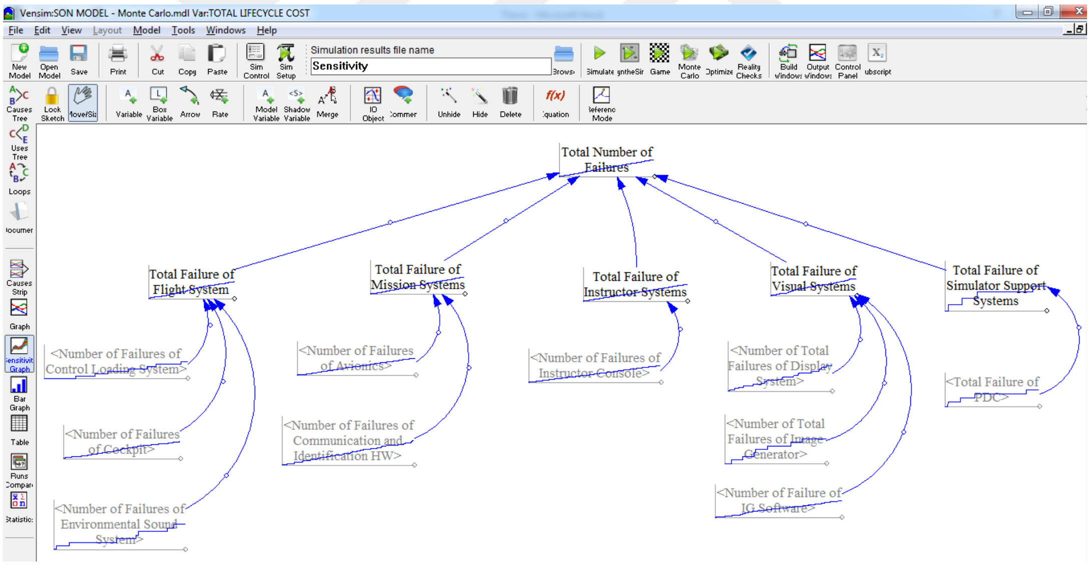

Figure 4.9: Total Number of Failures and Causes Tree

4.2 Simulation Model Results

After running the two scenarios for 10 years,the Total Operating and Maintenance Cost Estimation is shown in Figure 4.10.

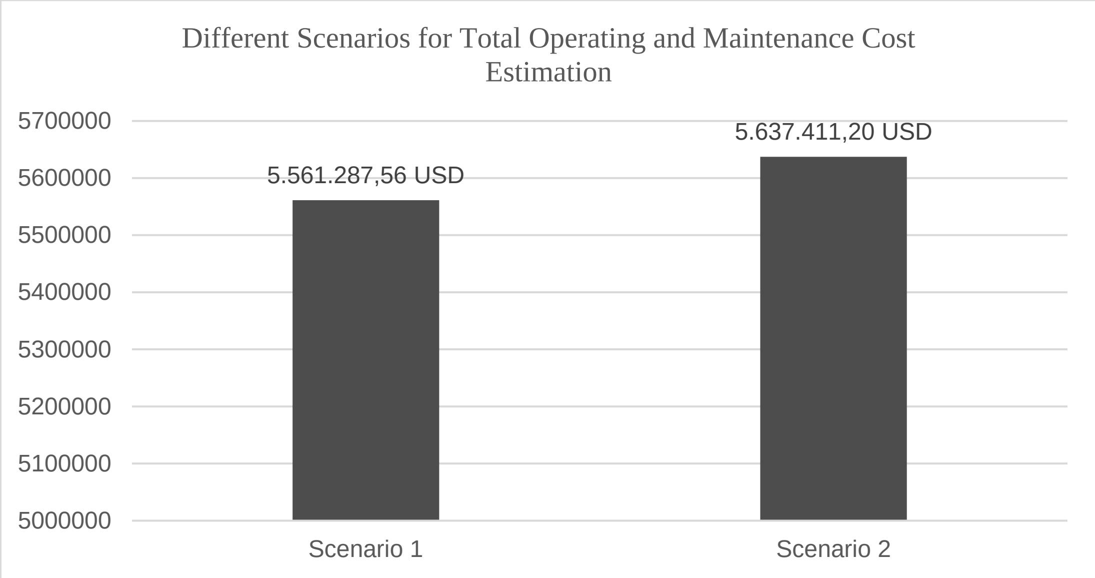

Figure 4.10: Results of Two Scenarios for Operating and Maintenance Cost of Simulator

According to the results, the average annual cost varies from 5.561.287, 56 USD (with std.deviation of 1857.32) to 5.637.411, 20 USD (with std.deviation of 2050.74). This means; after 10 years the total operating and maintenance cost of simulator will be between 5.559.430, 24 USD and 5.639.461, 94 USD with a probability of 95%.

CHAPTER FIVE

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

With the development of technology, flight simulators are used for flight training much more than in the past. It is always thought that flight simulators are cost effective or not. There are many researches focused on this subject. Many of them made cost-effectiveness analysis by using database that are recorded previously for several years. They collected the data from airlines or flight training companies and compare the real flight platforms and flight simulators. Most of them calculated the cost effectiveness ratio of the flight simulator to help deciders to make "buy or not to buy" decisions.

Recording data for several years and then comparing it for two or more alternatives is good and reliable method to get the real results. But it may be too late to calculate the life cycle cost of flight simulator or hourly training cost. Manufacturers, and companies that want to know the life cycle cost of flight simulator always prefer to know (in the meaning of estimation) the cost that they will encounter. To make budget planning, to determine the offer for tenders, to make "buy or do not buy" decisions it is necessary to examine the total life cycle cost of flight simulator at the beginning.

This study aims to estimate Total Operating and Maintenance Cost of a flight simulator which is an important part of Total Life Cycle Cost. To do this, all fix and variable costs were analysed deterministically or stockastically. The most important and hardest part of the study was determining the corrective maintenance cost. The main difficulties were collecting data from several sources and with various qualities, drawing the Bill of Materials until correct level and finding costs of components since there are too many components in the system and lack of cost information for some components.

After determining and classification of the cost types and collecting necessary data to use in calculations, a simulation model was created with help of VENSIM simulation software. For calculation of fix costs, deterministic analysis and formulation was done in the model. In order to estimate corrective maintenance costs, a special calculation module was used including Random Poisson data distrubition function for each component. According to this function, the parameters were determined such as mini, maxi, mean etc. To use in model, Mean Time Between Failures data are collected or calculating by using databases and Windchill Quality Solutions software. For all components a calculation module was created. Model structure was built compatible with BOM. All components were linked to subsystems and all subsystems were linked to system; flight simulator.

In the next step, simulation parameters were entered according to real life and simulation model was run. The results was both generetad as graph and table. If life cycle of simulator is accepted as 20 years or different than 10 years; model settings can be changed.

According to results of the simulation model, Total Operational Cost is 5.069.850 USD, Total Preventive Simulator Maintenance is 392.594 USD Total Corrective Maintenance Cost is between 96.800 and 146.600 USD and Total Number of Breakdowns is between 441 and 562. The Minimum Total Operational & Maintenance Cost is about 5.559.430, 24 USD and the Maximum Total Operatioanal & Maintenance Cost is about 5.639.461, 94 USD . If is purchasing cost of OFT is 7.000.000 USD, estimated percentage of total operating and maintenance cost is about %80 of the product price. The scrap / 2^{nd} hand price changes according to condition of the product. If the product will be sold with a higher price, Total LCC will be drop. The product may be used again with renewal or modernization instead of selling it. It may be much profitable option for owner. If the product cannot be sold or reused, the cost of scrap may arise due to legal requirements, necessary procedures and the cost of resources to be used to carry out these operations.

In this study, Life Cycle Cost of an Operational Flight Trainer was analysed and Total Operating and Maintenance Costs are tried to be estimated. It has been seen that these costs can be estimated with using the simulation model. This model allows to see total preventive maintenance and total corrective maintenance cost of components, subsystems and completely flight simulator in its life cycle. It also allows to examine number of breakdowns of components,subsystems or simultor that may occur in the next period.

5.2 Recommandations

To estimate the life cycle of a simulator and number of breakdowns that may occur in the future is necessary for airlines companies, manufacturers, training companies etc. They can be able to expect these informations at the beginning of the project / training activity by using such a method. It can be used in a wide range as calculation of necessary spare parts, budget planning, designing activities of engineers to improve the product etc.

In this study, BOM was detailed until fourth level in order to get accurate data which has been recorded previously until fourth level. There was constraints about data records to calculate MTBFs which were calculated with experimental data records.

Since the model is based on data, it is necessary to carry out the necessary studies to collect the correct and sufficient number of data. There were limited amount of data about cost. To find accurate data a detailed study had to be done. Cost data is very important to get accurate results for life cycle costs.

Cost items were identified with experimental information and with literature knowledge. Parameters may be changed according to organization but the whole method can be used to access these results. While sensitivity analysis, it is clear that data distrubitions are in a narrow range thus the data can be expected very near to the reality.

Recommended future studies would be;

- Repetition of the analyse at certain intervals to check whether the model fits real life or it should be updated with changing parameters.
- Recording breakdowns data accurately for each component and it may be much detailed. Database development is benefical for similar / common parts in different types of simulators.
- Defining BOM of simulator much detailed in order to earn time to analyse and keeping it up to date.

- Comparing simulation results with the feasibility and real life results and analyzing the difference.
- Keeping cost information up to date in the database.
- To carry out the necessary studies to include effective use of this study into the organizational processes for the price, feasibility, bid studies and spare parts planning of the products to be produced in the future.

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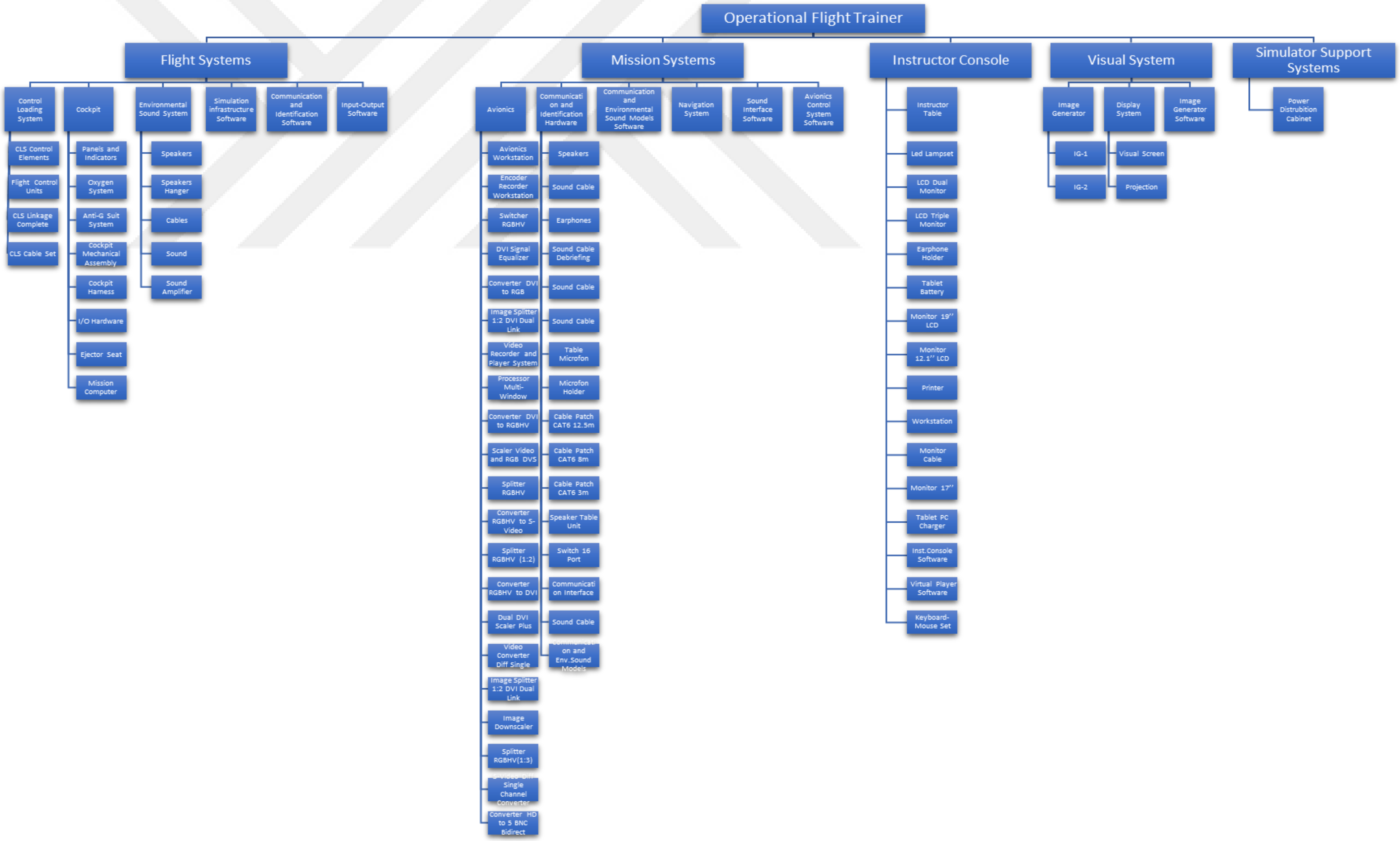
APPENDIX A – Product Tree of a Flight Simulator



RESUME

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