

ISTANBUL TECHNICAL UNIVERSITY ★ GRADUATE SCHOOL OF SCIENCE
ENGINEERING AND TECHNOLOGY

**ENGINE MAINTENANCE TIME PREDICTION WITH WEIBULL
DISTRIBUTION IN COMMERCIAL AVIATION**

M.Sc. THESIS

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Department of Aeronautics and Astronautics Engineering

Aeronautics and Astronautics Engineering Programme

JUNE 2013

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İSTANBUL TEKNİK ÜNİVERSİTESİ ★ FEN BİLİMLERİ ENSTİTÜSÜ

**TİCARİ HAVACILIKTA MOTORLARIN BAKIM ZAMANLARININ
WEIBULL ANALİZİ İLE ÖNGÖRÜLMESİ**

YÜKSEK LİSANS TEZİ

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To my spouse and family,

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April 2013

Kadir VAROL

Aircraft Powerplant Engineer

TABLE OF CONTENTS

	<u>Page</u>
FOREWORD	ix
TABLE OF CONTENTS	xi
ABBREVIATIONS	xv
LIST OF TABLES	xvii
LIST OF FIGURES	xix
SUMMARY	xxi
ÖZET	xxiii
1. INTRODUCTION	1
1.1 Purpose of Thesis	1
1.2 Literature Review	1
2. AVIATION AND MAINTENANCE	3
2.1 Aircraft Maintenance Checks	3
2.1.1 A check	4
2.1.2 B check	4
2.1.3 C check	4
2.1.4 D check	5
2.2 Maintenance References	5
2.2.1 Manufacturers' service bulletins/instructions	5
2.2.2 Maintenance manual	6
2.2.3 Overhaul manual	6
2.2.4 Structural repair manual	6
2.2.5 Illustrated parts catalog	7
2.2.6 Code of Federal Regulations (CFRs)	7
2.3 Airlines Cost Items	7
2.3.1 Airline profitability	8
2.3.2 Airline revenue and costs	8
2.3.3 Detailed airline costs	9
2.3.4 Maintenance cost distribution	11
3. ENGINE	15
3.1 Engine General Concept	15
3.1.1 Fan and booster	15
3.1.2 High pressure compressor (HPC)	16
3.1.3 Combustor	16
3.1.4 High pressure turbine (HPT)	16
3.1.5 Low pressure turbine (LPT)	17
3.1.6 Accessory drive	17
3.1.7 Airworthiness limitations	18
3.2 Engine Maintenance	20
4. AN INTRODUCTION TO RELIABILITY	23
4.1 Definition of Reliability	23

4.2 Definition of Failure	23
4.3 Classification of Failures	24
4.3.1 As to cause	24
4.3.2 As to suddenness	24
4.3.3 As to degree.....	24
4.4 Reliability Economics	24
4.5 Failure Rate, λ	25
4.6 Bathtub Curve.....	26
4.7 The Failure Probability Density Function, $f(t)$	27
4.8 The Relation between Reliability, Failure Rate and Probability Density Functions	28
5. RELIABILITY AND RATES OF FAILURE	29
5.1 Reliability Concepts	29
5.2 Probability Distributions in Reliability Evaluation	29
6. WEIBULL DISTRIBUTION AND ANALYSIS	33
6.1 Engineering Usage of Weibull Analysis	33
6.2 Scope of Weibull Analysis	34
6.3 Advantage of Weibull Analysis.....	35
6.4 Life Data and Aging: FH or FC.....	35
6.5 Weibull Probability Density Function.....	37
6.6 Failure Distribution	37
6.6.1 TheeEffect of β on the pdf.....	38
6.6.2 Characteristic effects of the η , for the Weibull distribution.....	38
6.6.3 Characteristic effects of the γ , for the Weibull distribution	39
6.7 Cumulative Distribution Function with Weibull Parameters	40
6.8 The Weibull Reliability Function.....	40
6.9 Weibull Failure Rate Function	41
6.10 Estimation of Weibull Parameters.....	42
6.10.1 Graphical Method.....	42
6.10.2 MLE (Maximum Likelihood) parameter estimation	46
6.10.3 MLE of accelerated life data	46
7. FAILURE FORECASTING.....	47
7.1 Forecasting Techniques	47
7.2 Calculating Failure Forecasts	47
7.2.1 Expected failures now	47
7.2.2 Failure forecast when failed units are not replaced.....	48
7.2.3 Failure forecasts when failed units are replaced	48
8. ENGINE FAILURE TIME PREDICTION WITH WEIBULL ANALYSIS .	49
8.1 Engine Failures for All CFM56-7B Engine Fleet	49
8.2 Data Analysis.....	50
8.2.1 Pareto analysis.....	50
8.3 Weibull Parameter Estimation.....	52
8.3.1 Weibull probability density function.....	54
8.3.2 Cumulative distribution function	54
8.3.3 Weibull reliability function	55
8.3.4 Weibull failure rate function	55
8.4 Evaluation of Engine Fleet Behavior and Life Prediction.....	56
8.4.1 Estimating the total engine failures quantity since 2009.....	56
8.4.2 Estimating the risk and failure quantities for a possible lease engines	57
9. CONCLUSIONS AND RECOMMENDATIONS	59

9.1 Recommendations	59
9.2 Conclusion.....	60
10. REFERENCES.....	62
11. APPENDICES	63
APPENDIX A:	63
APPENDIX B:	66
APPENDIX C:	72
CURRICULUM VITAE.....	75

ABBREVIATIONS

AC	: Aircraft
AD	: Airworthiness Directive
CAMP	: Continues Airworthiness Maintenance Program
CDF	: Cumulative distribution function
DGCA	: Directorate of General Civil Aviation
EASA	: European Aviation and Safety Authority
FAA	: Federal Aviation Administration
FADEC	: Full Authority Engine Digital Control
FC	: Flight Cycle
FH	: Flight Hour
IATA	: International Air Transport Association
LLP	: Life limited part
MTBF	: Mean time between failure
MTTF	: Mean time to failure
OpSpecs	: Operation Specifications
PDF	: Probability density function
SB	: Service Bulletin

LIST OF TABLES

	<u>Page</u>
Table 2.1 : Operational expenses of an airline.	10
Table 8.1 : Pareto analysis list.....	50
Table 8.2 : The most important failures which is effecting whole engine fleet.....	52
Table 8.3 : A sample list of Weibull Parameter Estimation.....	53
Table 8.4 : Weibull parameters for CFM fleet.	54
Table 8.5 : Lease aircrafts engines condition.....	58
Table 8.6 : Engine failure forecast for next five years lease term.....	58
Table A.11.1 : Table of failure times and failure reasons from CFMI Workslope Planning Guide for CFM56-7B engine type	64
Table B.11.2 : Weibull Parameter estimation table for engine source.....	66
Table C.11.3 : Sample engine failure quantity forecast for 2010	72
Table C.11.4 : Sample engine failure quantity forecast for 2011	72
Table C.11.5 : Sample engine failure quantity forecast for 2012	73

LIST OF FIGURES

	<u>Page</u>
Figure 2.1 : Operating expenses of an airline	11
Figure 2.2 : Maintenance expenses	12
Figure 3.1 : Primary and secondary flow	16
Figure 3.2 : General CFM56-7B engine concept.....	17
Figure 3.3 : Life Limited Parts (LLP) of CFM56-7B engine.....	18
Figure 3.4 : Engine general design	19
Figure 3.5 : Modular design of CFM56-7B engine.	20
Figure 3.6 : Engine on-condition monitoring.	21
Figure 4.1 : Balancing initial and post-production costs to determine optimum reliability	25
Figure 4.2 : The bathtub curve	26
Figure 5.1 : Frequency distribution and probability mass function	29
Figure 5.2 : Probability Distribution Function, $F(t)$	31
Figure 5.3 : Probability Density Function, $f(t)$	31
Figure 6.1 : The Weibull data plot	36
Figure 6.2 : The effect of the Weibull shape parameter on the <i>pdf</i> for a common η .38	38
Figure 6.3 : The effects of η on the Weibull pdf for a common β	38
Figure 6.4 : The effect of a positive γ , on the position of the Weibull <i>pdf</i>	39
Figure 8.1 : CFM56-7B Failure times and reasons in 2009.....	49
Figure 8.2 : Pareto plot.....	51
Figure 8.3 : Regression plot for β estimation.....	53
Figure 8.4 : Weibull Probability Density Function Curve	54
Figure 8.5 : Cumulative Distribution Function for general fleet	55
Figure 8.6 : Reliability function	55
Figure 8.7 : Weibull failure rate function plot for CFM56-7B engine fleet	56
Figure 8.8 : Comparison of estimation and real engine failure quantities	57

ENGINE MAINTENANCE TIME PREDICTION WITH WEIBULL DISTRIBUTION IN COMMERCIAL AVIATION

SUMMARY

"Aeronautics was neither an industry nor a science. It was a miracle." Igor Sikorsky said. In airlines perspective, aviation is the industry of this miracle.

Aviation is one of the most important transportation methods in the world. It is very different from other transportation types. Most important difference is three-dimensional movement of the aircraft that is not a common for human nature. This movement happens in the air over 30000 feet height for a narrow body aircraft. Therefore, choosing this type of transportation depends on feeling safe by human.

Safety is one of the most important thing in aviation. Number one rule called in aviation is "Safety Comes First".

Aircraft have high-level technological systems. These systems are manufactured and certified by aviation authorities to obtain optimum life and critical safety level. Technically all of components in the aircraft have to maintain continue to their operation in safe condition. On the other hand, safety has inverse ratio with profitability. Therefore, airlines try to take safety on optimum for making profitable business.

A Boeing 737-800 aircraft price is averagely 40 million dollars, which has average modification and with two CFM56-7B installed engines. Each engines price is 15 million dollars. It shows that engines are very important and expensive components. Additionally, aircrafts heavy maintenance cost is approximately 300,000 USD. However, engines heavy maintenance cost is approximately 2.5 million dollars.

If airlines may reduce their maintenance cost to not compromising safety, they may increase their profitability.

In this thesis, Weibull method is used for prediction of engine failure times and unscheduled failures number. Pareto analysis has been done to understand most effective failure modes to the whole failures. Life prediction method used for a sample fleet to obtain risk of engine failure of fleet. Additionally, same method applied to a lease aircraft candidate to understand its effect to an airline. At last, comparison was made and results were discussed.

As a result of this study, operators may evaluate their engine fleet and may decide their fleet's reliability. They also may predict the failure time of their engines before failure happens and can optimize their maintenance program with preventive maintenance activities.

Next step about this thesis may be about to expose failure reasons before they happen.

In this study, firstly, aviation and aviation related cost items are described. Then, importance of maintenance and engines are described. Additionally, Weibull method described and used for general and sample engine fleet.

TİCARİ HAVACILIKTA MOTORLARIN BAKIM ZAMANLARININ WEIBULL ANALİZİ İLE ÖNGÖRÜLMESİ

ÖZET

“Havacılık, ne bir bilim ne de bir endüstridir. O bir mucizedir.” demiş Igor Sikorsky. Havayollarına göreyse, havacılık mucizenin endüstridir.

Havacılık, ulaşım çeşitleri arasında en önemli olan yollardan biridir ve diğer ulaşım yöntemlerinden tamamen farklıdır. Bu farkların başındaysa hava ulaşım araçlarının üç boyutlu hareket etmesi gelmektedir ki bu tip hareket insan doğasının alışkın olmadığı bir hareket türüdür. Bu üç boyutlu hareket ortalama bir yolcu uçağında yaklaşık olarak 30000 feet yükseklikte meydana gelmektedir. İnsanların kendi doğalarına aykırı olan bu ulaşım yöntemini seçebilmeleri için kendilerini güvende hissetmeleri gerekmektedir. Bu yüzden güvenlik, havacılık için en önemli şarttır. Havacılıkta en büyük kural “Önce Güvenlik” kuralıdır.

Hava araçları yüksek teknolojiye sahip sistemlerden oluşmaktadır. Bu sistemler imal edilirken otoritelerin koyduğu standartlara göre en optimum ömürde ve en kritik seviyede güvenliği sağlayarak operasyonlarına devam edecek şekilde tasarlanırlar. Diğer yandan, güvenlik ve karlılık arasında ters orantı mevcuttur. Bu yüzden hava aracı işletmeleri güvenliği izin verilen en alt seviyede tutarak, karlılığı olabildiğince maksimumda tutmak isterler. Bunun için şirketler, bütün departmanlarında harcamaları en az seviyelere indirmek için çalışmalar yürütürler. Ancak, üçüncü şirketler yapılan alış veriş ve hizmet alımlarında, mevcut katalog fiyatlarıyla çok fazla oynayamazlar. Katalog fiyatları ise sertifikasyon ve standart zorunlulukları, yüksek teknoloji üretim zorunluluğuyla bir hayli yüksektir. Örneğin, CFM56 motorlarında takılı bulunan bir yüksek basınç türbün palasının katalog fiyatı 2013 değerlerine göre 10,000 amerikan dolarıdır. Bu palalardan bir diskin etrafında seksen adet mevcut. Yani bir motorda yüksek basınç türbününün fiyatı disk ile birlikte 1,000,000 amerikan dolarını bulmaktadır. Eğer bu palaların hasarlanması önlenebilirse, sadece bir motor başına yüksek miktarda tasarruf yapmak mümkün olabilecektir. Bir uçahta bu motordan iki tane olduğu dikkate alınırsa ve teorik olarak motor revizyonları yapıldığı müddetçe motor ömrünün sonsuz olduğu düşünülürse, uzun vadeli motor operasyonlarında çok büyük miktarlarda tasarruf yapmak mümkün olacaktır.

Bir B 737-800 uçağının ortalama modifikasyonlarla fiyatı yaklaşık olarak 30 milyon dolardır. Bu fiyata uçağa montaj edilmiş 2 adet CFM56-7B motorları da dahildir. Bu motorların her birinin fiyatı ise 10 milyon dolardır ki toplamda 20 milyon dolar etmektedir. Bu da motorların ne kadar önemli ve pahalı komponentler olduğunu göstermektedir. Buna ek olarak, aynı uçağın ağır bakımının fiyatı yaklaşık olarak 300000 amerikan doları bulurken, aynı motorların her birinin ağır bakımları yaklaşık olarak 2.5 milyon amerikan dolarını bulmaktadır.

Eğer havayolları bakım maliyetlerini güvenlikten ödün vermeden düşürebilirlerse, karlılıklarını arttırarak operasyonlarını devam ettirebilirler.

Bu tezde, Weibull metodu kullanılarak motorların öngörülemez hasarlanma ve servis dışı kalma zamanları hesaplanmaya çalışılmıştır. Motor bakımları; planlı ve plansız veya öngörülemez bakımlar olmak üzere ikiye ayrılmaktadır. Planlı bakımlar, üreticinin tavsiye ettiği aralıklarla veya motorda takılı bulunan ömürlü parçaların, ömürlerinin dolmasıyla yapılmaktadır. Bu bakımların zamanları bilinmektedir ve havayolları şu anda ancak bu verilere dayanarak bakım planlamalarını motorlar için yapabilmektedir.

Weibull analizinde önemli olan weibull parametrelerinin hesaplanmasıdır. Parametrelerin hesaplanmasında analitik ve grafik metodları kullanılmaktadır. Çalışmada, grafik metodu kullanılmıştır. Bunun sebebi, grafik metodunun, mühendislik çalışmalarında sık kullanılması ve sağlama yapma imkanını vermesidir. Hesaplamaları hızlandırmak için Excel Microsoft Office 2010 paket programı kullanılmıştır.

Servis dışı kalma sebeplerinden en önemli etkiye sahip olanları Pareto Analizi ile sınırlandırılmıştır. Weibull metoduyla ise bütün motorların servis dışı kalma zamanları analiz edilmiş ve bu analizle elde edilen Weibull parametreleri örnek bir filo için değerlendirilmiştir. Buna ek olarak kiralama adayı bir uçağın motorları da örnek olarak incelenmiş ve kira süresi boyunca motorların ağır bakım gerektirme riskleri hesaplanmıştır. Bu risklere göre örnek havayolu şirketini bekleyen mali yükümlülükler ortaya konulmuş ve muhtemel motor arıza sayıları tespit edilmiştir. Kiralanacak uçaklar arasında yapılacak analizlerle en uygun uçaklar belirlenebilecek ve yapılan genel analiz çalışmalarında bir madde olarak yer alabilecektir. Yüksek motor bakım maliyetleri dikkate alındığında bu çalışmanın vereceği geri bildirim, havayolu şirketleri için hayati öneme sahiptir.

Bu çalışmanın sonucu olarak, herhangi bir operatör elindeki motor filosunu ya da kiralayacağı uçaklara ait motorların durumlarını değerlendirerek, filosunun güvenilirlik seviyesini ölçebilir. Aynı zamanda filosunun muhtemel servis dışı kalma sürelerini de önceden öngörerek, planlamasını ve bütçe yapısını buna göre belirleyebilir.

Şu anda operasyonuna devam etmekte olan bir filonun motor bilgileri alınarak, hesaplanan değerlerle karşılaştırılmış ve sonuçlar tartışılmıştır. Bunun yanında dünya üzerindeki motorların genel güvenilirlik değerleri ve kümülatif arıza olasılıkları değerlendirilmiştir. Motorların ağır bakım zamanlarının genel aşınma tipi hasarlar olduğu sonucuna Küvet Eğrisi analizi ile varılmıştır. Bu eğriyi elde etmek için Hasar Oranı hesaplanmıştır.

Çalışmanın pratikte kullanılması için, kaynak bilginin sürekli güncel tutulması faydalı olacaktır. Bunu sağlamak için, üreticiden bu bilginin sürekli akması gerekmektedir. Ancak üretici bu bilgiyi yıllık olarak güncellemektedir. Dolayısıyla, kaynak bilgi her yıl güncellenmeli ve motorların genel durumlarının seyri incelenmelidir. Bu değişim eğrisine göre havayolu şirketlerinin teknik departmanları kendi filoları için yaptıkları analizlerle, genel filo için yapılan analizleri karşılaştırmalıdır. Elde edilen sonuçlara göre gerekli adımlar atılabilir ve motor bakımları açısından sürprizlerle karşılaşılmasının önüne geçilebilir.

Bu çalışmanın ileriki aşamalarında motorun sadece servis dışı kalma zamanının tahmin edilmesi değil bununla birlikte servis dışı kalma sebeplerinin de önceden tahmin

edilmesi hedeflenmektedir. Bu geliřtirmeyle birlikte operatörler engelleyici bakım adımlarını uygulamak için geri bildirimini bu çalışmadan alabileceklerdir.

Bu çalışmada ilk olarak havacılık ve havacılıktaki bütçe maddeleri açıklanmıştır. Devamında, ilgili motordan ve uçaktan bahsedilerek havacılıkta bakım anlatılmıştır. Ardından, motorun çalışma prensibi anlatılmıştır. Buna ek olarak Weibull metodu ve gerçek bir filoda yapılmış örnek uygulamalar anlatılmış, çalışmanın ne kadar güvenilir olduğu gösterilmiş ve ardından çalışma sonlandırılmıştır.

1. INTRODUCTION

1.1 Purpose of Thesis

Cost efficiency is critical for an airline's ability to compete and survive. Yet not every airline should seek to be the lowest cost operator. Reducing the maintenance cost will be the aim of this thesis.

Engine maintenance cost is the one of the biggest item in the overall maintenance cost. This thesis will use Weibull method for predicting the engine failure time. Reliability and failure rate will be estimated during failure time prediction.

Engine failure data will be the most important data for airlines for estimating their fleet maintenance status.

1.2 Literature Review

For reducing maintenance cost several steps in maintenance may developed. Li Wenjuan, Ma Cunbao, Song Dong and He Enning tried to improve the maintenance planning guide and developed an optimized schematic for it. Their flow chart totally depends on predictioning the maintenance time. Therefore, estimating the failure time also helps to estimate maintenance time (Wenjuan, Cunbao, Dong, & Enning, 2011). This study may give a useful method to use their schematic during maintenance planning.

The Weibull method is used for several disciplines. Such as statistics, weather forecasting, insurance and engineering. Followings can be examples of engineering related usage of Weibull methods; engine cost and risk estimation (D.S.Pascovici, Kyprianidis, Colmenares, Ogaji, & Pilidis, 2008), engine design reliability (Zaretsky, Hendricks, & Soditus, 2002) and Wind speed distribution calculation (The Renewable Energy Website).

Yabsley and Ibrahim used Weibull method for APU in their study to calculate economical effect of maintenance. They used operational cost per hour of the APU

and draw probability density function. Their method also gives actions to operators for reducing maintenance cost. (Yabsley & Ibrahim, 2008)

Weibull parameters and related functions were used to estimate reliability of components (Demirci, 1998).

Estimation of unscheduled failure time, in respect to flight hours, will be possible with this method. Weibull analysis does not only give the failure time but also give failure reason. Because of knowing failure reason, operators schedule their maintenance according to possible failures. This type of maintenance called preventive maintenance.

2. AVIATION AND MAINTENANCE

Low cost operation is the most important issue for airlines within today's competitive aviation industry. Airlines try to reduce their costs without compromising safety. There is an inverse ratio between safety and low cost.

Maintenance means the preservation, inspection, overhaul, and repair of aircraft, including the replacement of parts. The purpose of maintenance is to ensure that the aircraft remains airworthy throughout its operational life. A properly maintained aircraft is a safe aircraft. (Federal Aviation Administration, 2008)

Operators or airlines are responsible for holding aircraft in airworthy condition.

Airlines are forced to do their maintenance items on the time by Authorities. All details of maintenance have been explained by Federal Aviation Authority (FAA) and European Aviation and Safety Authority (EASA). The local Authorities generally accept their maintenance logic and apply to their countries some specific changes. Their rules are called Regulations and open access for public use. Everybody may use and search the details of regulations from EASA and FAA's websites. All parts and subparts explain the general rules of aviation, such as aircraft airworthiness.

The maintenance time is measured with Flight Hours (FH), Flight Cycles (FC) or days. FH means that the time the aircraft is flying. Takeoff and landing is considered an aircraft "cycle". For example, flight from Antalya to Frankfurt takes 4 hours. In that case, FH of an aircraft is four and FC is only one.

2.1 Aircraft Maintenance Checks

Airlines utilize a continuous maintenance program that includes both routine and detailed inspections. However, the detailed inspections may include different levels of detail. Often referred to as "checks," the A-check, B-check, C-check, and D-checks involve increasing levels of detail. A-checks are the least comprehensive and occur frequently. D-checks, on the other hand, are extremely comprehensive, involving major disassembly, removal, overhaul, and inspection of systems and

components. They might occur only three to six times during the service life of an aircraft. (FAA-Aircraft Maintenance Technicians Handbook, 2011) Airlines and other commercial operators of large or turbine-powered aircraft follow a continuous inspection program approved by the Federal Aviation Administration (FAA) in the United States, or by other airworthiness authorities such as Transport Canada or the European Aviation Safety Agency (EASA). Under FAA oversight, each operator prepares a Continuous Airworthiness Maintenance Program (CAMP) under its Operations Specifications or "OpSpecs". The CAMP includes both routine and detailed inspections. Airlines and airworthiness authorities casually refer to the detailed inspections as "checks", commonly one of the following: A check, B check, C check, or D check. A and B checks are lighter checks, while C and D are considered heavier checks. (Wikipedia, 2012)

2.1.1 A check

This is performed approximately every 500 - 800 flight hours. It is usually done overnight at an airport gate. The actual occurrence of this check varies by aircraft type, the cycle count, or the number of hours flown since the last check. The occurrence can be delayed by the airline if certain predetermined conditions are met.

2.1.2 B check

This is performed approximately every 3-6 months. It is usually done in 1-3 days at an airport hangar. A similar occurrence schedule applies to the B check as to the A check. B checks may be incorporated into successive A checks, i.e.: A-1 through A-10 complete all the B check items.

2.1.3 C check

This is performed approximately every 15–21 months or a specific amount of actual Flight Hours (FH) as defined by the manufacturer. This maintenance check is more extensive than a B Check, as pretty much the whole aircraft is inspected. This check puts the aircraft out of service and until it is completed, the aircraft must not leave the maintenance site. It also requires more space than A and B Checks - usually a hangar at a maintenance base. The time needed to complete such a check is generally 1-2 weeks. The schedule of occurrence has many factors and components as has been described, and thus varies by aircraft category and type.

2.1.4 D check

This is - by far - the most comprehensive and demanding check for an airplane. It is also known as a Heavy Maintenance Visit (HMV). This check occurs approximately every 5–6 years. It is a check that, more or less, takes the entire airplane apart for inspection and overhaul. Also if required the paint can be removed for further inspection on the fuselage metal skin. Such a check can generally take from 3 weeks to 2 months, depending on the aircraft and number of technicians involved (it is not uncommon to have as many as 100 technicians working on a Boeing 747 at the same time). It also requires the most space of all maintenance checks, and as such must be performed at a suitable maintenance base.

Because of the nature and the cost of such a check, most airlines - especially those with a large fleet - have to plan D Checks for their aircraft years in advance. Often, older aircraft being phased out of a particular airline's fleet are stored or scrapped upon reaching their next D Check, due to the high costs involved in it in comparison to the aircraft's value. Many Maintenance, Repair and Overhaul (MRO) shops state that it is virtually impossible to perform a D Check profitably at a shop located within the United States. As such, only few of these shops offer D checks.

Engine Heavy Repair is different way to call Engine D Check.

2.2 Maintenance References

Aeronautical publications are the sources of information for guiding aviation mechanics in the operation and maintenance of aircraft and related equipment. The proper use of these publications will greatly aid in the efficient operation and maintenance of all aircraft. These include manufacturers' service bulletins, manuals, and catalogs; FAA regulations; airworthiness directives; advisory circulars; and aircraft, engine and propeller specifications.

2.2.1 Manufacturers' service bulletins/instructions

Service bulletins or service instructions are two of several types of publications issued by airframe, engine, and component manufacturers.

The bulletins may include:

- purpose for issuing the publication,
- name of the applicable airframe, engine, or component,

- detailed instructions for service, adjustment, modification or inspection, and source of parts, if required and
- estimated number of man hours required to accomplishment of the job.

2.2.2 Maintenance manual

The manufacturer's aircraft maintenance manual contains complete instructions for maintenance of all systems and components installed in the aircraft. It contains information for the mechanic who normally works on components, assemblies, and systems while they are installed in the aircraft, but not for the overhaul mechanic. A typical aircraft maintenance manual contains:

- A description of the systems (i.e., electrical, hydraulic, fuel, control)
- Lubrication instructions setting forth the frequency and the lubricants and fluids which are to be used in the various systems,
- Pressures and electrical loads applicable to the various systems,
- Tolerances and adjustments necessary to proper functioning of the airplane,
- Methods of leveling, raising, and towing,
- Methods of balancing control surfaces,
- Identification of primary and secondary structures,
- Frequency and extent of inspections necessary to the proper operation of the airplane,
- Special repair methods applicable to the airplane,
- Special inspection techniques requiring x-ray, ultrasonic, or magnetic particle inspection, and
- A list of special tools.

2.2.3 Overhaul manual

The manufacturer's overhaul manual contains brief descriptive information and detailed step by step instructions covering work normally performed on a unit that has been removed from the aircraft. Simple, inexpensive items, such as switches and relays on which overhaul is uneconomical, are not covered in the overhaul manual.

2.2.4 Structural repair manual

This manual contains the manufacturer's information and specific instructions for repairing primary and secondary structures. Typical skin, frame, rib, and stringer

repairs are covered in this manual. Also included are material and fastener substitutions and special repair techniques.

2.2.5 Illustrated parts catalog

This catalog presents component breakdowns of structure and equipment in disassembly sequence. Also included are exploded views or cutaway illustrations for all parts and equipment manufactured by the aircraft manufacturer.

2.2.6 Code of Federal Regulations (CFRs)

The CFRs were established by law to provide for the safe and orderly conduct of flight operations and to prescribe airmen privileges and limitations. A knowledge of the CFRs is necessary during the performance of maintenance, since all work done on aircraft must comply with CFR provisions. The cost items about maintenance for segment are engine, airframe and components.

2.3 Airlines Cost Items

In contrast with many service businesses, airlines today need more than storefronts and telephones to get started. They need an enormous range of expensive equipment and facilities, from airplanes to flight simulators to maintenance hangars, aircraft tugs, airport counter space and gates. Consequently, the airline industry is a capital-intensive business, requiring large sums of money to operate effectively. Most equipment is financed through loans or the issuance of stock. Airlines also lease equipment, including assets they owned previously but sold to someone else and leased back. Whatever arrangements an airline chooses to pursue, its capital needs require consistent profitability. Because airlines own large fleets of expensive aircraft that depreciate in value over time, they historically have generated a substantial positive cash flow (profits plus depreciation). Most airlines use their cash flow to repay debt, acquire new aircraft or upgrade facilities. When cash flow is significant, airlines may also issue dividends to shareholders.

The airline industry employs several hundred thousand pilots, flight attendants, mechanics, baggage handlers, reservation and customer service representatives, cleaners, analysts, salespersons, accountants, lawyers, engineers, schedulers, auditors, computer programmers and others. About half of airline workers belong to

professional unions and are governed by collective bargaining agreements. Over the years, technological developments have enabled airlines increasingly to automate many tasks and operate more efficiently. Yet the industry remains labor-intensive, with a substantial share of airline revenue set aside to pay the wages, benefits and payroll taxes of its workforce.

2.3.1 Airline profitability

Airlines, through the years, have earned a net profit margin consistently below the average for U.S. industry as a whole. Indeed, in recent years they have typically lost money and, perhaps more importantly, failed to generate a return on investment that covers their cost of capital – the weighted average cost of debt and equity. That phenomenon, due to a host of economic and governmental factors, transcends the U.S. market, as confirmed by data assembled by the International Air Transport Association (IATA).

One way to think about airline industry profitability, particularly in the passenger sector, is to consider the metric known as break-even load factor. For every flight, and at the aggregate system level, there is an average occupancy rate – technically the ratio of revenue passenger miles to available seat miles – at which revenues and expenses are equal. At a given level of expenses, cargo and ancillary revenues and average passenger yield (price paid per mile), it is the percentage of seats the airline (or industry) must sell to cover its costs. Any combination of higher unit costs or lower average fares will raise the break-even load factor. In the early years of deregulation, the industry experienced an average break-even load factor of 65 percent, but rising fuel, labor and security costs over time, as well as decreasing real yields have driven that number closer to 80 percent. Even in a profitable year, airlines typically operate very close to their break-even load factor. The sale of just one or two more seats on each flight can mean the difference between profit and loss.

2.3.2 Airline revenue and costs

On average, more than 90 percent of a passenger airline's revenue comes from the sale of tickets to passengers for scheduled air travel. Of the balance, the majority comes from cargo and other transport-related services. For the all-cargo sector, of course, freight, express and mail is the sole source of transport revenue. Approximately three-fourths of all airline passenger revenue is generated from

domestic service. The majority of tickets for international travel are processed by travel agents, most of whom rely on global distribution systems to keep track of schedules and fares, to book reservations and to print tickets for customers. Similarly, freight forwarders book the majority of air-cargo space. Like travel agents, freight forwarders are independent intermediaries that match shippers with cargo suppliers. (Airlines For America)

Customer demand for personal transportation is seasonal – the summer months are extremely busy, as students are out of school and many individuals and families take vacations. Winter, on the other hand, sees less traffic, with the exception of the Thanksgiving and winter holidays. Accordingly, passenger traffic and revenue rise and fall throughout the course of any given year. Airlines have responded in kind by adjusting their schedules periodically to realign their scheduled capacity to better fit this ebb and flow.

Airline expenses can be grouped into the following major functions: flying operations (e.g., fuel, flight crew compensation, aircraft ownership), maintenance (e.g., parts, labor), aircraft and traffic service (e.g., ground service equipment, cargo handling, baggage, dispatch, gate agents), promotion and sales (e.g., advertising, reservations agents, travel agency commissions), passenger service (e.g., food and beverage, in-flight crew compensation), transport-related (e.g., outsourced regional flying, cost of generating in-flight sales) and administration.

Labor costs are common to nearly all of these categories. When looked at as a whole, labor and fuel combined consistently account for approximately half of passenger airline operating expenses. Transport-related costs have grown sharply in recent years as many airlines have outsourced a substantial portion of their flying needs to smaller regional carriers to align supply and costs more closely with demand.

2.3.3 Detailed airline costs

According to reports filed with the USA Department of Transportation airline costs were as follows (IATA, 2010):

- Flying Operations - essentially any cost associated with the operation of aircraft, such as fuel and pilot salaries - 35 %;
- Maintenance - 11 %;

- Aircraft and Traffic Service - basically the cost of handling passengers, cargo and aircraft on the ground and including such things as the salaries of baggage handlers, dispatchers and airline gate agents – 14 %;
- Promotion/Sales - including advertising, reservations and travel agent commissions – 5 %;
- Passenger Service - mostly in-flight service and including such things as food and flight attendant salaries – 6 %;
- Transport Related - delivery trucks and in-flight sales – 18 %;
- Depreciation/Amortization - equipment and plants – 5 %.
- Administrative – 7.5 %;

Table 2.1 and Figure 2.1 shows the overall cost expenses of an airline.

Table 2.1 : Operational expenses of an airline.

Operating Expenses	Expenses (mi US Dollars)	Percentage
Flying Operations	\$ 53260	34,97 %
Maintenance	\$ 16094	10,57 %
Passenger Service	\$ 8853	5,81 %
Aircraft and Traffic Servicing	\$ 21421	14,06 %
Promotion and Sales	\$ 7556	4,96 %
General and Administrative	\$ 11301	7,42 %
Depreciation and Amortization	\$ 7537	4,95 %
Transport Related	\$ 26289	17,26 %
Total Operating Expenses	\$ 152311	100

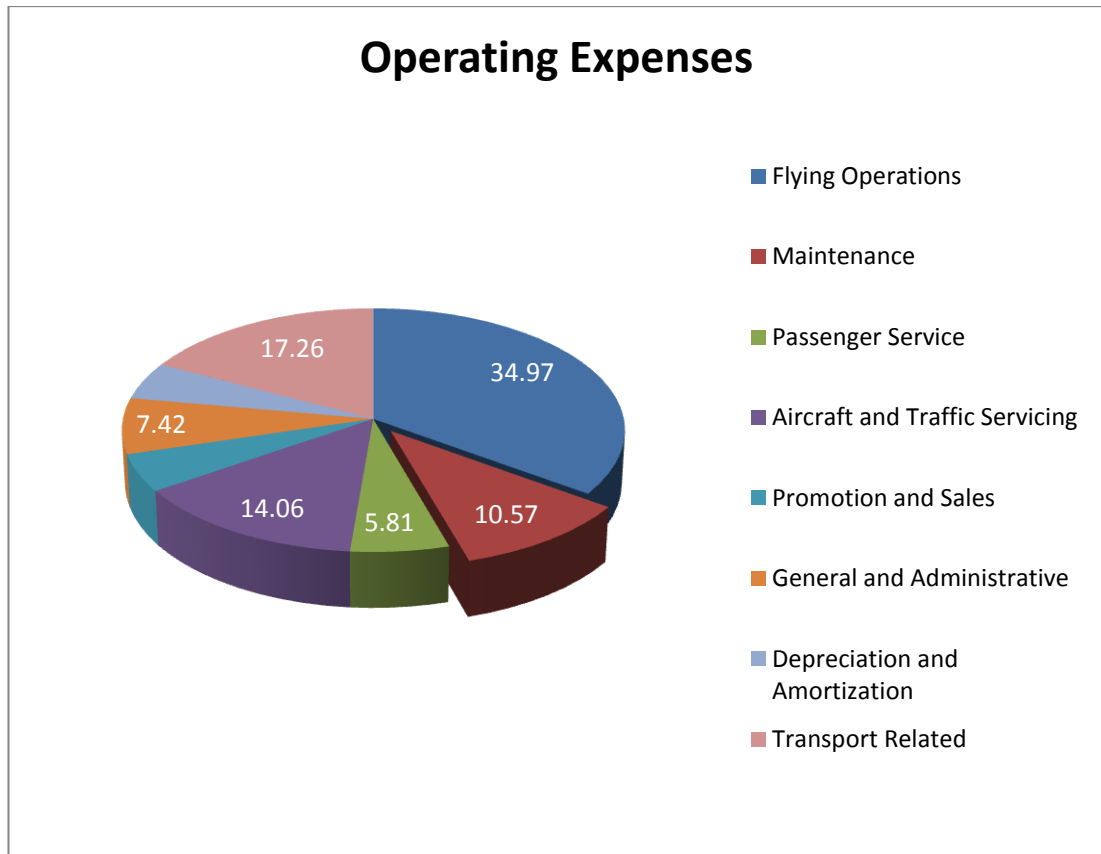


Figure 2.1 : Operating expenses of an airline

In this study, engine maintenance cost reduction with a statistical method which called Weibull method is studied.

2.3.4 Maintenance cost distribution

Maintenance cost is the one of the controllable cost item in general cost distribution of an airline. It is the 11 % of total value. The total proportional distribution of maintenance cost is as follows; (Bureau of Transportation Statistics, 2010)

- Outsource Engine Maintenance – 38 %
- Engine Maintenance Labor – 2 %;
- Outsource Airframe Maintenance – 23 %
- Airframe Maintenance Labor – 17 % ;
- Airframe Materials – 14 %;
- Engine Materials – 6 %.

Figure 2.2 shows the graphical distribution of maintenance expenses.

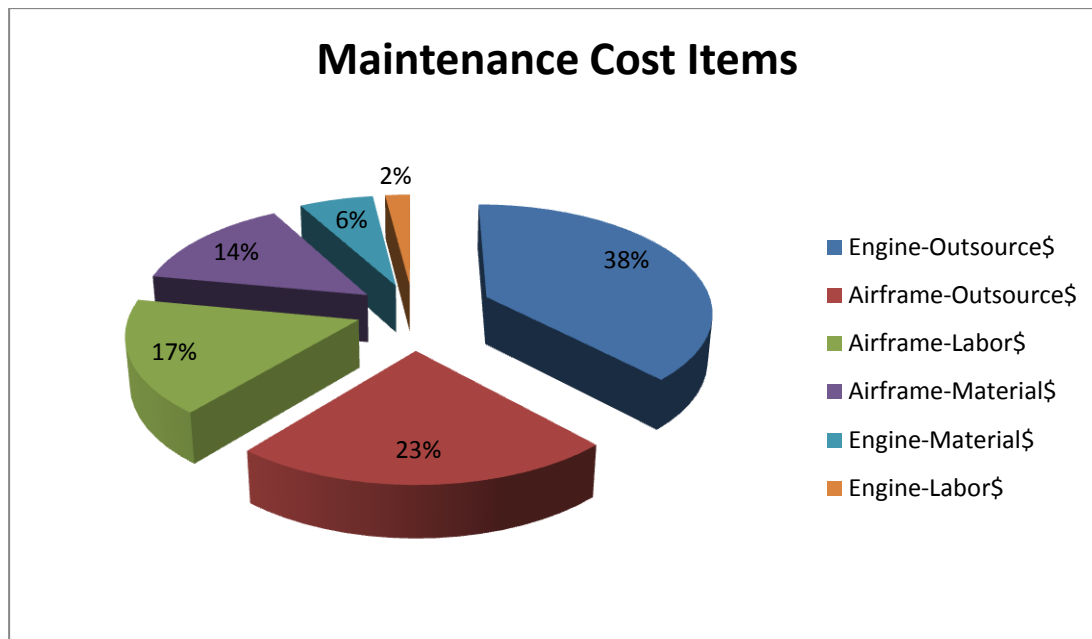


Figure 2.2 : Maintenance expenses

The biggest cost item of the maintenance for an airline is Engine outsource cost. This outsourced value also contains not only outsourced labor but also material costs. Totally Engine maintenance cost is 46 %. This condition because of high values of Mean Time Between Failure (MTBF) and Mean Time To Failure (MTTF). Airframe total cost is remaining portion of total cost, 54 %.

Airlines generally establish their own line maintenance departments for reduce the cost of maintenance. As result of this they can obtain constant labor cost.

For preventing the high material expenses, airlines generally makes component pool agreements with MRO's. According to these contracts, they pay constant monthly fees in order the material needs.

The most important proportion of maintenance cost has become from outsourced maintenance. Generally components are repaired according to their maintenance manuals (CMM). Only MRO's and their relevant shops have the capability of using CMM. Therefore, airlines have to send damaged components to the shop for repair if they want to prevent the cost of new spare part replacement.

Engine is the most important and the most expensive component that is repaired with authorized MRO's or shops.

The total cost a new and average modified Boeing 737-800 aircraft is 35,000,000 USD. Only one engine cost is 10,000,000 USD. Remaining components and airframe

cost is thus 15,000,000 USD. Because of that engine maintenance cost is very important for direct operational cost of an airline.

Small savings in engine maintenance directly affects 46 % of total maintenance cost.

It is nearly 5 % of the total airline operational cost.

3. ENGINE

An aircraft engine is the component of the propulsion system for an aircraft that generates mechanical power. Aircraft engines are almost always either lightweight piston engines or gas turbines.

In this study CFM56-7B engines were discussed.

The CFM56-7 powers the Boeing 737 Next Generation series (737-600/-700/-800/-900). The CFM56-7 is rated with takeoff thrust from 19,500 to 27,300 lbf (86.7 kN to 121 kN). It has higher thrust ranges, improved efficiency, and lower maintenance costs than its predecessor, the CFM56-3 series.

3.1 Engine General Concept

The CFM56-7 is a high bypass, dual rotor, axial flow turbofan engine. The engine fan diameter is 61 inches (1.55 meters). The bare engine weight is 5257 pounds (2385 kilograms).

The engine has these sections (See Figure 3.4):

- Fan and booster
- High pressure compressor (HPC)
- Combustor
- High pressure turbine (HPT)
- Low pressure turbine (LPT)
- Accessory drive.

The fan and booster rotor and the LPT rotor are on the same low pressure shaft (N1).

The HPC rotor and the HPT rotor are on the same high pressure shaft (N2).

3.1.1 Fan and booster

The fan and booster is a four-stage compressor.

The fan increases the speed of the air. A splitter fairing divides the air into these two air flows (see Figure 3.1):

- Primary
- Secondary.

The primary air flow goes into the core of the engine. The booster increases the pressure of this air and sends it to the HPC.

The secondary air flow goes in the fan duct. It supplies approximately 80 percent of the thrust during take-off.

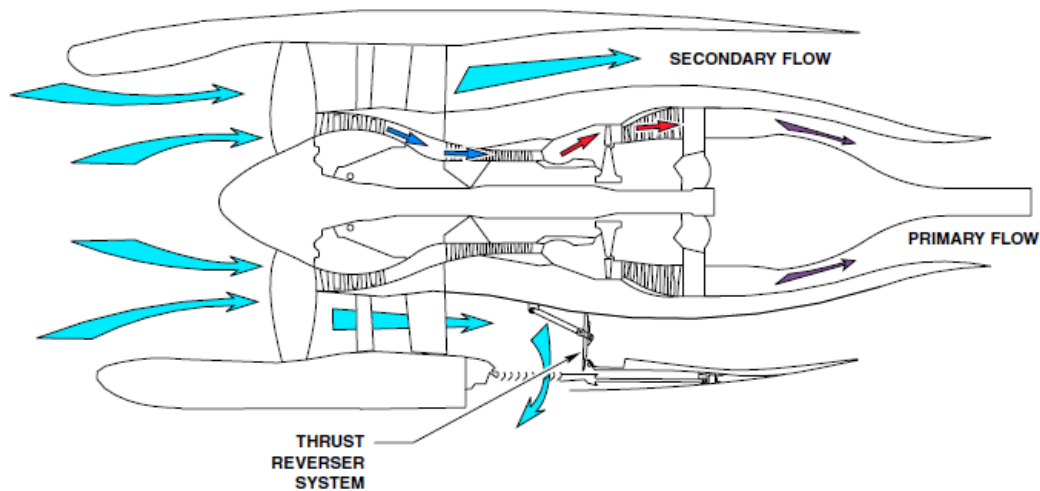


Figure 3.1 : Primary and secondary flow

3.1.2 High pressure compressor (HPC)

The HPC is a nine-stage compressor. It increases the pressure of the air from the LPC and sends it to the combustor. The HPC also supplies bleed air for the aircraft pneumatic system and the engine air system.

3.1.3 Combustor

The combustor mixes air from the compressors and fuel from the fuel nozzles. This mixture of air and fuel burns in the combustion chamber to make hot gases. The hot gases go to the HPT.

3.1.4 High pressure turbine (HPT)

The HPT is a single-stage turbine. It changes the energy of the hot gases into a mechanical energy. The HPT uses this mechanical energy to turn the HPC rotor and the accessory drive.

3.1.5 Low pressure turbine (LPT)

The LPT is a four-stage turbine. It changes the energy of the hot gases into a mechanical energy. The LPT uses this mechanical energy to turn the fan and booster rotor.

3.1.6 Accessory drive

The accessory drive has these components:

- Inlet gear box (IGB)
- Radial drive shaft (RDS)
- Transfer gear box (TGB)
- Horizontal drive shaft (HDS)
- Accessory gear box (AGB).

The N2 shaft turns the AGB through these shafts and gearboxes:

- IGB
- RDS
- TGB
- HDS.

The AGB holds and operates the airplane accessories and the engine accessories.

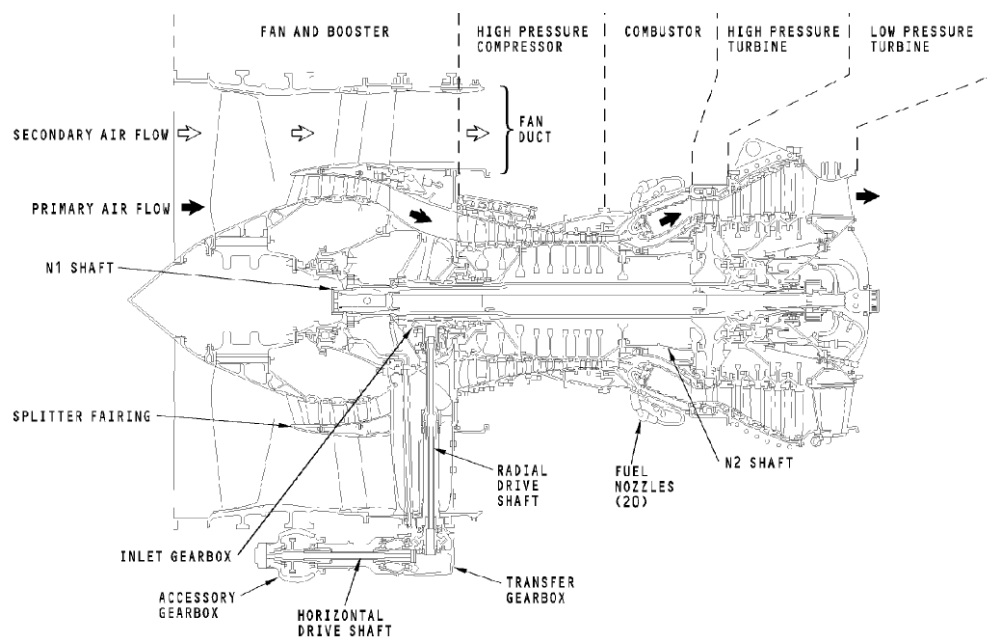


Figure 3.2 : General CFM56-7B engine concept

3.1.7 Airworthiness limitations

The airworthiness limitations section in maintenance manual of manufacturer contains the life limits for rotating and static engine parts (see Figure 3.3) and the approved mandatory inspection intervals for specific engine parts. The life of parts is given in flight cycles. The cycles for each part serial number must be counted continuously from its first entry into service.

It is the operators responsibility to maintain accurate records of the total number of cycles operated and the number of cycles remaining.

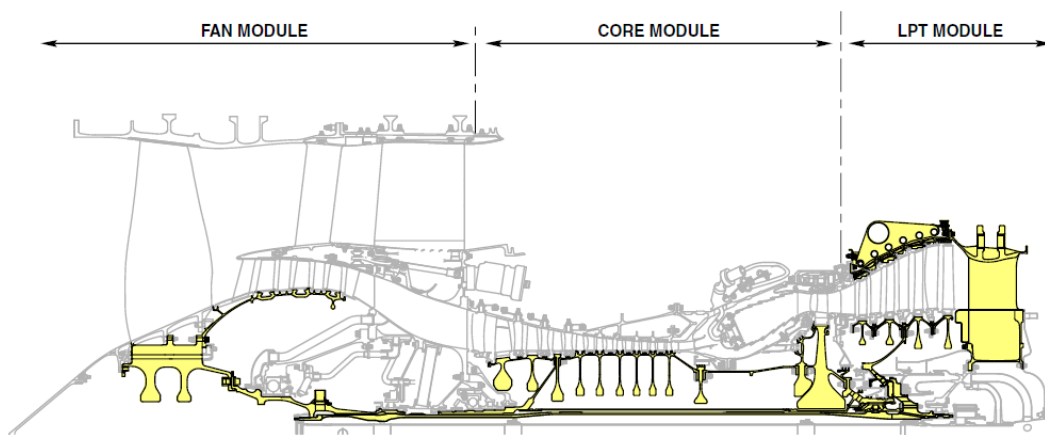


Figure 3.3 : Life Limited Parts (LLP) of CFM56-7B engine

The engine rotors are supported by 5 bearings, identified in manuals as numbers 1 thru 5, where No. 1 is the most forward and No. 5 the most aft (see Figure 3.4). These bearings are housed in 2 dry sump cavities provided by the fan and turbine frames. Engine structural rigidity is obtained with short lengths between two main structures (frames). The accessory drive system uses energy from the high pressure compressor rotor to drive the engine and aircraft accessories. It also plays a major role in starting.

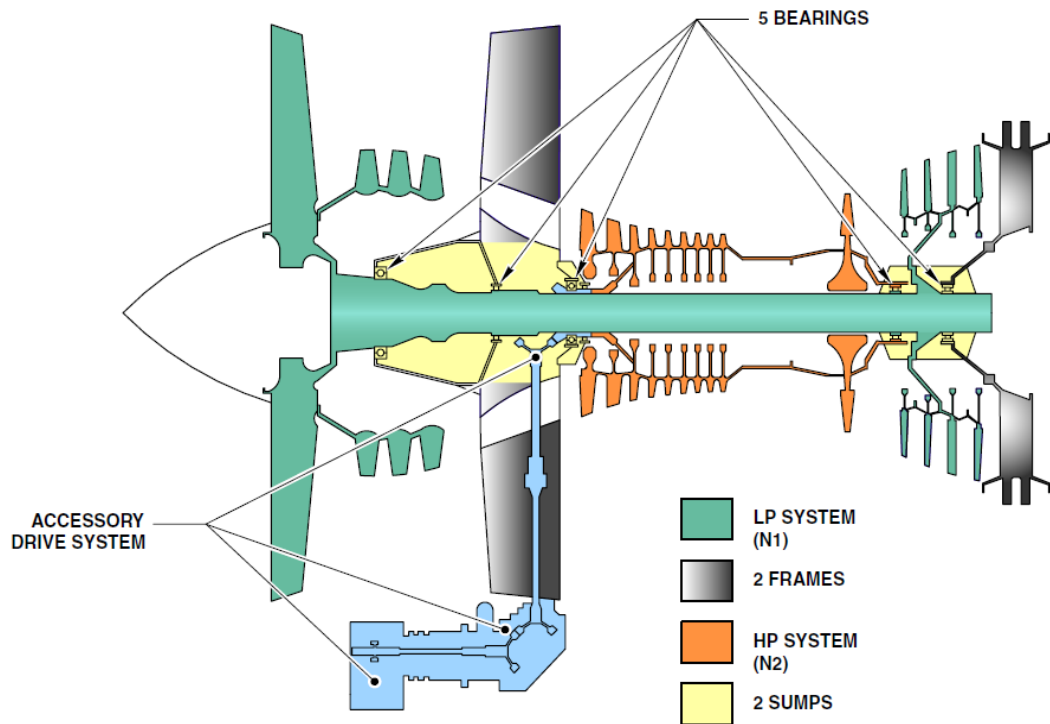


Figure 3.4 : Engine general design

The CFM56-7B is a modular concept design engine. It has 17 different modules that are enclosed within three major modules and an accessory drive system. The 3 modules are (see Figure 3.5):

- The Fan Major Module.
- The Core Engine Major Module.
- The Low Pressure Turbine Major Module.

The accessory drive system is also a modular design.

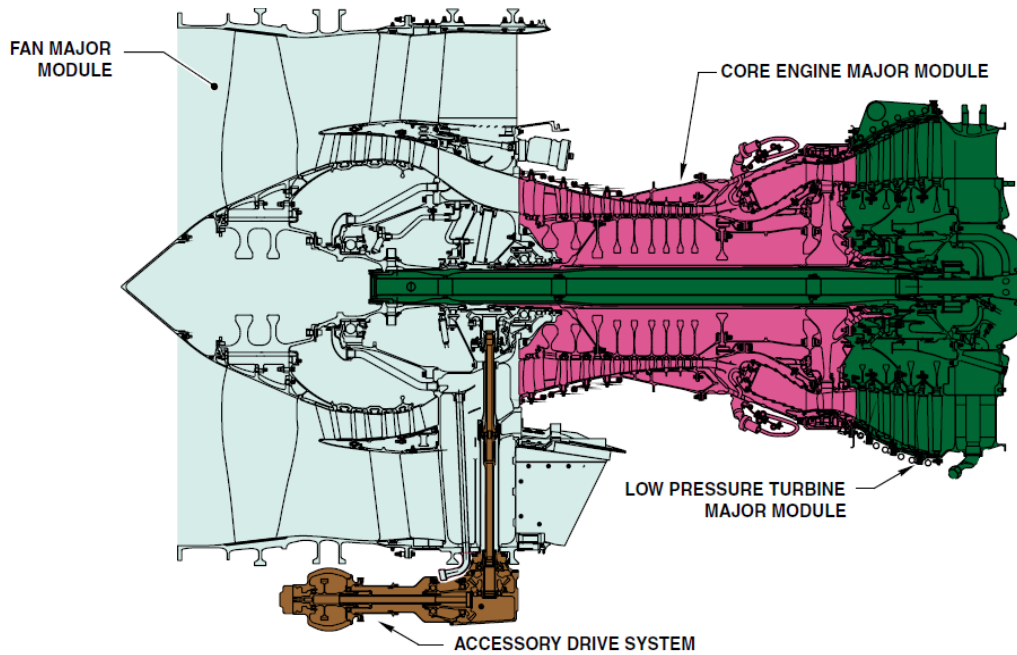


Figure 3.5 : Modular design of CFM56-7B engine.

3.2 Engine Maintenance

The CFM56-7B engine uses a maintenance concept called ‘On Condition Maintenance’ (Figure 3.6). This means that the engine has no periodic overhaul schedules and can remain installed under the wing until something important occurs, or when lifetime limits of parts are reached. For this reason, to monitor and maintain the health of the engine, different tools are available, which are:

- Engine performance trend monitoring, to evaluate engine deterioration over a period of use: engine parameters, such as gas temperature, are recorded and compared to those initially observed at engine installation on the aircraft.
- Borescope inspection, to check the condition of engine internal parts: when parts are not accessible, they can be visually inspected with borescope probes inserted in ports located on the engine outer casing.
- Lubrication particles analysis: while circulating in the oil system, lubrication oil is filtered, and large, visible-to-the-eye particles (larger than 10 microns) coming from worn engine parts are collected in filters and magnetic chip detectors, for visual inspection and analysis.
- Engine vibration monitoring system: sensors located in various positions in the engine, send vibration values to the on-board monitoring system. When

vibration values are excessive, the data recorded can be used to take remedial balancing action.

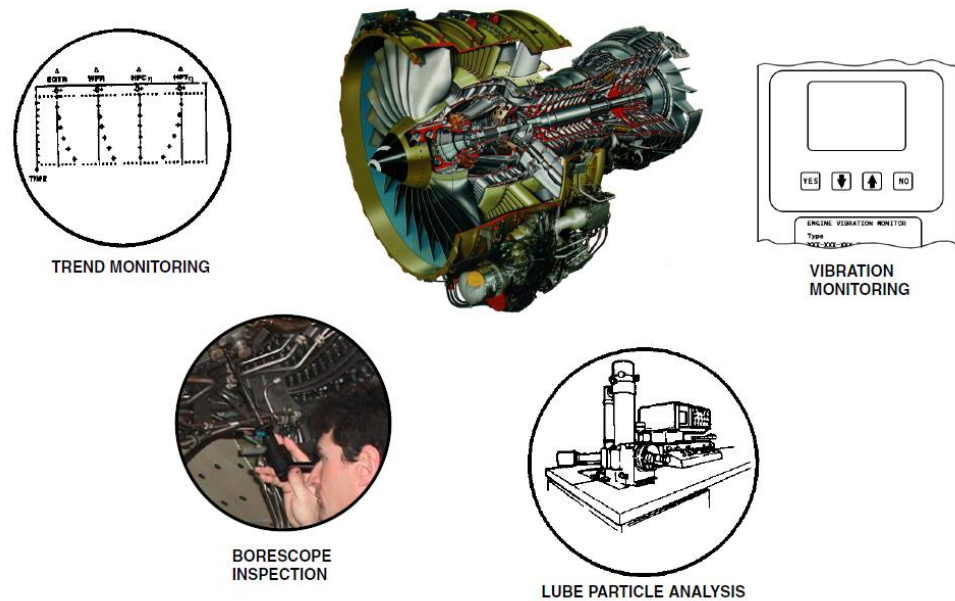


Figure 3.6 : Engine on-condition monitoring.

Above condition monitoring methods are also give an opinion about engine condition. Operators periodically control engines condition with above systems. These systems are the mandatory way to check engine parameters. However, they are not give enough information about engine unscheduled maintenance time. Therefore, a probability method used for prediction of engine unscheduled maintenance time.

4. AN INTRODUCTION TO RELIABILITY

4.1 Definition of Reliability

Reliability is defined by the “IATA Technical Reference Manual” as: The probability that an item will perform a required function, under specified conditions, without failure, for a specified period of time. Therefore, if there are large number of tested components available, then;

$$\text{Reliability at time } t = \frac{\text{Number Surviving at instant } t}{\text{Number at start when } t = 0} \quad 4.1$$

The definition breakdowns to four basic parts;

- 1- Probability
- 2- Adequate performance
- 3- Time
- 4- Operating Conditions

The first parameter, probability, provides numerical input for assessment of reliability.

Other three parameters depend on engineering analysis and related with the operation environment.

4.2 Definition of Failure

When a component no longer works it is called a failed component, and in respect of this definition of the Failure is the termination of the ability of an item to perform its required function.

Required function of the component is defined by the designer and manufacturer. An EGT thermocouple sensor can be given as an example for this. These sensors are designed and manufactured for measuring exhaust gas temperature and their required function is also that. If this component not or wrong measures the temperature of specified area that is called as a failed component and it is called as a failure of EGT sensor.

4.3 Classification of Failures

Failures may be classified as following.

4.3.1 As to cause

A misuse failure, as a definition, “a failure due to the application of stresses during use which exceed the stated capabilities of the item”.

An inherent weakness failure, as a definition, “a failure due to the application of stresses during use which exceed the stated capabilities of the item”

4.3.2 As to suddenness

A sudden failure is one which could not be anticipated by prior examination.

4.3.3 As to degree

A partial failure is one resulting “from deviations in characteristic(s) beyond specified limits, but not such a to cause complete lack of the required function”. Thus the item does not work as well as should, but it has not completely failed. A complete failure is one resulting from “deviations in characteristic(s) beyond specified limits, such as to cause complete lack of required function. The limits referred to in this category are special limits for this purpose”

4.4 Reliability Economics

With a good grasp of the reliability of components and systems, it is possible to devise specifications and designs that result in the optimum level of reliability performance. Designing a product with inexpensive and unreliable parts will result in a product with low initial costs, but high support and warranty costs. On the other hand, over-designing a product with costly, highly reliable parts will result in a final product with low support and warranty costs, but that is prohibitively expensive. Application of information from a reliability engineering program can result in a design that balances out both of these factors, resulting in a design reliability that minimizes the overall cost of the product. Figure 4.1 gives a graphical representation of this concept. (Demirci, 1998)

Figure 4.1 also shows that the reliability is increasing with the investment.

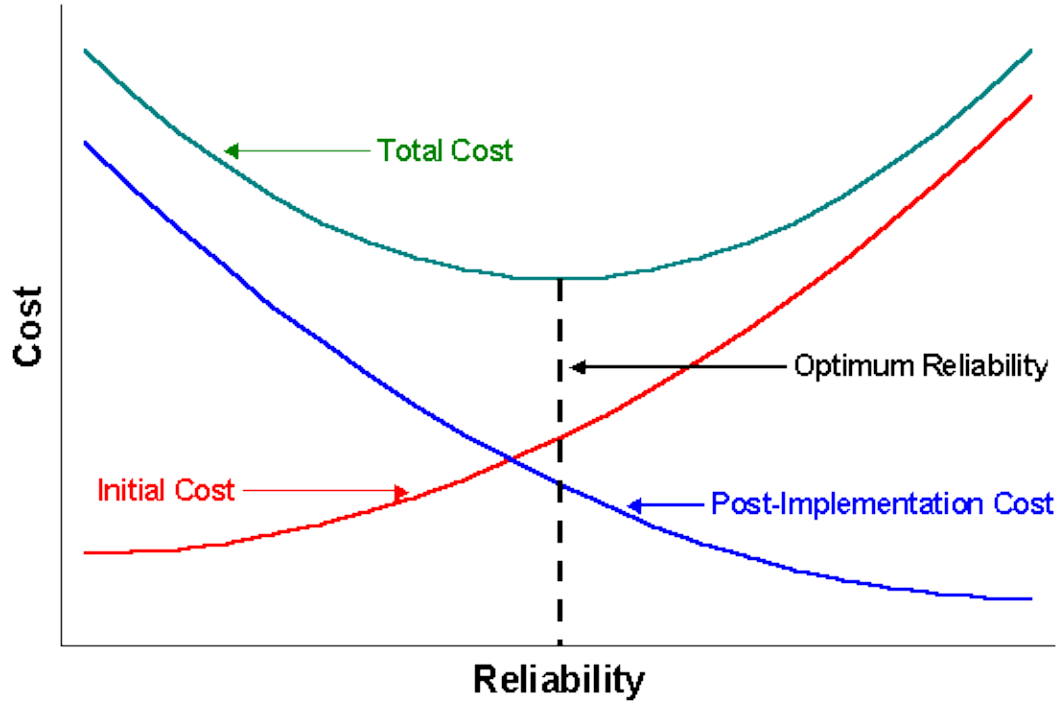


Figure 4.1 : Balancing initial and post-production costs to determine optimum reliability

4.5 Failure Rate, λ

Failure rate is the frequency with which an engineered system or component fails, expressed, for example, in failures per hour. It is often denoted by the Greek letter λ and is important in reliability engineering. As a mathematical expression;

$$\lambda(t) = \frac{\text{Number of failures at instant } t}{\text{Number surviving at instant } t} \quad 4.2$$

The failure rate of a system usually depends on time, with the rate varying over the life cycle of the system. For example, an automobile's failure rate in its fifth year of service may be many times greater than its failure rate during its first year of service. One does not expect to replace an exhaust pipe, overhaul the brakes, or have major transmission problems in a new vehicle.

In practice, the mean time between failures (MTBF, $1/\lambda$) is often reported instead of the failure rate. This is valid and useful if the failure rate may be assumed constant - often used for complex units / systems, electronics - and is a general agreement in

some reliability standards (Military and Aerospace). It does in this case only relate to the flat region of the bathtub curve, also called the "useful life period". Because of this, it is incorrect to extrapolate MTBF to give an estimate of the service life time of a component, which will typically be much less than suggested by the MTBF due to the much higher failure rates in the "end-of-life wear out" part of the "bathtub curve".

4.6 Bathtub Curve

The bathtub curve is widely used in reliability engineering. It describes a particular form of the hazard function ($\lambda(t)$) which comprises three parts:

- The first part is a decreasing failure rate, known as early failures.
- The second part is a constant failure rate, known as random failures.
- The third part is an increasing failure rate, known as wear-out failures.

These parts may be shown on the Figure 4.2. (Wikipedia, 2013).

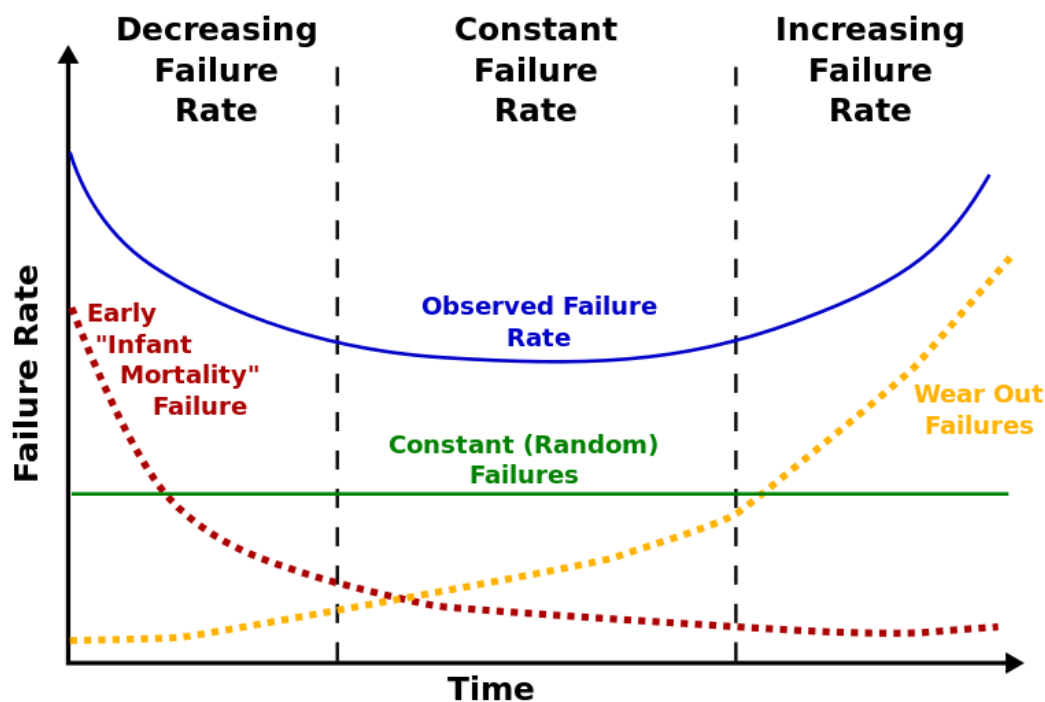


Figure 4.2 : The bathtub curve

The name is derived from the cross-sectional shape of a bathtub.

The bathtub curve is generated by mapping the rate of early "infant mortality" failures when first introduced, the rate of random failures with constant failure rate

during its "useful life", and finally the rate of "wear out" failures as the product exceeds its design lifetime.

In less technical terms, in the early life of a product adhering to the bathtub curve, the failure rate is high but rapidly decreasing as defective products are identified and discarded, and early sources of potential failure such as handling and installation error are surmounted. In the mid-life of a product—generally, once it reaches consumers—the failure rate is low and constant. In the late life of the product, the failure rate increases, as age and wear take their toll on the product. Many consumer products strongly reflect the bathtub curve, such as computer processors.

In reliability engineering, the cumulative distribution function corresponding to a bathtub curve may be analyzed using a Weibull chart.

4.7 The Failure Probability Density Function, $f(t)$

In probability theory, a probability density function (pdf), or density of a continuous random variable, is a function that describes the relative likelihood for this random variable to take on a given value. The probability for the random variable to fall within a particular region is given by the integral of this variable's density over the region. The probability density function is nonnegative everywhere, and its integral over the entire space is equal to one.

Observed value of failure probability density function for instant t ;

$$f(t) = \frac{\text{Number failing per hour at } t}{\text{Number at start } (t = 0)} \quad 4.3$$

The total failure of each instant time will become 1 at the end of total time of component. As a mathematical expression;

$$\int_0^{\infty} f(t) dt = 1 \quad 4.4$$

4.8 The Relation between Reliability, Failure Rate and Probability Density Functions

From Equations 4.1 and 4.2;

$$\begin{aligned} &= \frac{\text{Number Surviving at instant } t}{\text{Number at start when } t = 0} \times \frac{\text{Number of failures at instant } t}{\text{Number surviving at instant } t} \\ &= \frac{\text{Number failing per hour at } t}{\text{Number at start } (t = 0)} = f(t) \end{aligned} \quad 4.3$$

As a result;

$$R(t) \times \lambda(t) = f(t) \quad 4.5$$

5. RELIABILITY AND RATES OF FAILURE

5.1 Reliability Concepts

The most important parameter of the reliability is time. Because, reliability terms investigated within an interval of time. Evaluating failures respect to occurrence time helps engineers to understand nature of failures. Additionally, it is also helps to understand differences between failures. Each failure types are called as failure mode. Reliability effect on engineering evaluation can be discovered after understanding failure nature on the component.

5.2 Probability Distributions in Reliability Evaluation

Collected data must be analyzed and assessed to take a value in evaluation of the system nature. This can be done by using probability density function and probability density functions . For example, a CFM56-7B engine failed at the end of 20000 flight hours. Responsible engineer listed 20 failures within 2000 FH as 3 of them at 10000 FH, 5 of them at 14000 FH, 4 of them at 16000 FH and 8 of them at 18000 FH. This situation may be plotted as Figure 5.1 as frequency of failure.

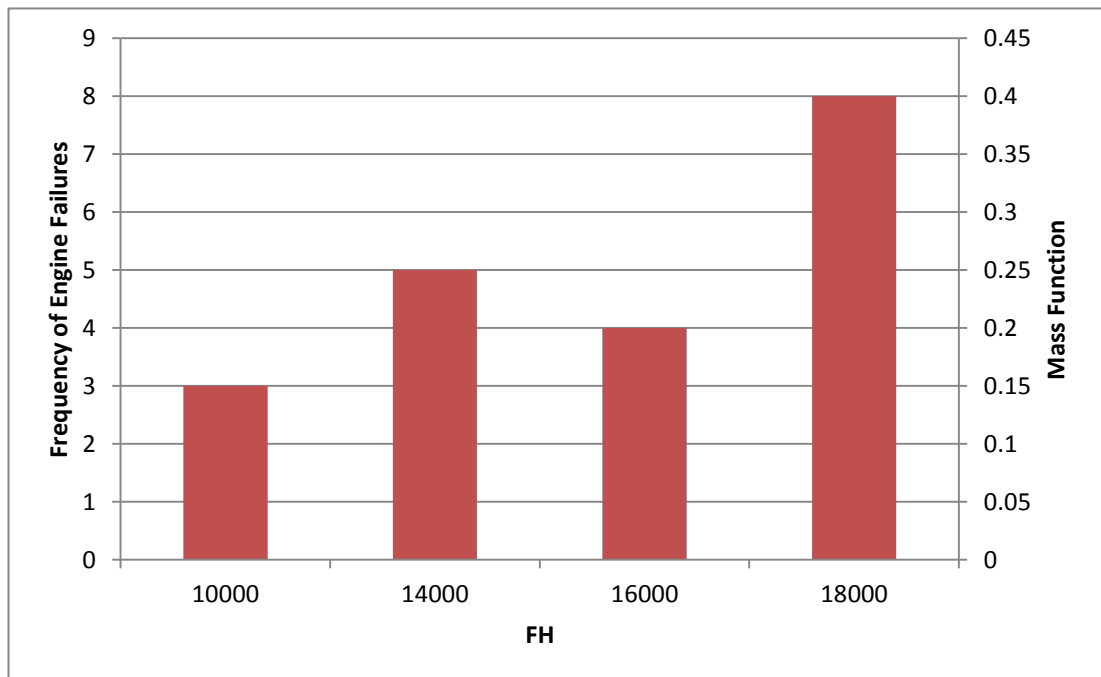


Figure 5.1 : Frequency distribution and probability mass function

According to probability theory, total outcomes should be equal to 1. Equation 5.1 shows this definition;

$$\sum_{i=1}^n P(x_i) = 1 \quad 5.1$$

Where x_i represents outcome i .

Another method of representing same data set is to use probability (cumulative) distribution function. This is obtained by ordering values in ascending or descending order and by starting with the probability of occurrence of the smallest (or largest) value, sequentially summate or cumulate, the probability of occurrence of each value until all such values have been cumulated.

When all possible probability outcomes listed and sum of them must be unity.

For a continues random variable the probability distribution function is a continues curve starting from zero.

The probability distribution function is obtained by summing the mass (density) function. Similarly a probability density function $f(x)$ can be obtained by differentiating probability function $F(x)$ of a continues variable;

$$f(x) = \frac{dF(x)}{dx} \quad 5.2$$

or

$$F(x_i) = \int_{-\infty}^{x_i} f(x) dx \quad 5.3$$

Equation 5.3 equals to the summation of probability with the interval of $-\infty$ to x_i . The limits can be changed to the new limits, in that case resulting integration gives probability of the random variables between new interval.

There are many different probability distributions theories available. Most widely used theory on technical components lifetime analysis is Weibull Distribution.

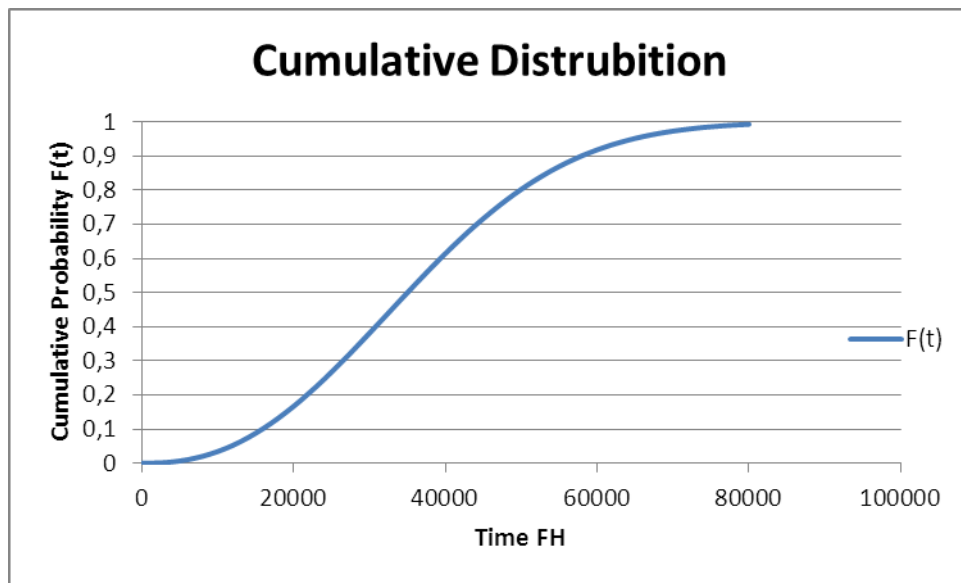


Figure 5.2 : Probability Distribution Function, $F(t)$

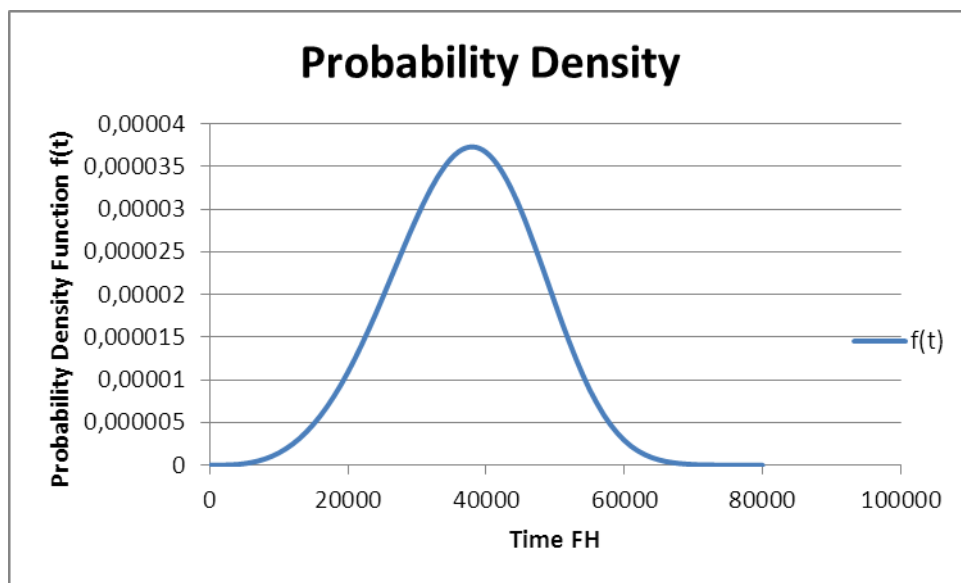


Figure 5.3 : Probability Density Function, $f(t)$

6. WEIBULL DISTRIBUTION AND ANALYSIS

Waloddi Weibull invented the Weibull distribution in 1937 and delivered his hallmark American paper on this subject in 1951. He claimed that his distribution applied to a wide range of problems. He illustrated this point with seven examples ranging from the strength of steel to the height of adult males in the British Isles. He claimed that the function "...may sometimes render good service." He did not claim that it always worked. Time has shown that Waloddi Weibull was correct in both of these statements. (Abernethy, 2002)

The reaction to his paper in the 1950s was negative, varying from skepticism to outright rejection. Weibull's claim that the data could select the distribution and fit the parameters seemed too good to be true. However, pioneers in the field like Dorian Shainin and Leonard Johnson applied and improved the technique. The U.S. Air Force recognized the merit of Weibull's method and funded his research until 1975. Today, Weibull analysis is the leading method in the world for fitting life data. Dorian Shainin introduced the author to statistical engineering at the Hartford Graduate Center (RPI) in the mid-fifties. He strongly encouraged the author and Pratt & Whitney Aircraft to use Weibull analysis. He wrote the first booklet on Weibull analysis and produced a movie on the subject for Pratt & Whitney Aircraft. (Abernethy, 2002)

6.1 Engineering Usage of Weibull Analysis

The Weibull distribution is one of the most widely used lifetime distributions in reliability engineering. It is a versatile distribution that can take on the characteristics of other types of distributions, based on the value of the shape parameter, β . The following are examples of engineering problems solved with Weibull analysis: (Abernethy, 2002)

- A project engineer reports three failures of a component in service operations during a three-month period. The Program Manager asks, "How many failures will we have in the next quarter, six months, and year?" What will it cost? What is the best corrective action to reduce the risk and losses?

- To order spare parts and schedule maintenance labor, how many units will be returned to depot for overhaul for each failure mode month-by-month next year?
- A state Air Resources Board requires a fleet recall when any part in the emissions system exceeds a 4% failure rate during the warranty period. Based on the warranty data, which parts will exceed the 4% rate and on what date?
- After an engineering change, how many units must be tested for how long, without any failures, to verify that the old failure mode is eliminated, or significantly improved with 90% confidence?
- An electric utility is plagued with outages from boiler tube failures. Based on limited inspection data forecast the life of the boiler based on plugging failed tubes.
- A machine tool breaks more often than the vendor promised. The vendor says the failures are random events caused by abusive operators, but you suspect premature wear out is the cause.
- The cost of an unplanned failure for a component, subject to a wear out failure mode, is twenty times the cost of a planned replacement. What is the optimal replacement interval?

6.2 Scope of Weibull Analysis

Weibull analysis includes:

- Plotting the data and interpreting the plot
- Failure forecasting and prediction
- Evaluating corrective action plans
- Engineering change substantiation
- Maintenance planning and cost effective replacement strategies
- Spare parts forecasting
- Warranty analysis and support cost predictions

- Calibration of complex design systems, i.e., CAD\CAM, finite element analysis, etc.
- Recommendations to management in response to service problems

Failure types include:

- Development, production and service
- Mechanical, electronic, materials, and human failures
- Nature: lightning strikes, foreign object damage, woodpecker holes in power poles
- Quality control, design deficiencies, defective material

6.3 Advantage of Weibull Analysis

The primary advantage of Weibull analysis is the ability to provide reasonably accurate failure analysis and failure forecasts with extremely small samples. Solutions are possible at the earliest indications of a problem without having to "crash a few more." Small samples also allow cost effective component testing.

For example, "sudden death" Weibull tests are completed when the first failure occurs in each group of components, (say, groups of four bearings). If all the bearings are tested to failure, the cost and time required is much greater.

Another advantage of Weibull analysis is that it provides a simple and useful graphical plot. The data plot is extremely important to the engineer and to the manager. The Weibull data plot is particularly informative as Weibull pointed out in his 1951 paper. (Weibull, 1951)

6.4 Life Data and Aging: FH or FC

Ideally, each Weibull plot depicts a single failure mode.

To determine failure time precisely, there are three requirements:

1. A time origin must be unambiguously defined,
2. A scale for measuring the passage of time must be agreed to and finally,
3. The meaning of failure must be entirely clear

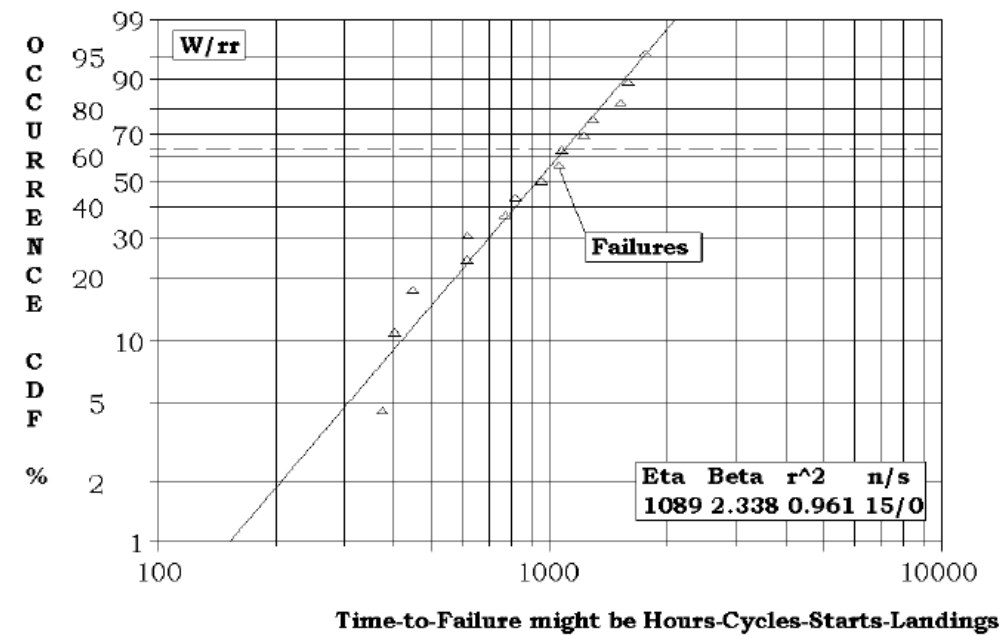


Figure 6.1 : The Weibull data plot

The age of each part is required, both failed and unfailed. The units of age depend on the part usage and the failure mode. For example, low cycle and high cycle fatigue may produce cracks leading to rupture. The age units would be fatigue cycles. The age of a starter may be the number of starts. Burner and turbine parts may fail as a function of time at high temperature or as the number of cold to hot to cold cycles. Usually, knowledge of the physics-of-failure will provide the age scale. When there is uncertainty, several age scales are tried to determine the best fit. This is not difficult with good software. The "best" aging parameter data may not exist and substitutes are tried. For example, the only data on air conditioner compressors may be the date shipped and the date returned. The "best" data, operating time or cycles, is unobtainable, so based on the dates above, a calendar interval is used as a substitute. These inferior data will increase the uncertainty, but the resulting Weibull plot may still be accurate enough to provide valuable analysis. The data fit will tell us if the Weibull is good enough.

6.5 Weibull Probability Density Function

The three-parameter Weibull probability density function is given by Equation 6.1:

$$f(T) = \frac{\beta}{\eta} \left(\frac{T - \gamma}{\eta} \right)^{\beta-1} e^{-\left(\frac{T - \gamma}{\eta} \right)^{\beta}} \quad 6.1$$

$$f(T) \geq 0, T \geq 0, \beta > 0, \eta > 0, -\infty < \gamma < \infty$$

Where;

- η = scale parameter,
- β = shape parameter (or slope),
- γ = location parameter.

Depending on the values of the parameters, the Weibull distribution can be used to model a variety of life behaviors. Generally location parameter assume '0' and in this situation Weibull pdf becomes two parameter distribution.

6.6 Failure Distribution

The slope of the Weibull plot, beta, (β), determines which member of the family of Weibull failure distributions best fits or describes the data. The slope, β , also indicates which class of failures is present:

- $\beta < 1.0$ indicates infant mortality
- $\beta = 1.0$ means random failures (independent of age)
- $\beta > 1.0$ indicates wear out failures

The horizontal scale is the age to failure. The vertical scale is the Cumulative Distribution Function (CDF), describing the percentage that will fail at any age. The complement of the CDF scale, (100 - CDF) is reliability. The characteristic life η is defined as the age at which 63.2% of the units will have failed, the B63.2 life, (indicated on the plot with a horizontal dashed line). For $\beta = 1$, the MTTF and η are equal. For $\beta > 1.0$, MTTF and η are approximately equal.

6.6.1 The Effect of β on the pdf

Figure 6.2 shows the effect of different values of the shape parameter, β , on the shape of the pdf. One can see that the shape of the pdf can take on a variety of forms based on the value of β .

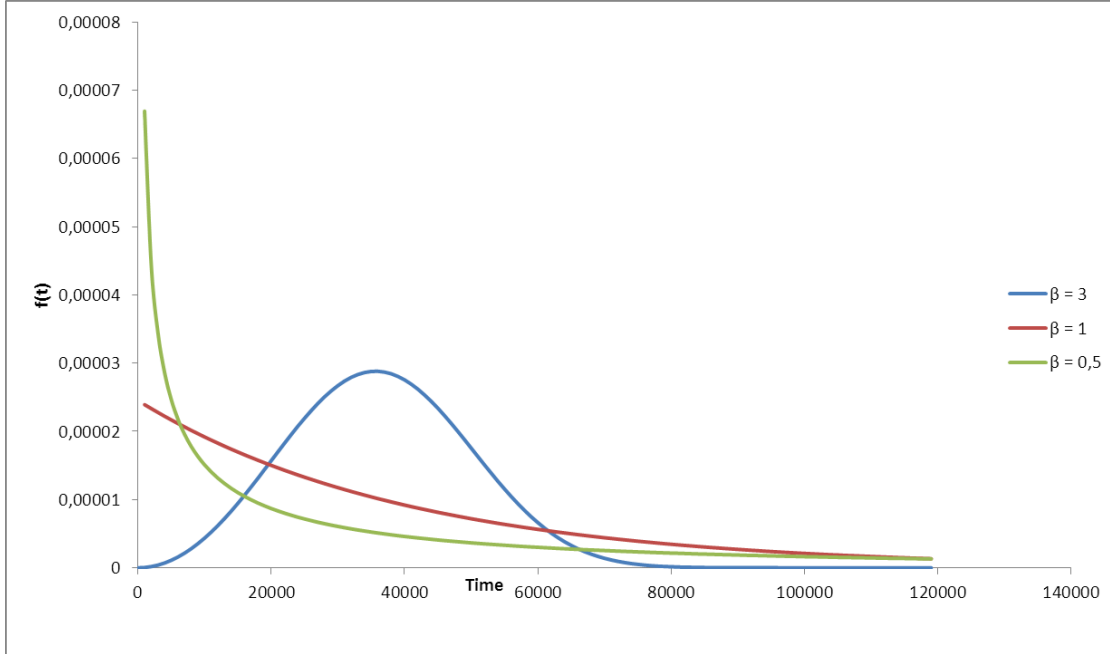


Figure 6.2 : The effect of the Weibull shape parameter on the *pdf* for a common η .

6.6.2 Characteristic effects of the η , for the Weibull distribution

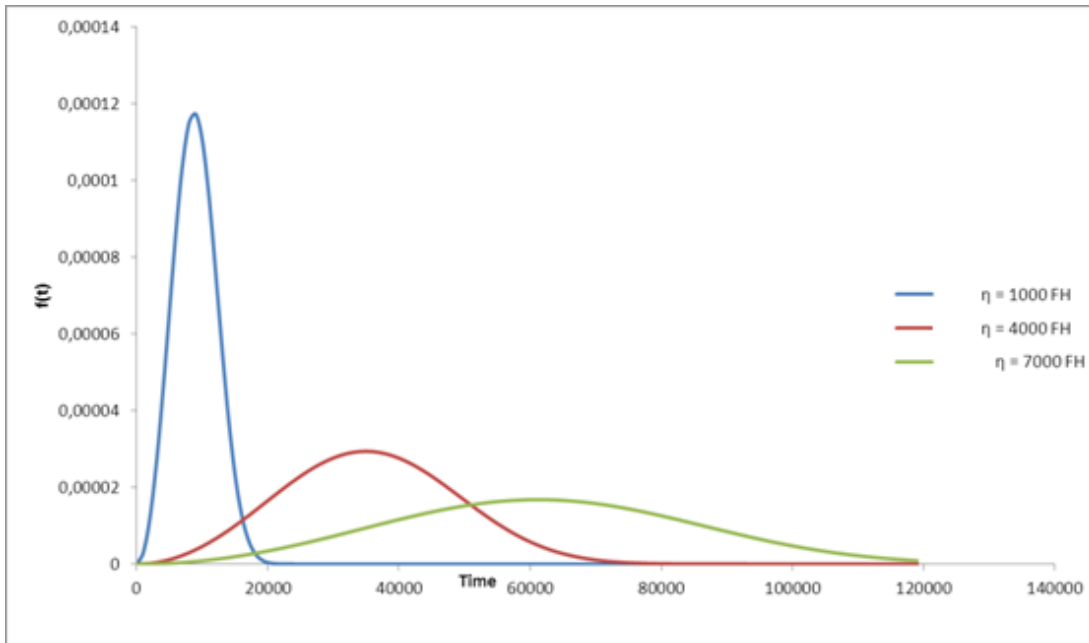


Figure 6.3 : The effects of η on the Weibull pdf for a common β .

A change in the scale parameter η has the same effect on the distribution as a change of the abscissa scale. Increasing the value of η while holding β constant has the effect of stretching out the pdf. Since the area under a pdf curve is a constant value of one, the "peak" of the pdf curve will also decrease with the increase of η , as indicated in Figure 6.2.

- If η is increased while β and γ are kept the same, the distribution gets stretched out to the right and its height decreases, while maintaining its shape and location.
- If η is decreased while β and γ are kept the same, the distribution gets pushed in towards the left (i.e. towards its beginning or towards 0 or γ), and its height increases.
- η has the same units as T , such as hours, miles, cycles, actuations, etc.

6.6.3 Characteristic effects of the γ , for the Weibull distribution

The location parameter, γ , as the name implies, locates the distribution along the abscissa. Changing the value of γ has the effect of "sliding" the distribution as in Figure 6.4 and its associated function either to the right (if $\gamma > 0$) or to the left (if $\gamma < 0$).

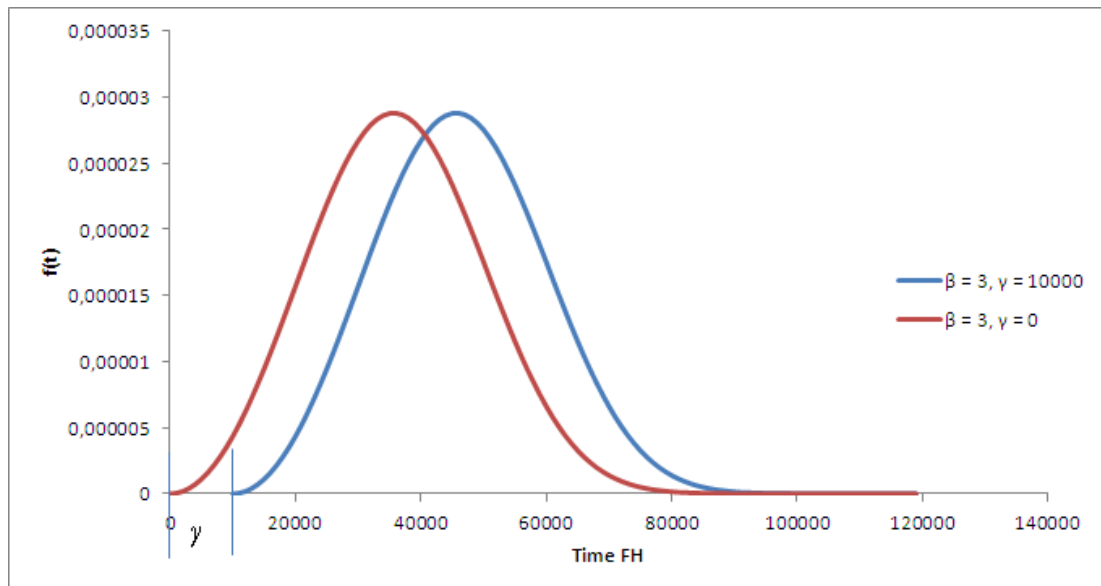


Figure 6.4 : The effect of a positive γ , on the position of the Weibull *pdf*.

- When $\gamma = 0$, the distribution starts at $T = 0$ or at the origin.
- If $\gamma > 0$, the distribution starts at the location γ to the right of the origin.
- If $\gamma < 0$, the distribution starts at the location γ to the left of the origin.
- γ provides an estimate of the earliest time-to-failure of such units.
- The life period 0 to $+\gamma$ is a failure free operating period of such units.
- The parameter γ may assume all values and provides an estimate of the earliest time a failure may be observed. A negative γ may indicate that failures have occurred prior to the beginning of the test, namely during production, in storage, in transit, during checkout prior to the start of a mission, or prior to actual use.
- γ has the same units as T , such as hours, miles, cycles, actuations, etc.

6.7 Cumulative Distribution Function with Weibull Parameters

In probability theory and statistics, the cumulative distribution function (CDF), or just distribution function, describes the probability that a real-valued random variable X with a given probability distribution will be found at a value less than or equal to x . Intuitively, it is the "area so far" function of the probability distribution. Cumulative distribution functions are also used to specify the distribution of multivariate random variables. Equation 6.2 shows weibull *cdf*.

$$F(T) = 1 - e^{-\left(\frac{T-\gamma}{\eta}\right)^\beta} \quad 6.2$$

6.8 The Weibull Reliability Function

Recalling that the reliability function of a distribution is simply one minus the cdf, the reliability function for the three-parameter Weibull distribution is given by Equation 6.3.

$$R(T) = 1 - F(T) = e^{-\left(\frac{T-\gamma}{\eta}\right)^\beta} \quad 6.3$$

6.9 Weibull Failure Rate Function

Failure rate is the frequency with which an engineered system or component fails, expressed for example in failures per hour. It is often denoted by the Greek letter λ (lambda) and is important in reliability engineering.

The failure rate of a system usually depends on time, with the rate varying over the life cycle of the system. For example, an automobile's failure rate in its fifth year of service may be many times greater than its failure rate during its first year of service. One does not expect to replace an exhaust pipe, overhaul the brakes, or have major transmission problems in a new vehicle.

In practice, the mean time between failures (MTBF, $1/\lambda$) is often reported instead of the failure rate. This is valid and useful if the failure rate may be assumed constant - often used for complex units / systems, electronics - and is a general agreement in some reliability standards (Military and Aerospace). It does in this case only relate to the flat region of the bathtub curve, also called the "useful life period". The reason of the preferred use for MTBF numbers is that the use of large positive numbers (like 150.000 hours) is more intuitive and easier to remember than very small numbers (like 1.3×10^{-4} per hour)

The MTBF is an important system parameter in systems where failure rate needs to be managed, in particular for safety systems. The MTBF appears frequently in the engineering design requirements, and governs frequency of required system maintenance and inspections. In special processes called renewal processes, where the time to recover from failure can be neglected and the likelihood of failure remains constant with respect to time, the failure rate is simply the multiplicative inverse of the MTBF ($1/\lambda$).

The Weibull failure rate function, $\lambda(T)$, is given by Equation 6.4.

$$\lambda(T) = \frac{f(T)}{R(T)} = \frac{\beta}{\eta} \left(\frac{T - \gamma}{\eta} \right)^{\beta-1} \quad 6.4$$

6.10 Estimation of Weibull Parameters

Once a life distribution and a life-stress relationship have been selected, the parameters (i.e. the variables that govern the characteristics of the pdf) need to be determined. Several parameter estimation methods, including probability plotting, least squares and maximum likelihood, are available. Estimation methods are;

- Graphical Method
- MLE (Maximum Likelihood) Parameter Estimation
- MLE of Accelerated Life Data

In this study only Graphical Method will be discussed and used for parameters estimation.

6.10.1 Graphical Method

Graphical analysis is the simplest method for obtaining results in both life data and accelerated life testing analysis. Although they have limitations in general graphical methods are easily implemented and easy to interpret. (ReliaSoft Corporation, 2012)

The graphical method for estimating the parameters of accelerated life data involves generating two types of plots. First, the life data at each individual failure times are plotted on a probability paper appropriate to the assumed life distribution. The parameters of the distribution at failure times are then estimated from the plot. Once these parameters have been estimated at each stress level, the second plot is created on a paper that linearizes the assumed life-failure relationship. The parameters of the life-failure relationship are then estimated from the second plot. The life distribution and life-failure relationship are then combined to provide a single model that describes the accelerated life data.

Probability plotting looks at the cdf (cumulative density function) of the distribution and attempts to linearize it by employing a specially constructed paper. For example, in the case of the 2-parameter ($\gamma = 0$) Weibull distribution, the cdf can be shown to be:

$$F(T) = 1 - e^{-\left(\frac{T}{\eta}\right)^\beta} \quad 6.5$$

This function can then be linearized (i.e. put into the common form of $y = a + bx$) as follows:

$$\ln(1 - F(T)) = \ln(e^{-(\frac{T}{\eta})^\beta}) \quad 6.6$$

$$\ln(1 - F(T)) = \ln(e^{-(\frac{T}{\eta})^\beta}) \quad 6.7$$

$$\ln(1 - F(T)) = -\left(\frac{T}{\eta}\right)^\beta \quad 6.8$$

$$\ln(-\ln(1 - F(T))) = \beta \ln\left(\frac{T}{\eta}\right) \quad 6.9$$

$$\ln(\ln\left(\frac{1}{1 - F(T)}\right)) = \beta \ln(T) - \beta \ln(\eta) \quad 6.10$$

Then setting:

$$y = \ln(\ln\left(\frac{1}{1 - F(T)}\right)) \quad 6.11$$

And,

$$x = \ln(T) \quad 6.12$$

The equation can be written as:

$$y = \beta x - \beta \ln(\eta) \quad 6.13$$

which is now a linear equation with a slope of β and an intercept of $\beta \ln(\eta)$.

To determine the scale parameter, η , a little more work is required. Note that from before:

$$F(T) = 1 - e^{-(\frac{T}{\eta})^\beta} \quad 6.14$$

so at $T = \eta$:

$$F(\eta) = 1 - e^{-\left(\frac{\eta}{\eta}\right)^\beta} \quad 6.15$$

$$F(\eta) = 1 - e^{-1} \quad 6.16$$

$$F(\eta) = 0.632 \quad 6.17$$

$$F(\eta) = 63.2 \% \quad 6.18$$

Thus if we entered the y axis at $F(T) = 63.2\%$, the corresponding value of T will be equal to η . Using this simple, but rather time-consuming methodology, then, the parameters of the Weibull distribution can be determined. For data obtained from accelerated tests, this procedure is repeated for each maintenance time.

6.10.1.1 Determining the X and Y positions of the plot points

The points plotted on the probability plot represent our data, or more specifically in life data analysis, times-to-failure data. So if we tested four units that failed at 10, 20, 30 and 40 hours at a given failure times, we would use these times as our x values or time values. Determining the appropriate y plotting position, or the unreliability, is a little more complex. To determine the y plotting positions, we must first determine a value called the median rank for each failure.

6.10.1.2 Median ranks

Median ranks are used to obtain an estimate of the unreliability, $F(T_j)$ for each failure. It represents the value that the true probability of failure, $F(T_j)$, should have at the j^{th} failure out of a sample of N units, at a 50% confidence level (Equation 6.20). This is an estimate of the value based on the binomial distribution. The rank can be found for any percentage point, P, greater than zero and less than one, by solving the cumulative binomial distribution for Z (rank for the jth failure). (ReliaSoft Corporation, 1997)

$$P = \sum_{k=j}^N \binom{N}{k} Z^k (1 - Z)^{N-k} \quad 6.19$$

where N is the sample size and j the order number.

The median rank is obtained by solving the following equation for:

$$0.50 = \sum_{k=j}^N \binom{N}{k} Z^k (1 - Z)^{N-k} \quad 6.20$$

For example if $N = 4$ and we have four failures at that particular failure time, we would solve the median rank equation, Equation 6.20, four times; once for each failure with $j = 1, 2, 3$ and 4 , for the value of Z . This result can then be used as the unreliability for each failure, or the y plotting position. Solution of Equation 6.20 requires numerical methods.

A more straightforward and easier method of estimating median ranks is to apply two transformations to Equation 6.20, first to the beta distribution and then to the F distribution, resulting in (ReliaSoft Corporation, 1997):

$$MR = \frac{1}{1 + \frac{N-j+1}{j} F_{0.50,m,n}} \quad 6.21$$

$$m = 2(N - j + 1) \quad 6.22$$

$$n = 2j \quad 6.23$$

$F_{0.50,m,n}$ denotes the F distribution at the 0.50 point, with m and n degrees of freedom, for the j^{th} failure out of N units.

A quick and less accurate approximation of Equation 6.21 the median ranks is also given by;

$$MR = \frac{j - 0.3}{N + 0.4_{(22)}} \quad 6.24$$

This approximation of the median ranks is also known as Benard's approximation.

6.10.2 MLE (Maximum Likelihood) parameter estimation

The idea behind maximum likelihood parameter estimation is to determine the parameters that maximize the probability (likelihood) of the sample data. From a statistical point of view, the method of maximum likelihood is considered to be more robust (with some exceptions) and yields estimators with good statistical properties. In other words, MLE methods are versatile and apply to most models and to different types of data. In addition, they provide efficient methods for quantifying uncertainty through confidence bounds. Although the methodology for maximum likelihood estimation is simple, the implementation is mathematically intense. Using today's computer power, however, mathematical complexity is not a big obstacle. This method will not be used for this study.

6.10.3 MLE of accelerated life data

Due to its nature, maximum likelihood offers a very powerful method in estimating the parameters of accelerated testing models, making possible the analysis of very complex models. Above graphical method discussed for obtaining the parameters of accelerated testing models was illustrated. It involved estimating the parameters of the life distribution separately for each individual failure time and then plotting the life-failure relationship in a linear manner on a separate life vs. failure plot. In other words, the life distribution and the life-failure relationship were treated separately. However, using the MLE method, the life distribution and the life-failure relationship can be treated as one complete model that describes both. This can be accomplished by including the life-failure relationship into the pdf of the life distribution.

7. FAILURE FORECASTING

Airlines need failure forecasts to set priorities and allocate resources for corrective action. This is risk analysis, a prediction of the magnitude of the problem, a clear view of the future. "Risk" is employed as a synonym for "failure forecast." The method will be applied to the Weibull, normal, and log normal life distributions in this section.

This section presents failure forecasting. It should be emphasized that a failure forecast is only as good as the quality and quantity of the failure data.

A risk analysis or failure forecast predicts the expected number of incidents that may occur in a specific period of time.

7.1 Forecasting Techniques

Forecasting requires additional input:

- the age of the components in service,
- usage rate per unit,
- introduction rate of new units (if they are subject to this failure mode) and
- whether failed parts are replaced with zero time parts.

With this information a failure forecast can be produced.

7.2 Calculating Failure Forecasts

The next three sections describe the calculations to predict:

- Expected failures now,
- Future failures when failed units are not replaced and
- Future failures when failed units are replaced.

7.2.1 Expected failures now

The first step is to calculate the expected number of failures at the current time, t_i . If there is a population of N items and each has accumulated t_i hours or cycles, the expected number of failures from this population is the probability of failure by time

t_j summed over the number of units, N , including both failures and suspensions. The expected number of failures is:

$$\begin{aligned} \text{Expected Failures} &= \sum_{i=1}^N F(t_i) \\ \text{Expected Failures} &= \sum_{i=1}^N \left(1 - e^{-\left(\frac{t_i}{\eta}\right)^\beta} \right) \end{aligned} \quad 7.1$$

7.2.2 Failure forecast when failed units are not replaced

Failure forecasts can be made for any time interval. $F(t_i)$ is the probability of pump i failing in the first t_i hours of service, assuming it follows a Weibull failure distribution, u is the prediction interval.

$$\text{Failure Forecast} = \sum_{i=1}^N \frac{F(t_i + u) \cdot F(t_i)}{1 - F(t_i)} \quad 7.2$$

7.2.3 Failure forecasts when failed units are replaced

Failure forecasts with replacement, called "renewal," are equal to or greater than the failures forecast without replacement. Without replacement the fleet size will decrease with time. With replacement the fleet size is constant and the failure of the replacements increases the number of failures. The replacement unit is assumed to be a new, zero-timed, addition to the fleet of the same design.

Continued production may add units to the fleet in the months ahead. The production rate will increase the fleet size and therefore the failure prediction. The production rate may be constant, or it may be seasonal varying by the month of the year, or it may be sampled from a distribution.

Similarly the usage rate may be constant, or it may be seasonal varying by the month of the year, or it may be sampled from a distribution.

8. ENGINE FAILURE TIME PREDICTION WITH WEIBULL ANALYSIS

Stack data for engine failure is required for application of mentioned Weibull Probability distribution. Manufacturer (CFMI) publishes a general fleet report for attention to operators. Operators are managing engines and/or aircraft in regards of published data. In this study CFMI's statistical analysis will be used for prediction of engine failures. Such kind of analysis previously done for Auxiliary Power Unit. (Yabsley & Ibrahim, 2008)

In this study last available engine fleet data will be used for evaluation for Weibull analysis.

8.1 Engine Failures for All CFM56-7B Engine Fleet

Figure 8.1 shows engine failure reasons and times. This figure published by engine manufacturer in Workscope Planning Guide. (CFM International, 2011) This guide gives general information to the operator during engine overhaul. It contains steps of engine overhaul.

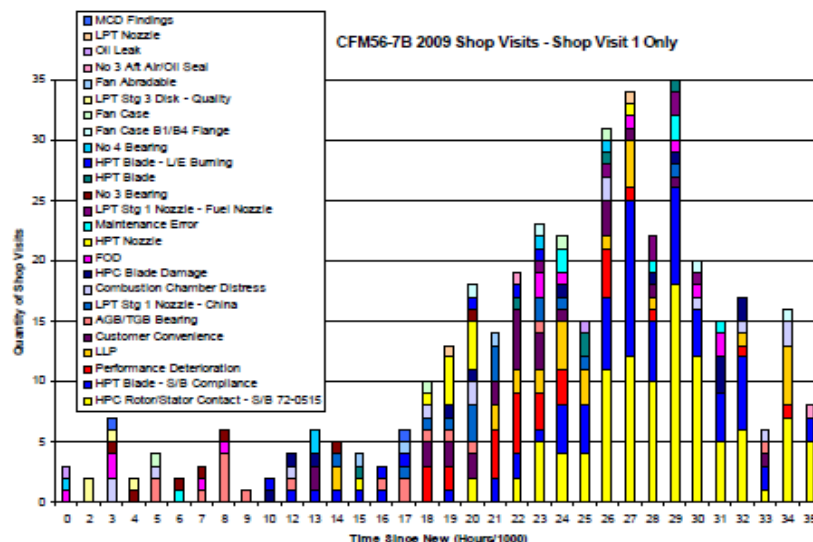


Figure 8.1 : CFM56-7B Failure times and reasons in 2009

Figure 8.1 not only shows failure reason but also shows failure times. From here times means FH. All data with its details, transferred to the Table A.11.1.

8.2 Data Analysis

There are lots of data available in different order and mode. For obtaining the most effective data list, pareto analysis is performed.

8.2.1 Pareto analysis

Pareto analysis is a statistical technique in decision making that is used for selection of a limited number of tasks that produce significant overall effect. It uses the Pareto principle – the idea that by doing 20% of work, 80% of the advantage of doing the entire job can be generated.

Table 8.1 : Pareto analysis list

Rank	Reason	SV Qty	Cumulative	Cum %
1	HPC Rotor/Stator Contact - S/B 72-0515	109	109	27%
2	HPT Blade - S/B Compliance	64	173	44%
3	Customer Convenience	28	201	51%
4	Performance Deterioration	28	229	58%
5	LLP	26	255	64%
6	AGB/TGB Bearing	17	272	69%
7	LPT Stg 1 Nozzle - China	15	287	72%
8	FOD	14	301	76%
9	Combustion Chamber Distress	14	315	79%
10	HPC Blade Damage	12	327	82%
11	HPT Blade - L/E Burning	11	338	85%
12	No 3 Bearing	9	347	87%
13	Maintenance Error	8	355	89%
14	Fan Case B1/B4 Flange	7	362	91%
15	HPT Blade	6	368	93%
16	HPT Nozzle	6	374	94%
17	LPT Stg 1 Nozzle - Fuel Nozzle	5	379	95%
18	LPT Stg 3 Disk - Quality	4	383	96%
19	Fan Case	4	387	97%
20	No 4 Bearing	3	390	98%
21	Oil Leak	2	392	99%
22	No 3 Aft Air/Oil Seal	2	394	99%
23	MCD Findings	1	395	99%
24	LPT Nozzle	1	396	100%
25	Fan Abradable	1	397	100%

The Table 8.1 was created to understand which failure modes are more dominant than other failures. Pareto manner is plotted and showed in the Figure 8.2. According to Figure 8.2 and pareto definition first seven failure and shop visit reasons are become more dominant that others and these are also driven failures of total list. However, a couple of them shall be removed from the list, because those failures are specific to a kind of operation or that cannot be called as a failure. Those are “LPT Stg 1 Nozzle – China” and “LLP”, respectively.

LPT Stg 1 Nozzle failures are very specific to the China operation of engines.

Life Limited Part (LLP) removal reason is one of the known and measured engine shop visit reason. This cannot called a failure, because this removal is scheduled removal and operators can easily manage their operation in regards with LLP replacement.

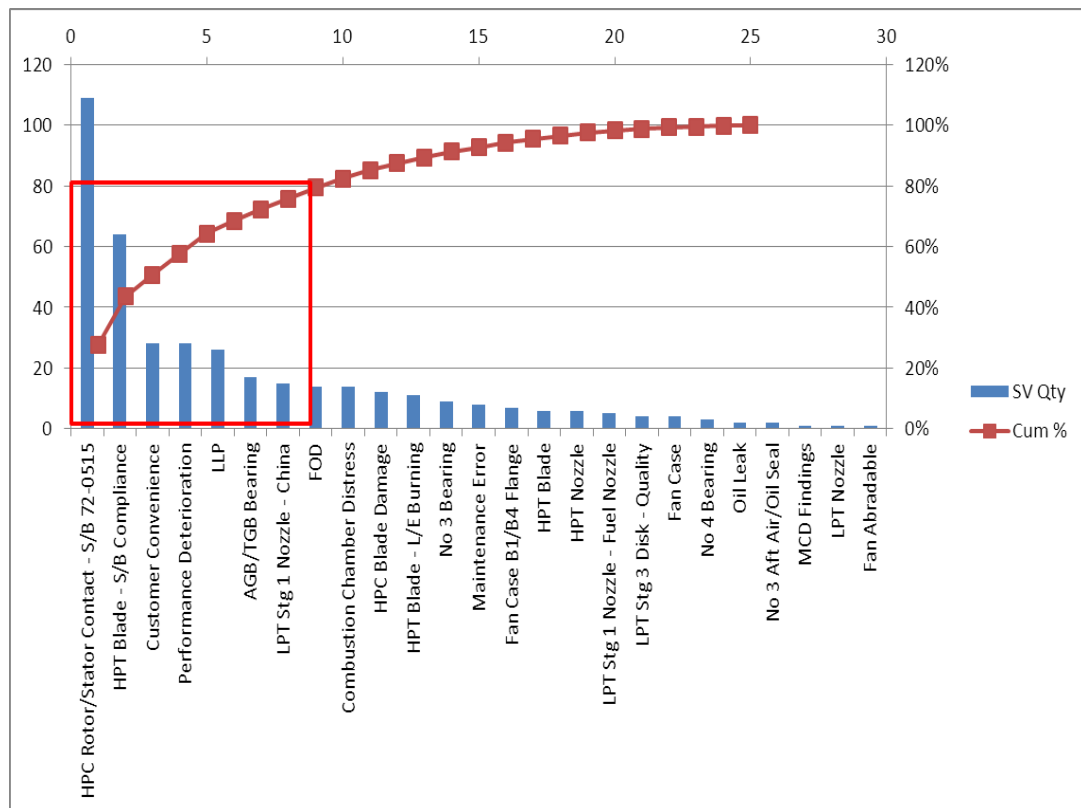


Figure 8.2 : Pareto plot

As a result of pareto analysis, failure reasons can be listed in Table 8.2.

Table 8.2 : The most important failures which is effecting whole engine fleet

Reason	SV Qty
HPC Rotor/Stator Contact - S/B 72-0515	109
HPT Blade - S/B Compliance	64
Customer Convenience	28
Performance Deterioration	28
AGB/TGB Bearing	17

Regarding to pareto analysis result only Table 8.2 listed reasons have been taken into account during estimation of Weibull parameters and at last estimating of failure prediction of engines.

8.3 Weibull Parameter Estimation

Microsoft Excel will be used for stacking time data analysis.

First, obtained failure time data which is listed in Table 8.3 shall be listed and aligned in increasing order.

Below steps will be followed for Weibull Analysis;

- 1- Put an order the failure times
- 2- Repeat failure times as the number of failures
- 3- Rank the failures and estimate Median Ranks as Equation 6.21.
- 4- Calculate values in respect to defined terms of Graphical Method of Weibull parameter estimation.
- 5- Make regression analysis $\ln(T)$ vs $\ln(\ln(\frac{1}{(1-MR)}))$ to obtain most fitted curve to the data.
- 6- The slop of the curve will give the β and then η can be obtained with to find 0,63 failure probability abscissa value.

Table 8.3 is limited for 7 values as an example of Step 1, originally 247 failures were used for calculations. Other steps has already applied to the table and regression analysis will be performed to last two column. Total list can be found from Table B.11.2.

Table 8.3 : A sample list of Weibull Parameter Estimation

<i>Time (T)</i>	<i>Rank</i>	<i>MR</i>	$\frac{1}{(1 - MR)}$	$\ln(\ln(\frac{1}{(1 - MR)}))$	$\ln(T)$
1000	1	0,002829	1,002837454	-5,86627	6,907755
3000	2	0,006871	1,006919007	-4,97693	8,006368
3000	3	0,010914	1,011033919	-4,51227	8,006368
5000	4	0,014956	1,015182602	-4,19515	8,517193
5000	5	0,018998	1,019365472	-3,95387	8,517193
7000	6	0,02304	1,023582954	-3,75891	8,853665
7000	7	0,027082	1,02783548	-3,5952	8,853665

Regression analysis performed with the Toolpack add-in of Excel, which is a close source and embedded feature of Microsoft Excel. Table 8.3 shows regression plot of the data.

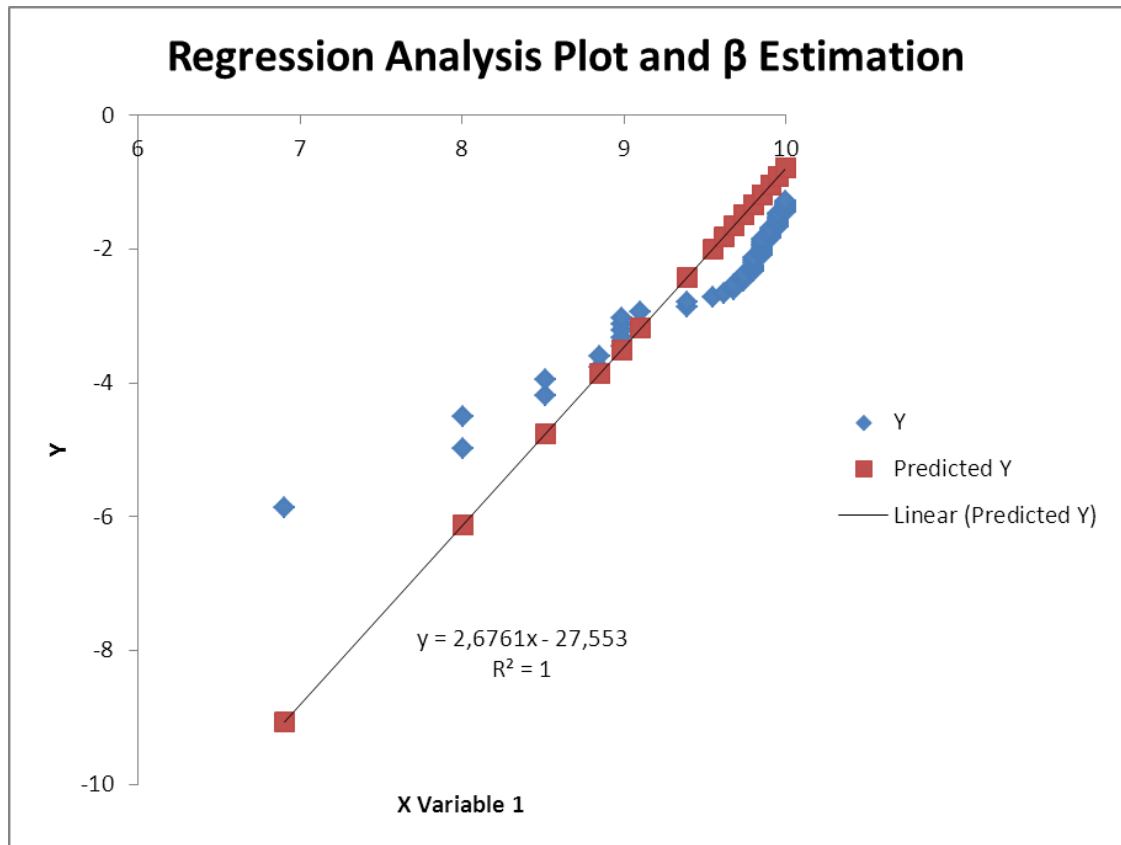


Figure 8.3 : Regression plot for β estimation.

When the steps are applied to the available data, parameters are obtained as Table 8.4.

Table 8.4 : Weibull parameters for CFM fleet.

Weibull Parameters		
	β	η
CFM Fleet	2,67	29617 FH

All other graphs and definitions can be obtained after Weibull parameter estimation.

8.3.1 Weibull probability density function

Equation 6.1 shows the Weibull Probability Density Function. It is calculated and plotted as Figure 8.4.

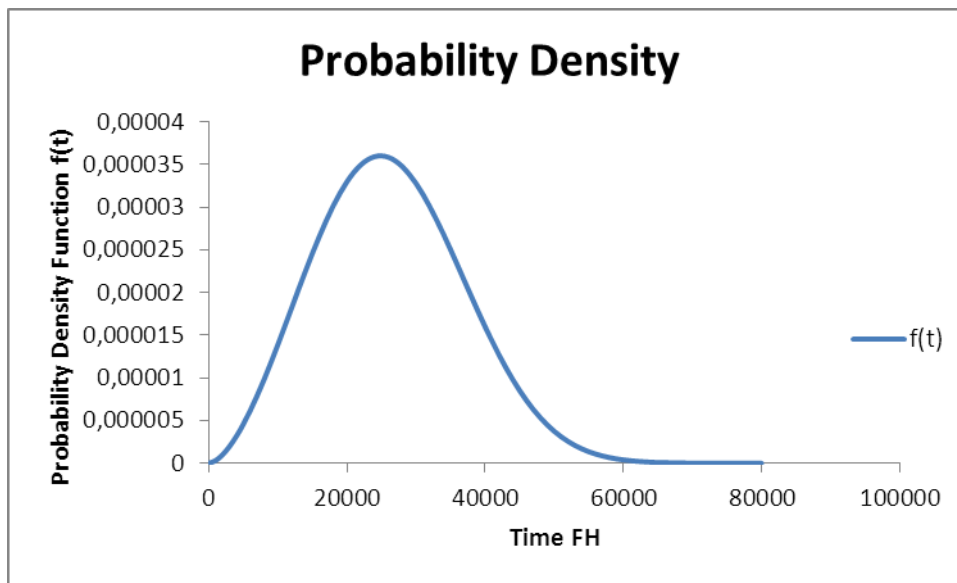


Figure 8.4 : Weibull Probability Density Function Curve

8.3.2 Cumulative distribution function

Cumulative distribution of CFM56-7B engine fleet data plotted as Figure 8.5 according to Equation 6.2.

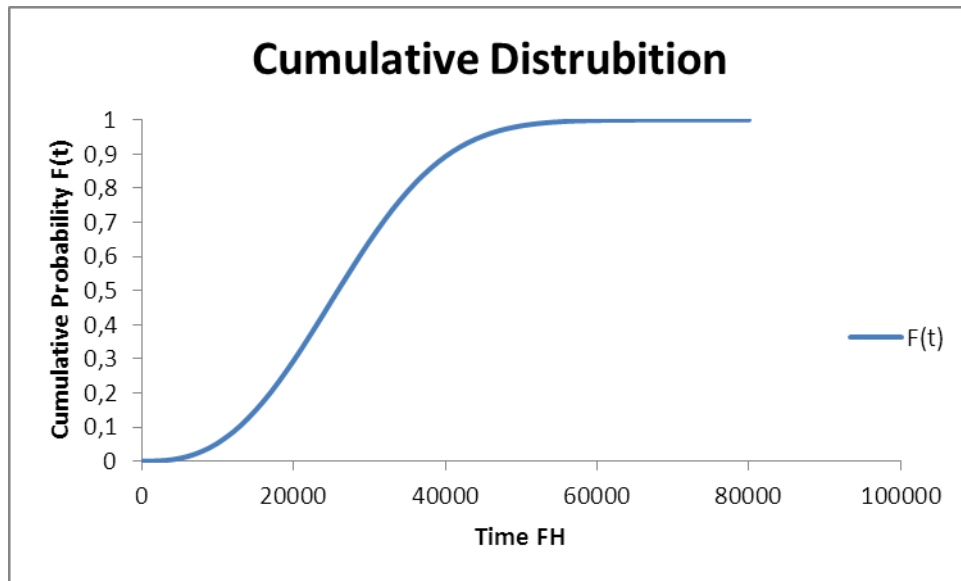


Figure 8.5 : Cumulative Distribution Function for general fleet

8.3.3 Weibull reliability function

Equation 6.3 is used for plotting reliability function. Figure 8.6 shows the plot of the function. This is also calculated as $R(T) = 1 - CDF$.

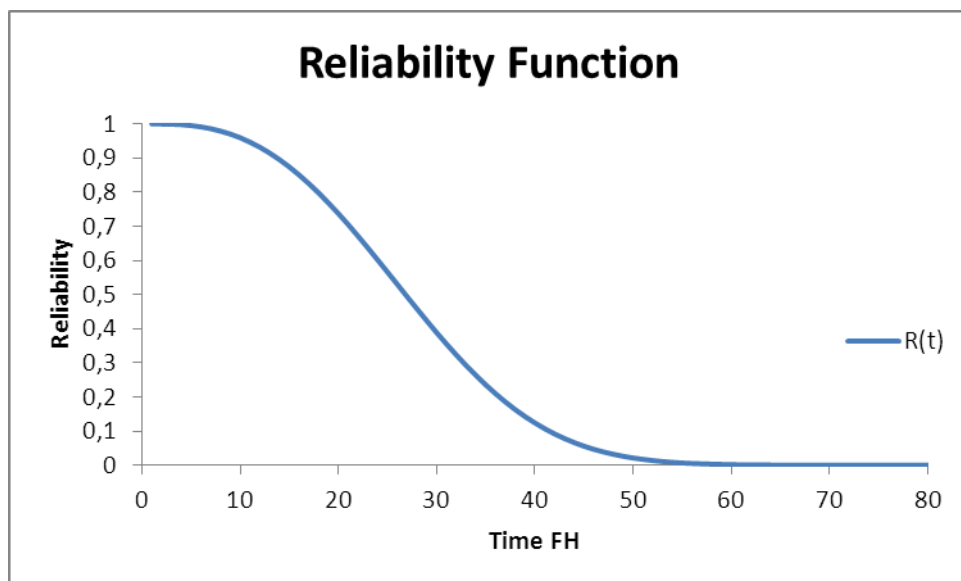


Figure 8.6 : Reliability function

8.3.4 Weibull failure rate function

Weibull failure rate function may be calculated with Equation 6.4. The function plotted as Figure 8.7 for CFM56-7B fleet.

According to the Figure 8.7, constant failure continues since the total engine time becomes approximately 25000 FH. After this threshold engines start to wear out failure period according to Figure 4.2 and bathtub curve theory.

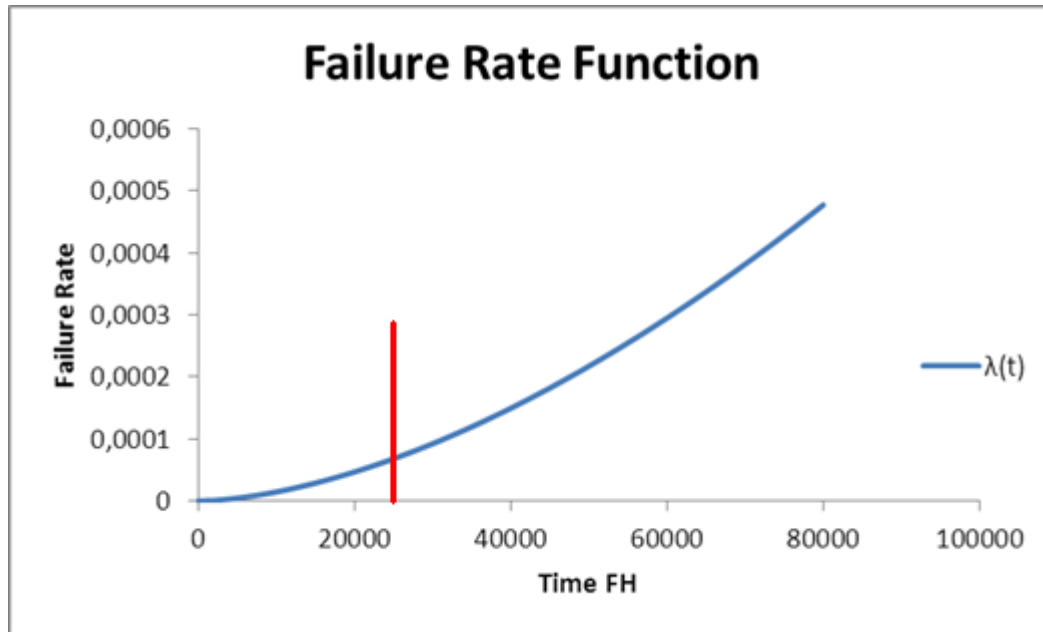


Figure 8.7 : Weibull failure rate function plot for CFM56-7B engine fleet

8.4 Evaluation of Engine Fleet Behavior and Life Prediction

8.4.1 Estimating the total engine failures quantity since 2009

In this section, estimated Weibull Parameters are used for life estimation of sample fleet. Predicted failures are listed for 3 years since 2009 in the Table C.11.3, Table C.11.4 and Table C.11.5, respectively.

For estimating the failure prediction of an engine for an interval time, some assumptions shall be made at first. Below assumptions have been made for this calculation;

- Engines are operated 4000 FH in a month.
- Estimated cumulative distribution values are used as a reference value for current and at the end of year. $F(t)$ and $F(t+u)$ values are symbolizing these estimations.
- Total values give predicted failure for that period of time.
- Predicted Failure column is estimated with $\frac{f(t+u)-f(t)}{1-f(t)}$ formula.

As a result of estimation, there were 9 unscheduled engine failures predicted for each year end and estimation. Real condition and estimated failure quantities summarized on the Figure 8.8

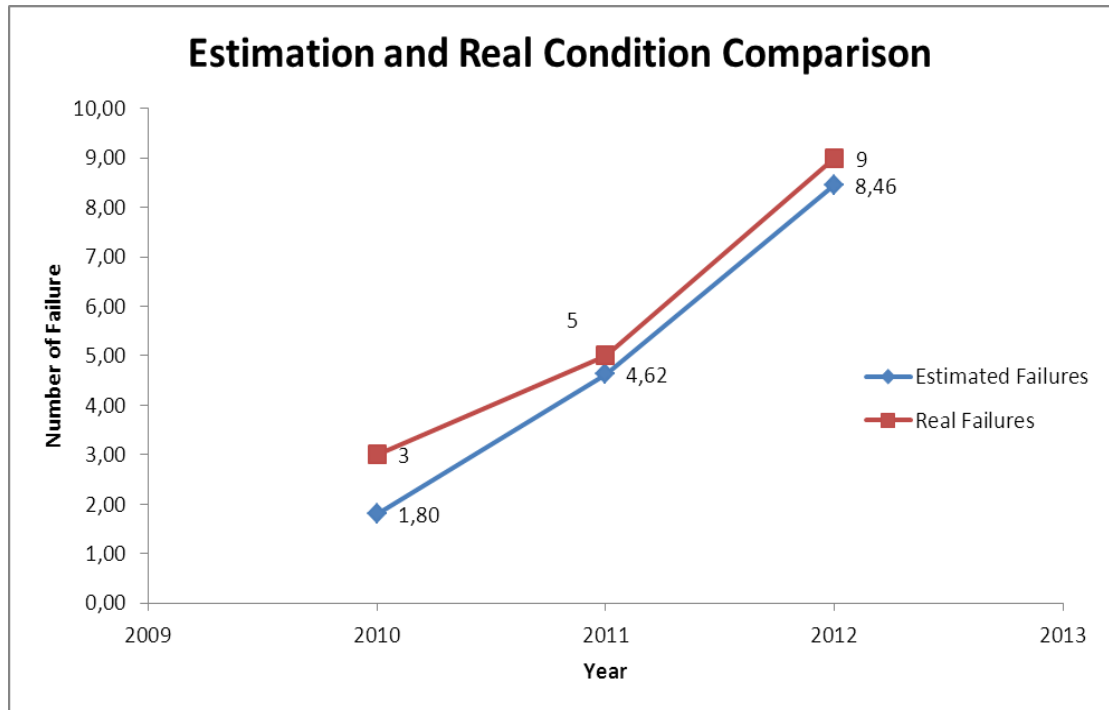


Figure 8.8 : Comparison of estimation and real engine failure quantities

According to comparison figure, real and estimated failures quantities seem similar. This also shows the reliability of the Weibull Distribution which is optimized for CFM56-7B engine failures.

8.4.2 Estimating the risk and failure quantities for a possible lease engines

In this example, a possible lease aircraft will be evaluated for a 5 years lease term in respect of engine failures. Following assumptions can be made for estimation,

- Aircraft model B737-800 will accumulate 4000 FH for a year.
- Both engine total time listed as Table 8.5 and these engines are first run engines which have not been overhauled before.
- Aircraft will be leased for 5 years.

Table 8.5 : Lease aircrafts engines condition

Engine Position	ESN	FH
1	889988	16400
2	889987	15600

Failure forecast can be seen on

Table 8.6. With respect to the feedback, airlines can estimate the engine failure and related cost risk for their fleet. Airlines can also estimate determine the effect of this aircraft to their plan and can establish their strategy accordingly.

As a result, 0.77 failures shall be taken into account for engine number 1 and 0.75 for engine 2. If airline wants to take themselves in the safe side then they shall be budgeted two more unscheduled engine overhauls for lease term. It means they should reserve additional 5 million USD for the next 5 years.

Table 8.6 : Engine failure forecast for next five years lease term.

Year	Engine Position	Engine Total Time (FH)	$F(t+u)$	$F(t)$	Predicted Failure
At 1st Year End	1	20400	0,295087275	0,175070717	0,145487086
	2	19600	0,262752154	0,149499629	0,133159877
at 2nd Year End	1	24400	0,434245627	0,175070717	0,314178336
	2	23600	0,398471098	0,149499629	0,292735285
at 3rd Year End	1	28400	0,577023727	0,175070717	0,487257537
	2	27600	0,54188969	0,149499629	0,461363774
at 4th Year End	1	32400	0,7077117	0,175070717	0,64568078
	2	31600	0,676910866	0,149499629	0,620118761
at 5th (Lease) Year End	1	36400	0,814697817	0,175070717	0,775372039
	2	35600	0,790567649	0,149499629	0,753753958

9. CONCLUSIONS AND RECOMMENDATIONS

As a conclusion, this study tried to improve a useful method for unscheduled engine maintenance time prediction. Weibull method was used for heavy maintenance time prediction.

Obtained Weibull parameters were not only used for calculation of sample fleet failure predictions but also used for lease aircraft engines total risk during lease period. Comparison of both estimation and real failure quantities were found similar in Figure 8.8. Weibull distribution found 8,46 failures at the end of 2012. However, there were 9 failures reported at real condition. Failure prediction method, which is found with Weibull parameters, predicted failure numbers with the % 6 error.

Airlines can easily estimate cost effect of unscheduled engine removals to their budget for a period of time. This study easily customize according to needs. If airlines collect total failures for components other than engines, this study also can be used for that purpose.

9.1 Recommendations

This study only gives failure times according to sorted failure data which is collected from all over the world operators.

Firstly, failure time prediction with failure reason will be further improvement to this theory. With this improvement operator may predict the time and failure reason before it happens. For instance, if the theory induct an engine failure because of HPT blade before it happens, operator may schedule a borescope inspection to the HPT module to prevent unscheduled maintenance.

Secondly, this study can be improved in the case of corrective action effect for failures. This is also depending on the predicting the failure reason.

Thirdly, operation environment was not taken into account in this study. At next stage, this data can also be added as a parameter of calculation.

For further studies, real engine conditions may be classified. Some scheduled conditions and engine overhaul levels will take into consideration and theory will be improved in accordance of them.

More detailed data will be requested from manufacturer for detailed failure time analysis.

9.2 Conclusion

In conclusion, a statistical tool was improved with this study. This tool gives an induction to the operator. Operators predict unscheduled failures for engines. It gives a big advantage to them with in today's competitive industry.

Engine maintenance is the most important maintenance item in aviation industry. Profit margin in aviation is very limited for airlines. Such kind of maintenance items are controllable actions. Therefore, postponing or preventing the maintenance activity is a vital goal for an airline.

The most important thing in the aviation is safety. Airlines easily measure their reliability with Weibull method.

Weibull's theory was used for understanding stacking sequence data. Parameter estimation is the most important thing for analyzing stacking data. In this study, graphical method presented for Weibull parameters estimation.

This study is only an introduction for estimating the failure time and number of failures for a period of time on first run CFM56-7B engine series.

10. REFERENCES

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11. APPENDICES

APPENDIX A:

Table A.11.1 : Table of failure times and failure reasons from CFMI Workscope Planning Guide for CFM56-7B engine type

Reason	Time/1000																																			
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	
MCD Findings			1																																	
LPT Nozzle																1																				
Oil Leak	1																							1												
No 3 Aft Air/Oil Seal																					1															1
Fan Abradable																				1																
LPT Stg 3 Disk - Quality		2	1	1																																
Fan Case					1																		1		1					1						
Fan Case B1/B4 Flange														1	1		1				1								2				1			
No 4 Bearing													1								1			1												
HPT Blade - L/E Burning										1	1	1	1	1	1	1		1	1			1	1													
HPT Blade													1								1				2	1			1							
No 3 Bearing			1	1		1	1	1					1						1				1						1							
LPT Stg 1 Nozzle - Fuel Nozzle																									1	1	2		1							
Maintenance Error	1					1						2											2				1			1						
HPT Nozzle																1		4									1									
FOD	1		2				1	1			1												2	1			1		1	1	2					
HPC Blade Damage										1		1						1	1				1				1	1		3	2					
Combustion Chamber Distress			2		1						1						1		2						2					1		1	1	2		
LPT Stg 1 Nozzle - China													1			1	2	1	3	3			2	1				1								
AGB/TGB Bearing					2		1	4	1		1					1	2	1	1	1			1										1			

Reason	Time/1000																																		
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35
Customer Convenience												2				1	1	2	2	2	5	3	1	1	3	1	1	2				1			
LLP													2							2	2	2	4	2	1	4	1				1		5		
Performance Deterioration																3	2		4	5	3	3		4	1	1				1		1			
HPT Blade - S/B Compliance															1					2	2	1	4	4	6	3	5	8	4	4	6	2		2	
HPC Rotor/Stator Contact														1				4	2		2	5	4	4	1	1	1	1	1	2	5	6	1	7	5

APPENDIX B:

Table B.11.2 : Weibull Parameter estimation table for engine source

<i>Time (T)</i>	<i>Rank</i>	<i>MR</i>	$\frac{1}{(1 - MR)}$	$\ln(\ln(\frac{1}{(1 - MR)}))$	$\ln(T)$
1000	1	0,002829426	1,002837454	-5,86626502	6,907755279
3000	2	0,006871463	1,006919007	-4,9769326	8,006367568
3000	3	0,0109135	1,011033919	-4,51227296	8,006367568
5000	4	0,014955538	1,015182602	-4,195148851	8,517193191
5000	5	0,018997575	1,019365472	-3,953869106	8,517193191
7000	6	0,023039612	1,023582954	-3,758908337	8,853665428
7000	7	0,027081649	1,02783548	-3,595202783	8,853665428
8000	8	0,031123686	1,032123488	-3,454018626	8,987196821
8000	9	0,035165724	1,036447424	-3,329837369	8,987196821
8000	10	0,039207761	1,040807741	-3,218948688	8,987196821
8000	11	0,043249798	1,045204901	-3,118737695	8,987196821
8000	12	0,047291835	1,049639372	-3,027292086	8,987196821
9000	13	0,051333872	1,054111632	-2,943170998	9,104979856
12000	14	0,055375909	1,058622165	-2,865261738	9,392661929
12000	15	0,059417947	1,063171465	-2,792687114	9,392661929
14000	16	0,063459984	1,067760035	-2,724743332	9,546812609
15000	17	0,067502021	1,072388383	-2,6608571	9,61580548
16000	18	0,071544058	1,077057031	-2,600555236	9,680344001
16000	19	0,075586095	1,081766506	-2,543442628	9,680344001
17000	20	0,079628133	1,086517347	-2,48918595	9,740968623
17000	21	0,08367017	1,091310101	-2,437501416	9,740968623
17000	22	0,087712207	1,096145326	-2,38814542	9,740968623
18000	23	0,091754244	1,101023587	-2,34090729	9,798127037
18000	24	0,095796281	1,105945463	-2,295603606	9,798127037
18000	25	0,099838319	1,11091154	-2,25207369	9,798127037
18000	26	0,103880356	1,115922418	-2,210175996	9,798127037
18000	27	0,107922393	1,120978704	-2,169785184	9,798127037
18000	28	0,11196443	1,12608102	-2,130789738	9,798127037
19000	29	0,116006467	1,131229995	-2,093090001	9,852194258
19000	30	0,120048504	1,136426275	-2,056596553	9,852194258
19000	31	0,124090542	1,141670512	-2,021228851	9,852194258
19000	32	0,128132579	1,146963375	-1,986914091	9,852194258
19000	33	0,132174616	1,152305543	-1,95358625	9,852194258
19000	34	0,136216653	1,157697707	-1,92118526	9,852194258
19000	35	0,14025869	1,163140574	-1,889656322	9,852194258
19000	36	0,144300728	1,168634861	-1,858949298	9,852194258

<i>Time (T)</i>	<i>Rank</i>	<i>MR</i>	$\frac{1}{(1 - MR)}$	$\ln(\ln(\frac{1}{(1 - MR)}))$	$\ln(T)$
20000	37	0,148342765	1,1741813	-1,8290182	9,903487553
20000	38	0,152384802	1,179780639	-1,799820742	9,903487553
20000	39	0,156426839	1,185433637	-1,771317953	9,903487553
20000	40	0,160468876	1,191141069	-1,743473838	9,903487553
20000	41	0,164510914	1,196903725	-1,716255081	9,903487553
20000	42	0,168552951	1,202722411	-1,689630789	9,903487553
21000	43	0,172594988	1,208597948	-1,663572253	9,952277717
21000	44	0,176637025	1,214531173	-1,638052756	9,952277717
21000	45	0,180679062	1,22052294	-1,613047386	9,952277717
21000	46	0,184721099	1,22657412	-1,588532878	9,952277717
21000	47	0,188763137	1,2326856	-1,564487472	9,952277717
21000	48	0,192805174	1,238858287	-1,540890782	9,952277717
21000	49	0,196847211	1,245093105	-1,517723689	9,952277717
21000	50	0,200889248	1,251390996	-1,494968228	9,952277717
21000	51	0,204931285	1,257752923	-1,472607504	9,952277717
22000	52	0,208973323	1,264179867	-1,450625605	9,998797732
22000	53	0,21301536	1,27067283	-1,429007528	9,998797732
22000	54	0,217057397	1,277232834	-1,407739107	9,998797732
22000	55	0,221099434	1,283860924	-1,386806954	9,998797732
22000	56	0,225141471	1,290558164	-1,366198405	9,998797732
22000	57	0,229183508	1,297325642	-1,345901461	9,998797732
22000	58	0,233225546	1,30416447	-1,325904748	9,998797732
22000	59	0,237267583	1,311075782	-1,306197473	9,998797732
22000	60	0,24130962	1,318060735	-1,28676938	9,998797732
23000	61	0,245351657	1,325120514	-1,26761072	10,04324949
23000	62	0,249393694	1,332256327	-1,248712213	10,04324949
23000	63	0,253435732	1,33946941	-1,230065022	10,04324949
23000	64	0,257477769	1,346761023	-1,211660722	10,04324949
23000	65	0,261519806	1,354132458	-1,193491273	10,04324949
23000	66	0,265561843	1,36158503	-1,175549	10,04324949
23000	67	0,26960388	1,369120089	-1,157826569	10,04324949
23000	68	0,273645918	1,376739009	-1,140316966	10,04324949
23000	69	0,277687955	1,384443201	-1,123013478	10,04324949
23000	70	0,281729992	1,392234102	-1,105909676	10,04324949
23000	71	0,285772029	1,400113186	-1,088999399	10,04324949
23000	72	0,289814066	1,408081958	-1,072276739	10,04324949
23000	73	0,293856103	1,416141958	-1,055736026	10,04324949
23000	74	0,297898141	1,424294761	-1,039371815	10,04324949
24000	75	0,301940178	1,43254198	-1,023178873	10,08580911
24000	76	0,305982215	1,440885265	-1,007152169	10,08580911
24000	77	0,310024252	1,449326303	-0,991286863	10,08580911
24000	78	0,314066289	1,457866824	-0,975578296	10,08580911
24000	79	0,318108327	1,466508595	-0,960021979	10,08580911

<i>Time (T)</i>	<i>Rank</i>	<i>MR</i>	$\frac{1}{(1 - MR)}$	$\ln(\ln(\frac{1}{(1 - MR)}))$	$\ln(T)$
24000	80	0,322150364	1,475253429	-0,944613586	10,08580911
24000	81	0,326192401	1,484103179	-0,929348945	10,08580911
24000	82	0,330234438	1,493059747	-0,91422403	10,08580911
24000	83	0,334276475	1,502125076	-0,899234955	10,08580911
24000	84	0,338318513	1,511301161	-0,884377966	10,08580911
24000	85	0,34236055	1,520590043	-0,869649433	10,08580911
24000	86	0,346402587	1,529993816	-0,855045847	10,08580911
24000	87	0,350444624	1,539514624	-0,840563815	10,08580911
25000	88	0,354486661	1,549154665	-0,826200048	10,1266311
25000	89	0,358528698	1,558916194	-0,811951364	10,1266311
25000	90	0,362570736	1,568801522	-0,797814679	10,1266311
25000	91	0,366612773	1,578813019	-0,783787	10,1266311
25000	92	0,37065481	1,588953115	-0,769865428	10,1266311
25000	93	0,374696847	1,599224305	-0,756047146	10,1266311
25000	94	0,378738884	1,609629148	-0,742329422	10,1266311
25000	95	0,382780922	1,620170269	-0,728709598	10,1266311
26000	96	0,386822959	1,630850363	-0,715185094	10,16585182
26000	97	0,390864996	1,641672196	-0,701753399	10,16585182
26000	98	0,394907033	1,652638611	-0,688412072	10,16585182
26000	99	0,39894907	1,663752522	-0,675158734	10,16585182
26000	100	0,402991108	1,675016926	-0,661991071	10,16585182
26000	101	0,407033145	1,686434901	-0,648906828	10,16585182
26000	102	0,411075182	1,698009609	-0,635903804	10,16585182
26000	103	0,415117219	1,709744299	-0,622979857	10,16585182
26000	104	0,419159256	1,72164231	-0,610132892	10,16585182
26000	105	0,423201293	1,733707078	-0,597360868	10,16585182
26000	106	0,427243331	1,745942131	-0,584661789	10,16585182
26000	107	0,431285368	1,758351102	-0,572033704	10,16585182
26000	108	0,435327405	1,770937724	-0,559474709	10,16585182
26000	109	0,439369442	1,78370584	-0,546982937	10,16585182
26000	110	0,443411479	1,796659405	-0,534556565	10,16585182
26000	111	0,447453517	1,809802487	-0,522193804	10,16585182
26000	112	0,451495554	1,823139278	-0,509892904	10,16585182
26000	113	0,455537591	1,836674091	-0,497652149	10,16585182
26000	114	0,459579628	1,850411369	-0,485469856	10,16585182
26000	115	0,463621665	1,86435569	-0,473344374	10,16585182
26000	116	0,467663703	1,878511769	-0,461274081	10,16585182
27000	117	0,47170574	1,892884468	-0,449257386	10,20359214
27000	118	0,475747777	1,907478797	-0,437292723	10,20359214
27000	119	0,479789814	1,922299922	-0,425378553	10,20359214
27000	120	0,483831851	1,937353171	-0,413513363	10,20359214
27000	121	0,487873888	1,952644041	-0,401695662	10,20359214
27000	122	0,491915926	1,968178202	-0,389923983	10,20359214

<i>Time (T)</i>	<i>Rank</i>	<i>MR</i>	$\frac{1}{(1 - MR)}$	$\ln(\ln(\frac{1}{(1 - MR)}))$	$\ln(T)$
27000	123	0,495957963	1,983961508	-0,378196878	10,20359214
27000	124	0,5	2	-0,366512921	10,20359214
27000	125	0,504042037	2,016299919	-0,354870704	10,20359214
27000	126	0,508084074	2,032867707	-0,343268837	10,20359214
27000	127	0,512126112	2,049710025	-0,331705949	10,20359214
27000	128	0,516168149	2,066833751	-0,320180681	10,20359214
27000	129	0,520210186	2,084245998	-0,308691693	10,20359214
27000	130	0,524252223	2,101954121	-0,297237654	10,20359214
27000	131	0,52829426	2,119965724	-0,285817251	10,20359214
27000	132	0,532336297	2,138288678	-0,27442918	10,20359214
27000	133	0,536378335	2,156931125	-0,263072148	10,20359214
27000	134	0,540420372	2,175901495	-0,251744873	10,20359214
27000	135	0,544462409	2,195208518	-0,240446082	10,20359214
27000	136	0,548504446	2,214861235	-0,229174509	10,20359214
27000	137	0,552546483	2,234869015	-0,217928896	10,20359214
27000	138	0,556588521	2,255241568	-0,206707992	10,20359214
27000	139	0,560630558	2,27598896	-0,195510551	10,20359214
27000	140	0,564672595	2,297121634	-0,184335332	10,20359214
27000	141	0,568714632	2,318650422	-0,173181096	10,20359214
27000	142	0,572756669	2,340586566	-0,162046609	10,20359214
27000	143	0,576798707	2,362941738	-0,150930637	10,20359214
28000	144	0,580840744	2,385728062	-0,139831948	10,23995979
28000	145	0,584882781	2,40895813	-0,12874931	10,23995979
28000	146	0,588924818	2,432645034	-0,117681489	10,23995979
28000	147	0,592966855	2,456802383	-0,106627251	10,23995979
28000	148	0,597008892	2,481444333	-0,095585356	10,23995979
28000	149	0,60105093	2,506585613	-0,084554564	10,23995979
28000	150	0,605092967	2,532241556	-0,073533628	10,23995979
28000	151	0,609135004	2,558428128	-0,062521296	10,23995979
28000	152	0,613177041	2,585161964	-0,051516307	10,23995979
28000	153	0,617219078	2,612460401	-0,040517395	10,23995979
28000	154	0,621261116	2,640341515	-0,029523284	10,23995979
28000	155	0,625303153	2,668824164	-0,018532687	10,23995979
28000	156	0,62934519	2,697928026	-0,007544306	10,23995979
28000	157	0,633387227	2,727673649	0,003443168	10,23995979
28000	158	0,637429264	2,758082497	0,01443106	10,23995979
28000	159	0,641471302	2,789177001	0,025420709	10,23995979
29000	160	0,645513339	2,820980616	0,036413469	10,27505111
29000	161	0,649555376	2,853517878	0,047410714	10,27505111
29000	162	0,653597413	2,886814469	0,058413836	10,27505111
29000	163	0,65763945	2,920897285	0,069424246	10,27505111
29000	164	0,661681487	2,955794504	0,08044338	10,27505111
29000	165	0,665723525	2,991535671	0,091472697	10,27505111

<i>Time (T)</i>	<i>Rank</i>	<i>MR</i>	$\frac{1}{(1 - MR)}$	$\ln(\ln(\frac{1}{(1 - MR)}))$	$\ln(T)$
29000	166	0,669765562	3,028151775	0,10251368	10,27505111
29000	167	0,673807599	3,065675341	0,113567839	10,27505111
29000	168	0,677849636	3,104140527	0,124636717	10,27505111
29000	169	0,681891673	3,143583227	0,135721883	10,27505111
29000	170	0,685933711	3,184041184	0,146824943	10,27505111
29000	171	0,689975748	3,225554107	0,157947535	10,27505111
29000	172	0,694017785	3,268163804	0,169091338	10,27505111
29000	173	0,698059822	3,311914324	0,180258069	10,27505111
29000	174	0,702101859	3,356852103	0,191449487	10,27505111
29000	175	0,706143897	3,403026135	0,202667399	10,27505111
29000	176	0,710185934	3,450488145	0,213913656	10,27505111
29000	177	0,714227971	3,499292786	0,225190165	10,27505111
29000	178	0,718270008	3,549497848	0,236498884	10,27505111
29000	179	0,722312045	3,601164483	0,247841831	10,27505111
29000	180	0,726354082	3,654357459	0,259221084	10,27505111
29000	181	0,73039612	3,709145427	0,270638788	10,27505111
29000	182	0,734438157	3,765601218	0,282097157	10,27505111
29000	183	0,738480194	3,823802164	0,29359848	10,27505111
29000	184	0,742522231	3,883830455	0,305145125	10,27505111
29000	185	0,746564268	3,945773525	0,316739544	10,27505111
29000	186	0,750606306	4,009724473	0,328384281	10,27505111
29000	187	0,754648343	4,075782537	0,340081972	10,27505111
30000	188	0,75869038	4,144053601	0,35183536	10,30895266
30000	189	0,762732417	4,214650767	0,363647294	10,30895266
30000	190	0,766774454	4,287694974	0,375520742	10,30895266
30000	191	0,770816492	4,363315697	0,387458796	10,30895266
30000	192	0,774858529	4,441651706	0,399464684	10,30895266
30000	193	0,778900566	4,52285192	0,411541775	10,30895266
30000	194	0,782942603	4,60707635	0,423693594	10,30895266
30000	195	0,78698464	4,694497154	0,435923832	10,30895266
30000	196	0,791026677	4,785299807	0,448236356	10,30895266
30000	197	0,795068715	4,879684418	0,460635226	10,30895266
30000	198	0,799110752	4,977867203	0,473124708	10,30895266
30000	199	0,803152789	5,080082136	0,485709291	10,30895266
30000	200	0,807194826	5,186582809	0,498393704	10,30895266
30000	201	0,811236863	5,29764454	0,511182937	10,30895266
30000	202	0,815278901	5,41356674	0,524082262	10,30895266
30000	203	0,819320938	5,534675615	0,537097257	10,30895266
30000	204	0,823362975	5,661327231	0,550233833	10,30895266
31000	205	0,827405012	5,793911007	0,563498264	10,34174248
31000	206	0,831447049	5,932853717	0,576897218	10,34174248
31000	207	0,835489086	6,078624079	0,590437796	10,34174248
31000	208	0,839531124	6,231738035	0,604127573	10,34174248

<i>Time (T)</i>	<i>Rank</i>	<i>MR</i>	$\frac{1}{(1 - MR)}$	$\ln(\ln(\frac{1}{(1 - MR)}))$	$\ln(T)$
31000	209	0,843573161	6,392764858	0,617974643	10,34174248
31000	210	0,847615198	6,562334218	0,631987672	10,34174248
31000	211	0,851657235	6,741144414	0,646175956	10,34174248
31000	212	0,855699272	6,929971989	0,660549488	10,34174248
31000	213	0,85974131	7,129682997	0,675119032	10,34174248
31000	214	0,863783347	7,341246291	0,689896213	10,34174248
31000	215	0,867825384	7,565749235	0,704893611	10,34174248
32000	216	0,871867421	7,804416404	0,720124877	10,37349118
32000	217	0,875909458	8,058631922	0,735604863	10,37349118
32000	218	0,879951496	8,32996633	0,751349772	10,37349118
32000	219	0,883993533	8,620209059	0,767377338	10,37349118
32000	220	0,888035557	8,931407942	0,783707026	10,37349118
32000	221	0,892077607	9,265917603	0,800360282	10,37349118
32000	222	0,896119644	9,626459144	0,817360815	10,37349118
32000	223	0,900161681	10,01619433	0,83473494	10,37349118
32000	224	0,904203719	10,43881857	0,852511991	10,37349118
32000	225	0,908245756	10,89867841	0,870724809	10,37349118
32000	226	0,912287793	11,40092166	0,88941035	10,37349118
32000	227	0,91632983	11,95169082	0,908610417	10,37349118
32000	228	0,920371867	12,55837563	0,928372581	10,37349118
33000	229	0,924413905	13,22994652	0,948751314	10,40426284
33000	230	0,928455942	13,97740113	0,96980944	10,40426284
33000	231	0,932497979	14,81437126	0,991619976	10,40426284
33000	232	0,936540016	15,75796178	1,014268531	10,40426284
34000	233	0,940582053	16,82993197	1,037856459	10,4341158
34000	234	0,944624091	18,05839416	1,062505074	10,4341158
34000	235	0,948666128	19,48031496	1,088361416	10,4341158
34000	236	0,952708165	21,14529915	1,115606275	10,4341158
34000	237	0,956750202	23,12149533	1,144465674	10,4341158
34000	238	0,960792239	25,50515464	1,175227768	10,4341158
34000	239	0,964834276	28,43678161	1,208268594	10,4341158
34000	240	0,968876314	32,12987013	1,244092958	10,4341158
35000	241	0,972918351	36,92537313	1,283402721	10,46310334
35000	242	0,976960388	43,40350877	1,327218303	10,46310334
35000	243	0,981002425	52,63829787	1,377113332	10,46310334
35000	244	0,985044462	66,86486486	1,435720904	10,46310334
35000	245	0,9890865	91,62962963	1,50801512	10,46310334
35000	246	0,993128537	145,5294118	1,605505834	10,46310334
35000	247	0,997170574	353,4285714	1,769459565	10,46310334

APPENDIX C:

Table C.11.3 : Sample engine failure quantity forecast for 2010

ENGINE	FH at 2010	Predicted Failure	ENGINE	FH at 2010	Predicted Failure	ENGINE	FH at 2010	Predicted Failure
1	12415	0,057	14	15669	0,087	27	4000	0,005
2	4000	0,005	15	16429	0,098	28	11677	0,048
3	13194	0,067	16	4232	0,005	29	11677	0,048
4	13194	0,067	17	4232	0,005	30	8809	0,025
5	13451	0,067	18	4000	0,005	31	8809	0,025
6	13451	0,067	19	4000	0,005	32	8216	0,025
7	12546	0,057	20	4000	0,005	33	8216	0,025
8	12546	0,057	21	4000	0,005	34	7762	0,019
9	12276	0,057	22	4000	0,005	35	7762	0,019
10	21493	0,158	23	4000	0,005	36	11202	0,048
11	19680	0,133	24	20871	0,145	37	11202	0,048
12	19680	0,133	25	4000	0,005			
13	21249	0,158	26	4000	0,005			
						Total	1,797	

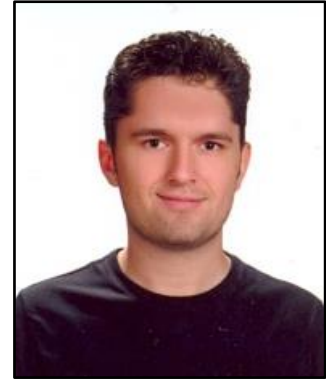
Table C.11.4 : Sample engine failure quantity forecast for 2011

ENGINE	FH at 2011	Predicted Failure	ENGINE	FH at 2011	Predicted Failure	ENGINE	FH at 2011	Predicted Failure
1	16415	0,150	14	19669	0,209	27	8000	0,030
2	8000	0,030	15	20429	0,229	28	15677	0,131
3	17194	0,169	16	8232	0,030	29	15677	0,131
4	17194	0,169	17	8232	0,030	30	12809	0,081
5	17451	0,169	18	8000	0,030	31	12809	0,081
6	17451	0,169	19	8000	0,030	32	12216	0,081
7	16546	0,150	20	8000	0,030	33	12216	0,081
8	16546	0,150	21	8000	0,030	34	11762	0,066
9	16276	0,150	22	8000	0,030	35	11762	0,066
10	25493	0,336	23	8000	0,030	36	15202	0,131
11	23680	0,293	24	24871	0,314	37	15202	0,131
12	23680	0,293	25	8000	0,030			
13	25249	0,336	26	8000	0,030			
						Total	4,622	

Table C.11.5 : Sample engine failure quantity forecast for 2012

ENGINE	FH at 2012	Predicted Failure	ENGINE	FH at 2012	Predicted Failure	ENGINE	FH at 2012	Predicted Failure
1	20415	0,274	14	23669	0,354	27	12000	0,085
2	12000	0,085	15	24429	0,382	28	19677	0,247
3	21194	0,300	16	12232	0,085	29	19677	0,247
4	21194	0,300	17	12232	0,085	30	16809	0,171
5	21451	0,300	18	12000	0,085	31	16809	0,171
6	21451	0,300	19	12000	0,085	32	16216	0,171
7	20546	0,274	20	12000	0,085	33	16216	0,171
8	20546	0,274	21	12000	0,085	34	15762	0,148
9	20276	0,274	22	12000	0,085	35	15762	0,148
10	29493	0,513	23	12000	0,085	36	19202	0,247
11	27680	0,461	24	28871	0,487	37	19202	0,247
12	27680	0,461	25	12000	0,085	Total8,458		
13	29249	0,513	26	12000	0,085			

CURRICULUM VITAE



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PUBLICATIONS/PRESENTATIONS ON THE THESIS

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