

Cranfield University

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**A TECHNOECONOMIC RISK ASSESSMENT
OF AERO-GAS TURBINE ENGINE
UPGRADES**

School Of Aerospace, Transport And Manufacturing

PhD Thesis

**Supervisor: Professor Pericles Pilidis
April 2018**

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ABSTRACT

Many, especially smaller operators, lack the analytical tools to carry out an effective cost-benefit analysis for upgrades they may be offered. The research aims to fill this gap and develop a methodology to carry out an effective quantitative evaluation of the performance, economics and risk outcomes and alternative uses of upgrade using the TERA (Techno-economic Environmental and Risk Assessment) framework.

The decision whether or not to adopt an engine upgrade is usually based on the cost-benefit and risk evaluation of the upgrade. For these non-mandatory upgrades/modifications or retrofits, the operator adapts its policy regarding estimation of the upgrade benefits relative to its unique operating environment, business models and cost structures. A handful of engine upgrade programmes exist in public literature with different methods of evaluating whether or not to adopt the engine upgrade for investment. The advantage this propose TERA – upgrade methodology has over the conventional methods is its ability to evaluate the engine upgrade from a multidisciplinary (performance, environmental, risk and economic) perspective. The method was developed by the careful adaptation and assembly of a collection of a wide range of technical models, and offers opportunity and adaptability for evaluating both current and novel engines, while reflecting the engine operating conditions and economic realities.

Three engine upgrade case studies were evaluated from both the aircraft operator's perspective and the manufacturer's perspective. There are; the thermal barrier coating (TBC), increase engine fan diameter and aircraft re-engine upgrades. Results were simulated through the adaptation of three main tools namely TURBOMATCH, HERMES and HESTIA, all of which are developed in Cranfield University, for gas turbine engine performance modelling, aircraft mission performance, maintenance costs, direct operating costs and time between overhaul prediction. Results for TBC upgrade on CEUP56 engine show that a life extension of 36.5% is possible with a $1.08\text{W/mK } K_{\text{tbc}}$ -value relative to baseline. In alternative use, a take-off thrust improvement of 33.32% is predicted delivering a payload increase of 3485kg, or a runway length reduction of 14%

assuming a constant cooling flow scenario. The small (< 1 inch) increase in fan diameter upgrade deployed on the CEUP6-80 engine delivered a maximum possible improvement of +2.47% and -0.436% in thrust and fuel burn savings relative to baseline, respectively. Re-engining upgrade of existing aircraft yielded engine SFC reduction of 9.5% and aircraft block fuel burn savings of up to 9.2% relative to baseline. The economics of these upgrades were evaluated on a cost-benefit analysis basis and the potential investment NPV estimated.

Results obtained show significant performance and economic benefits to merit investment in aero-engine upgrade project for all case study considered. The benefits of the methodology as a decision support tool is derived from the compelling relevance of this work embodied in the consistent approach to reveal informed insights on the performance and economics of each upgrade technology within a variety of operational space.

Keywords: Aero-engine Upgrades, Performance and Economic Improvement, Net Present Value

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LIST OF ABBREVIATIONS

AD	Airworthiness Directives	[-]
ATM	Air Traffic Management	[-]
BFL	Balance of Field Length	[m]
BPR	Bypass Ratio	[-]
CPV	Chemical Vapour Deposition	[-]
CAPEX	Capital Expenditure	[-]
DOC	Direct Operating Cost	[-]
EB-PVD	Electron-beam Physical Vapour Deposition	[-]
EMC	Engine Maintenance Cost	[-]
FAA	Federal Aviation Authority	[-]
HPC	High Pressure Compressor	[-]
HPT	High Pressure Turbine	[-]
ICAO	International Civil Aviation Organisation	[-]
ISA	International Standard Atmosphere	[-]
IT	Information Technology	[-]
IRR	Internal Rate of Return	[-]
MTOW	Maximum Takeoff Weight	[Kg]
NASA	National Aeronautics and Space Administration	[-]
NPV	Net Present Value	[-]
NEO	New Engine Option	[-]
NOx	Nitrogen Oxides	[-]
OEM	Original Equipment Manufacturing	[-]
OPEX	Operational Expenditure	[-]
OPR	Overall Pressure Ratio	[-]
OEW	Operating Empty Weight	[Kg]
SFC	Specific Fuel Consumption	[mg/Ns]
TBC	Thermal Barrier Coating	[-]
TBO	Time between Overhauls	[hrs]
TERA	Technoeconomic Environmental Risk Assessment	[-]
TET	Turbine Entry Temperature	[K]
TOC	Top of climb	[-]

NOTATION

Bi	Biot number	[-]
σ_u	Ultimate tensile strength	[MPa]
ε_f	Film Cooling Effectiveness	[-]
ε_0	Overall Cooling Effectiveness	[-]
h_g	Heat transfer coefficient of the hot gas stream	[W/(m ² K)]
K_{tbc}	Thermal Conductivity of TBC	[K]
N_f	Number of Cycles to failure	[hrs]
T_g	Gas stream temperature	[K]
T_m	Blade metal temperature	[K]
T_{co}	Blade cooling flow temperature	[K]
t_r	Time to failure in hours	[hrs]
ΔT_{tbc}	Temperature change across TBC of upgrade option	[K]
δT_{tbc}	Difference in temperature change across TBC between baseline and an upgrade option	[K]
$\Delta T_{baseline}$	Temperature change across TBC for baseline	[K]

Chapter One

1. Introduction

The desire to continuously reduce airline operating costs (OPEX) through decreasing engine fuel-burn (i.e., Improved specific fuel consumption – SFC and weight) and increase engine durability (reduce maintenance costs), remains a primary concern of airline companies, particularly in light of the increased public awareness and concern over the environmental impact of the aviation industry. This is particularly important considering the rapid growth experienced in recent times (i.e., predicted number of airline passenger growth at a compound annual growth rate (CAGR) of 4.7% over the next 20 years [1]). At the same time, operators are confronted with the challenges of meeting the ever-increasing demand of global air traffic while satisfying rising passenger's expectation for comfort, timely departure/arrival and safety in an environmentally friendly way. These market concerns have over the years been strong drivers for novel aero-engine designs and the development of advanced technologies with the goal of reducing engine fuel-burn, increased time-on-wing, reduction in CO₂ and NO_x emissions and lower noise levels, in line with the International Civil Aviation Organisation (ICAO) and Committee on Aviation Environment Protection (CAEP) legislations.

Airlines operating with fleets comprising ageing and mid-life assets are faced with the challenge of competing favourably with fleets of newer and advanced technologies within the fast-changing ATM environment, with more stringent emission regulations, noise and safety concerns. The impact is visible when considering the mission fuel burn, direct operating costs, engine maintenance costs, engine and airframe noise, emissions and global warming impact. To ensure assets maintain optimum productivity throughout their service life, most Original Equipment Manufacturers (OEM) offer opportunities for continuous technology improvements throughout the entire lifecycle of the aircraft, via

technology feedback programs such as upgrades, modifications and retrofits. Recent trend in aircraft performance enhancement have been through the infusion of new propulsion systems technology and major technology advancements. Over the years, a lot of engine performance enhancement packages have been developed by the OEM and issued as upgrades, modifications or retrofits. The ability of an operator to select a suitable upgrade investment for the target benefits is usually based on an independent detail analysis of the potential achievable benefits, economics and risk assessment of these upgrades or modifications.

There exists handful of engine upgrade programmes in public domain with different methods of evaluating whether or not to adopt the engine upgrade for investment. The RETROFIT project under the auspices of the “7 Seventh Framework Programme” carried out a cost-benefit studies of possible future retrofit programmes [107] analysing the aircraft avionics and the re-engine upgrades. Upgrades are widely used in military aircraft fleets to improve reliability and reduce fuel consumption during and off combat. The research commissioned by the Air Force Studies Board of the National Research Council (NRC) for improving the efficiency of engine for large nonfighter aircraft [3] recommended aircraft engine modification and re-engining upgrades. Although the calculation approach may differ, the central purpose of all the methods is the evaluation of the cost-benefit analysis of the upgrade investment. However, the value the propose TERA – upgrade methodology delivers over the conventional methods is its ability to evaluate the engine upgrade from a multidisciplinary (performance, environmental, risk and economic) perspective. The method was developed by the careful adaptation and assembly of a collection of a wide range of technical models, and offer users the opportunity create both current and novel engines, while reflecting the engine operating conditions and economic realities.

The deployed TERA–Upgrade method performs a detailed multidisciplinary evaluation of aero-engine upgrades from the perspective of the user (i.e. airline operator) and the manufacturer (OEMs), with the purpose of identifying and quantifying the potential benefits associated with the upgrades and its possible

impact. The thermal barrier coating (TBC) upgrade case study is evaluated from the perspective of the operators (i.e. airline owners), with a detailed TERA evaluation and sensitivity study to investigate the effect of fuel price and TBC upgrade acquisition costs variation on the project annual DOC gains and NPV estimation. This enables the creation of a feasible operational region within which the project investment returns are economically attractive. Implementation of TBC upgrade is intended as retrofits during shop visit for engine overhaul. The other two case studies: the increased engine fan diameter and the re-engining of existing aircraft upgrades are approached from the manufacturer's perspective since any implementation of the upgrade requires modification or some sort of alteration of the baseline engine. This evaluation involved identifying and quantifying potential benefits of the upgrade in terms of performance improvements and economic gains. The overall goal is to investigate whether the derived benefit in terms of fuel savings/direct operating costs (DOC) reduction, reduced field length and payload improvements is sufficient to offset the associated penalties of increased weight and drag, modification and installation costs, and still become an attractive investment in comparison with the conventional system. The operational range for a viable investment was further investigated using the sensitivity analysis to predict the effect of mission range, fuel and ticket price variation on the investment profitability. The value of this work to the engine manufacture (OEMs) can be seen in its ability to provide decision support in terms of accessing the economics of the project.

1.1 Aim and Objectives

The project aims to assess and quantify the potential performance and economic benefits that can be derived from investing on aircraft engine upgrade technologies on existing fleets from the Techno-economic, environmental and risk assessment (TERA) approach. The quantitative study of some promising upgrade technologies and novel concepts, and the risk associated with these technology deployment presents useful preliminary assessment and guide for decision (policy) makers from both the OEMs and aircraft operator (User's) perspective.

The overall aim of the study was to develop and deploy a TERA analysis from the viewpoint of both the aircraft operator (User) and OEMs to investigate potential upgrade technology candidates, to better understand the performance and economic benefits achievable and their associated risk. In this research, primary focus has been placed on three upgrade technologies.

The following research objectives were identified:

- Evaluate and establish baselines for evaluating the aircraft-engine upgrade technology case studies.
- Evaluate the performance benefit of the engine upgrade technologies and identify alternative ways of putting the upgrade to use.
- Perform economic analysis to determine whether the benefit attainable (in terms of cost savings or revenue increase) is sufficient to offset the upgrade costs and provide operational advantage.
- Undertake a sensitivity/parametric analysis to identify parameters that have the most impact on the solution, and establish operating range such as mission range, fuel price uncertainty and ticket price that gives desirable results with respect to economic benefits.
- Perform the technical risk analysis of the aero-engine upgrade technologies, in terms predicting the uncertainty associated with the technology benefit non-delivery with reference to the upgrade Technology Readiness Level (TRL) or maturity.

1.2 Contribution to Knowledge

From the review of relevant literatures, it is apparent that although a handful of feasibility assessments have been performed on engine upgrades and selection of viable candidates, these studies are usually carried out on behalf of national/international research organizations or OEMs to meet operational and economic demands, environmental and safety concerns. The end users of these upgrades: the airlines, especially small operators lack the analytical tools to carry out an effective cost-benefit analysis for upgrades they may be offered.

This study aims to help fill the gap by developing a methodology for accessing, and quantifying potential benefits of aero gas turbine engine upgrade used in current aircrafts to provide useful guide and insight for decision/policy makers, and financiers of engine upgrade investments. By investigating these engine upgrades, it is possible not only to determine the potential maximum benefit available but also to evaluate the impact of operational and economic dynamics on project investment for a given airline market strategy. The emphasis of this study is finding out whether the derived benefit of the upgrade is sufficient to make the technology a potential viable investment, and very importantly identify and analyse other ways putting the upgrades to use. To the author's knowledge, this investigation (aero-engine TERA-upgrade) has not been undertaken in this way before.

The contribution to knowledge derived from this study can be summarised as follows: to undertake a techno-economic and risk assessment of aero gas turbine upgrades in order to quantify and analyse the potential available performance and economic benefits, identify alternative ways of utilizing upgrades and analyse the risk associated with it, in terms of upgrade-option, fuel pricing, mission range and sensitivity to Δ DOC (gains in direct operating costs), annual profits and Net Present Value (NPV) of the upgrade investments.

1.3 Thesis Structure

The thesis structure is arranged into nine (9) chapters with the main content as follows:

- In **Chapter 2**, an overview of the relevant literature reviewed to identify the gap in knowledge and reason for this research work is presented. The growth trend in Aero-Gas turbine engines, new engine technologies and concepts that may be suitable for deployment as upgrade, retrofits or/modifications in existing in-service engines to address environmental concerns and/or improve performance and economy.
- In **Chapter 3**, the overall methodology deployed during this work and its individual component models is described.

- In **Chapter 4**, the baseline models of all aero-engine and aircraft models utilized for the upgrade investigation is presented.
- In **Chapter 5**, a technoeconomic risk assessment (TERA) of aircraft engine upgrade developed from the **user's (aircraft/engine owner) perspective**. Thermal barrier coating (TBC) upgrade **Case study** evaluated for any potential performance and economic benefits and alternative used of the upgrade.
- In **Chapter 6**, a technoeconomic risk assessment (TERA) of aircraft engine upgrade developed from the **manufacturers (OEM) perspective**, with two upgrade case studies presented: the increased engine fan diameter and engine cooling via reduction of cooling flow.
- In **Chapter 7**, a TERA evaluation of re-engine upgrade of current aircraft model is presented.
- In **Chapter 8**, the technology risk analysis evaluated in terms of TBC upgrade failure to meet the promised performance benefits and the impact of TRL (Technology readiness level) on TBC engine upgrade.
- In **Chapter 9**, the thesis conclusion is provided summarising the entire work and making recommendations for further investigations.

Chapter Two

2. Background

This chapter presents an overview of the aircraft engine development trends and discusses gas turbine engines performance and efficiency improvement methods. This is followed by a review of aero engine performance enhancement through upgrades, examples of recent upgrade offerings by OEMs (Original Equipment Manufacturers) and the technologies and innovation utilized for driving these engine improvements. Also provided within this chapter, is a detailed description of the TERA framework in the context of its capability for assessing current and future technologies and quantifying potential benefits obtainable, costs implication and risk associated with an investment for the purpose of providing insightful guide for decision-making.

2.1 Trends in Aero-Engine Growth

Jet engines have experienced rapid evolution since its development over 7 decades ago. While early engine designs were primarily focussed on obtaining maximum thrust and minimum weight [2] for military applications, today engine designs are a lot more complex as many factors such as fuel economy, emissions, noise, reliability, etc., are at the centre stage of design considerations. The advantage of gas turbine high power-to-weight density has made it the preferred choice for all commercial passenger aircraft propulsion system.

Aero-engines have seen steady improvement through the years. Advances in material and turbine cooling technologies are the key enablers for higher peak operating temperature (TET), overall pressure ratio (OPR) and thermal efficiency improvement achieved in modern engine as shown in Figure 2-1 and Figure 2-2.

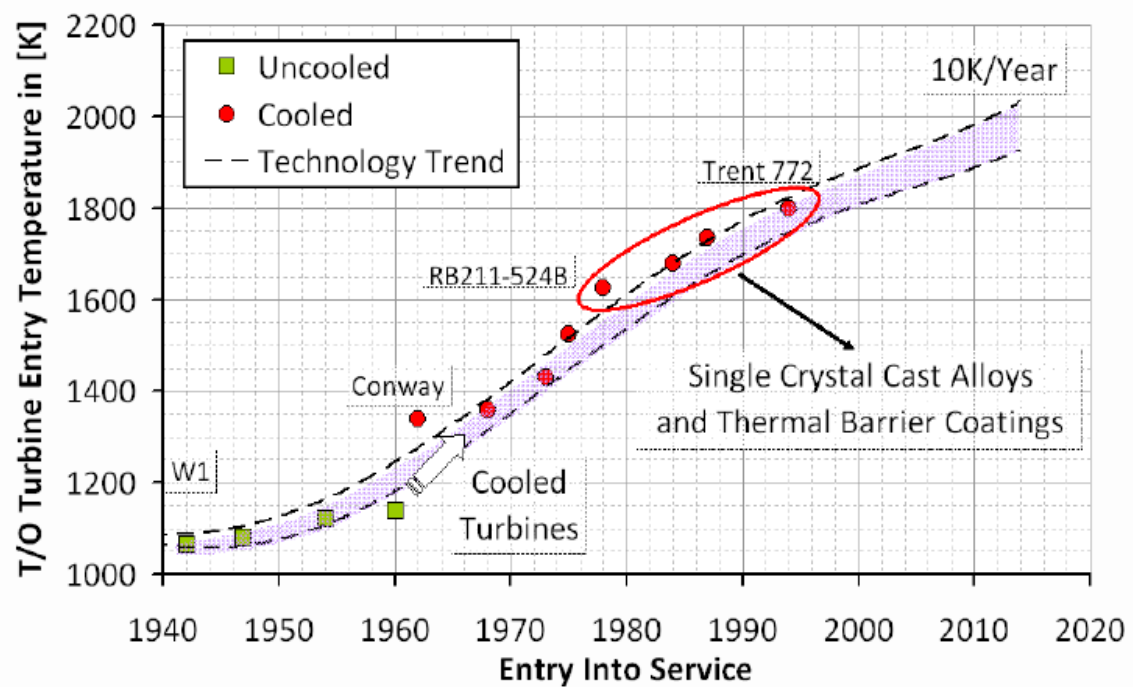


Figure 2-1: Increase TET with advances in material cooling technologies [4]

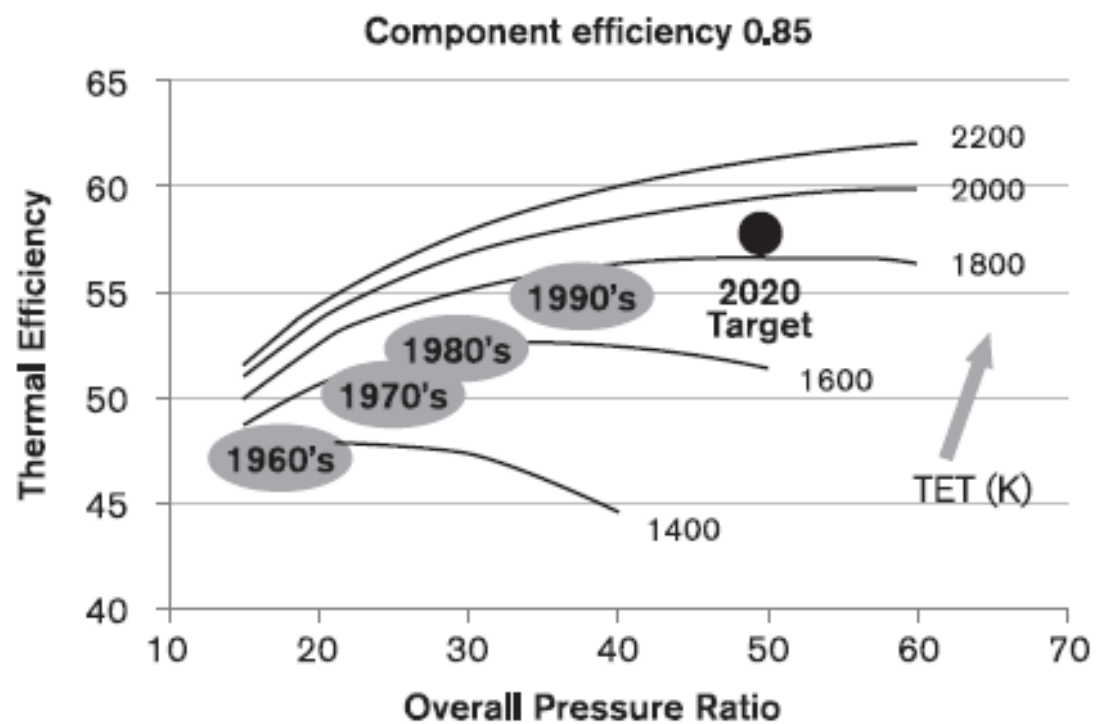


Figure 2-2: Impact of OPR and TET Increase on Thermal Efficiency [5]

According to ICAO, a global air traffic growth of around 3 – 5% annually is predicted for the next 20 years. This level of growth experienced in civil aviation, imposes a consequent environmental and societal impact in terms of increased emission of pollutants (i.e., CO₂, NO_x, CO and UHC) and aircraft noise. On the other hand, airline operators need steady reduction in operating cost in order to sustain profitability, within a competitive business environment of fuel price regime uncertainty and a hand full of regulatory and emission taxation policies. This demand for reduced environmental impact and lower direct operating costs, serve as strong driver for engine designer to investigate new engine architectures and improvements to reflect new balance between engine fuel burn, weight, maintenance costs and manufacturing requirements. Figure 2-3 shows a delicate balance between the requirements of all the stakeholders in the aircraft industry.

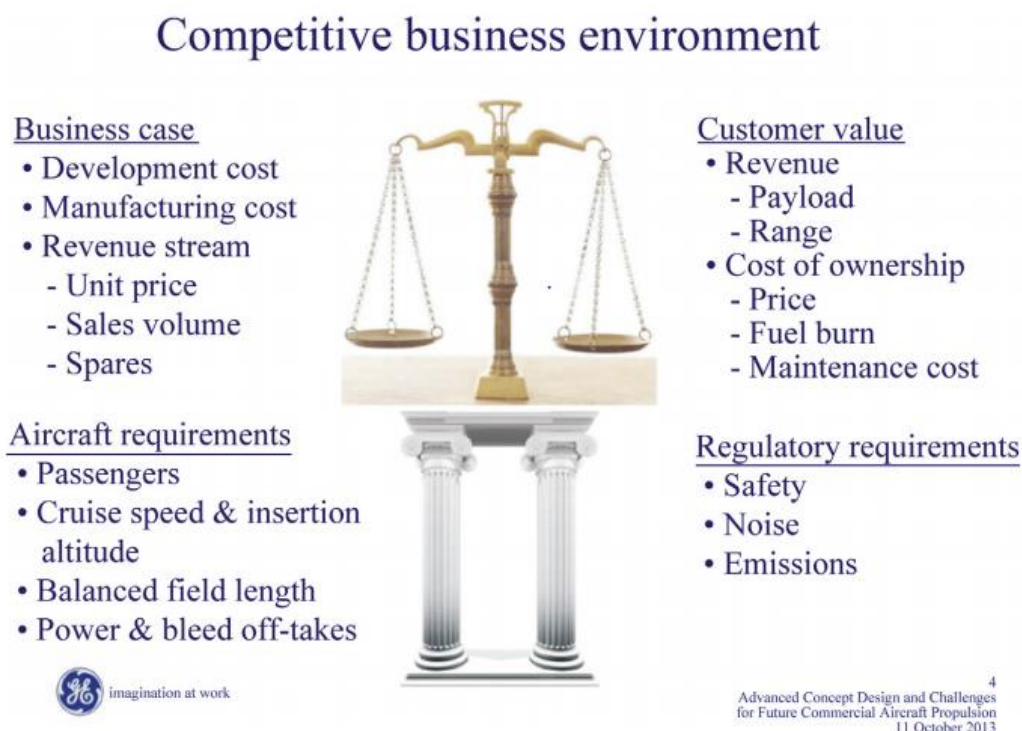


Figure 2-3: Aircraft Industry Stakeholders Requirements [6]

2.1.1 Aero Engine Fuel Consumption Improvement

Improvement in engine fuel consumption has been one of the major drivers of gas turbine engine development over the years. Historically, barely above 50% of engine fuel efficiency improvement have been achieved with approximately 1% per year over the last 50 years [6]. This rise in fuel burn efficiency is partly related to achieving higher engine operating temperatures (TET) and overall pressure ratios (OPR), component efficiencies, material advancements and better cooling technologies. The other reason is due to higher engine bypass ratio. The term specific fuel consumption (SFC) represents the ratio of fuel flow to the net thrust of the engine. It is a function of the engine propulsive and thermal efficiencies.

$$SFC = \frac{V_0}{FHV\eta_{overall}} = \frac{V_0}{FHV\eta_{th}\eta_{prop}} \quad \text{Equation 2-1}$$

Where V_0 is the flight speed, FHV is fuel calorific value, η_{th} is the thermal efficiency, and η_{prop} is the propulsive efficiency of the engine.

2.1.1.1 Engine Thermal Efficiency

Thermal efficiency expresses the efficiency at which an engine converts fuel energy to useful work. It is a function of the engine overall pressure ratio (OPR), peak operating temperature (TET) and component efficiencies. For a given engine specific thrust, any increase in thermal efficiency is due to the increased in OPR and TET, smaller engine core design and higher bypass ratio, which results in better engine fuel burn capability. However, this benefit is constrained by the higher TET limitation imposed by maximum permissible HP turbine blade metal temperatures at take-off and top of climb, HP compressor delivery temperature at take-off, component efficiencies and thermodynamic cycle losses due to cooling flows and duct pressure losses.

2.1.1.2 Engine Propulsive Efficiency

Engine propulsive efficiency is the ratio of the propulsive thrust power produced by the engine to the rate of kinetic energy added to the air [7], defined by Equation 2-2. The detailed expansion can be found in [2].

$$\eta_{prop} = \frac{2}{1 + \frac{V_j}{V_0}} \quad \text{Equation 2-2}$$

Where V_j is the nozzle jet velocity and V_0 the free stream velocity.

Propulsive efficiency of an engine is influenced by the capacity of the Low Pressure Fan to accelerate large amount of air slowly in order to minimize shear layer losses and consequently noise emission reduction [8]. This is achieved by increasing the engine bypass ratio (BPR) with larger diameter fans to increase the overall air flow and move it slowly ('reduce the fan pressure ratio [FPR]') though the engine, therefore reducing the engine specific thrust (SFN = Net thrust divided by the overall air mass flow).

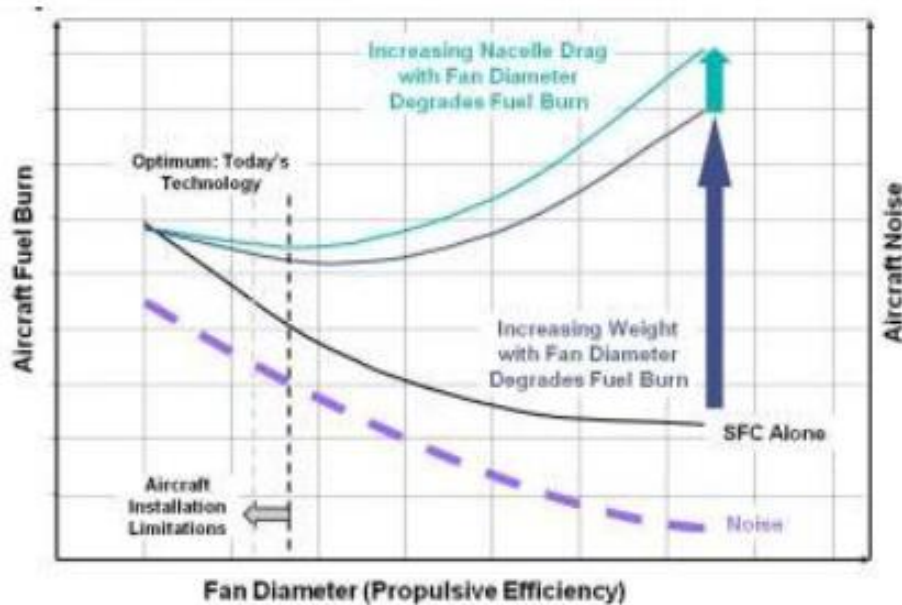


Figure 2-4: Impact of fan diameter on aircraft fuel burn and noise emission [8]

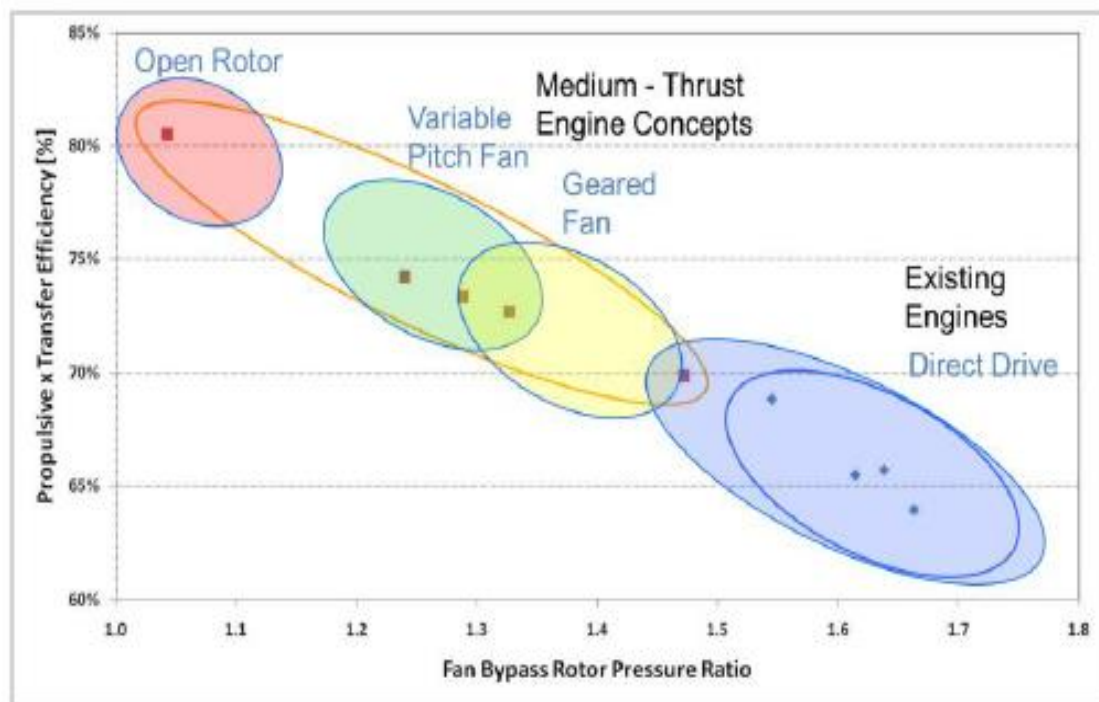


Figure 2-5: Impact of fan Pressure Ratio (FPR) on Propulsive Efficiency [8]

As engine BPR and overall mass flow increases (i.e., low specific thrust engine), the engine fuel burn decreases due to increased propulsive efficiency, however, the penalties of increased weight and nacelle drag may offset the potential gains of fuel burn. Figure 2-4 shows the impact of an increased diameter fan on the fuel burn, noise emission and nacelle drag.

Figure 2-5 shows the effect of fan pressure ratio (FPR) on propulsive efficiency and different engine cycles. The different engine architectures illustrate the improvement in propulsive efficiency achieved through fan pressure ratio (FPR) reduction. The existing direct-drive high BPR large civil engines operate with FPR of around 1.45 -1.8, which can be reduced further to around 1.2-1.45 with higher BPR geared concept engines with either fixed or variable pitch fan. The geared architecture for the higher BPR engine is needed to maintained fan tip speed within or near sub-sonic conditions delivery noise and efficiency improvements. However, the gains derived by this systems are somewhat balanced by the weight, losses and complexities associated with the heavy gearbox. The epicyclic gear system is used for the speed reduction from the LP turbine blade to the fan blade. The speed of the LP shaft attached to the gear system is reduced before

driving the fan blade. The gearbox removes the speed constraint on the LP compressor and LP turbine, therefore influencing the design with less stages LP compressor and LP turbine used in the geared engine architecture [9]. The open rotor engine architecture offers the lowest FPR of 1.04, which is a double fan propeller concept with no fan casing or nacelle.

2.2 Aero Engine Upgrades

Aircraft engines are particularly sensitive to advances in technology and economic conditions. During the engine design phase, it is important for the OEM to consider potential engine growth in order to meet forecasted future changes in customer and market requirements. During an engine's long productive life, several maintenance checks and shop-visits will be undergone. Some modifications, retrofits and/or upgrades would be needed to improve the performance and life of the engine. Upgrades are modifications that may alter the entire characteristics of the engine. Their development is aimed at making available the potential benefits of new technologies to operators of previous engine version of the same series. These benefits may vary from improved aircraft resale value, reduction in operating cost, decrease in fuel consumption, decrease in noise and emissions, increased reliability and durability to increased performance (i.e., thrust air speed and rate of climb). The extent of modification, upgrade or retrofit option a customer purchases is dependent on the condition of the engine/aircraft combination and the cost-benefit analysis of that investment.

2.2.1 Service Bulletin (SB)

Service bulletin (SB) is a notice to an aircraft operator from the manufacturer informing of a product change or improvement. An SB alert may also be issued when an unsafe condition develops that the OEM believes to be safety related rather than just a product improvement. This kind of SB may lead to the issuances of an airworthiness directive (AD) by the regulating authority (i.e., FAA or in European aviation the EASA) to mandate compliance with the referenced SB alert. Generally, compliance to SB is regarded as not automatically mandatory for the aircraft operator even if the manufacturers categorized them as

mandatory, except when they are accompanied with an airworthiness directive (AD).

However, compliance to service bulletins (SB) whether for performance improvement, detailed inspection or component replacement purposes requires high financial costs implications. The decision of an aircraft owner to comply with an SB would be based on a cost-benefit analysis of the potential benefits obtainable to the cost of compliance with the service bulletin.

2.2.2 Airworthiness Directive (AD)

Unsafe conditions originally not considered during the product design phase may be discovered during aircraft operations or as a result of an accident or incident investigation. Therefore, manufacturers are constantly issuing mandatory service bulletins (SB) through airworthiness directives (AD) to indicate modifications for safety [10]. An airworthiness directive (AD) is a directive issued by the Airworthiness regulatory authority (FAA or EASA) about unsafe product condition (aircraft engine, airframe, etc.) that could develop dangerous outcome if not addressed. Compliance to AD are mandatory and enforced by the regulating authority.

2.2.3 Engine Upgrade Programs

Upgrade kits consist of different individual improvements, which may be applied on a different engine module or part. This gives the operator the choice of choosing specific improvement without constraint to purchasing the entire upgrade kit. Over the years, several engine performance enhancement packages have been developed by different Original equipment manufacturer (OEM) in order to enable their customers maximize profitability in a highly competitive market. Some of the common upgrade programmes developed by the three major aero-engine manufactures are as follows:

2.2.3.1 CFM International Upgrade Programs

The first CFM56 engine ran in 1974, over 40 years later CFM56 have established itself as one of the most successful aero turbofan engine in the world, with more than 27,200 engine unite in operations clocking more than 630 million flight hours

(i.e., every 2.5 seconds, every single day, an aircraft with CFM56 engine takes off somewhere in the world) [11]. CFM56-2 is the earliest of the CFM family of engines and the first high bypass engine in the 10-tonne class. It first flew on a re-engine Boeing 707 aircraft in 1982 and was also chosen to re-engine KC-135 tankers for the USAF. Since then, the other CFM56 engines developed were CFM56-3, CFM56-5A and CFM56-5C referred to as the legacy engines. CFM56-5B and CFM56-7 are the current engines and lately the CFM LEAP series entered into service in 2016 and 2017 [11].

Today, CFM offers upgrade kits for the CFM56-3 known as '**the CFM56-3 advanced upgrade kits**'. It is a life extension and reduce maintenance package, which introduced 3-D aerodynamic design for the high-pressure compressor (HPC), fan derived from CF6-80 engine and the re-design of booster to match the fan. The upgrade provides a 1.6% improvement in SFC, up to 25 °C of additional EGT margin, 40% NO_x margin compared to ICAO limits and an expected first run life of 16,000 engine flight hours. The high performance CFM56-5B programme was initiated in 1989 and made its flight in 1992. The engine was the first to introduce advanced double annular combustor (DAC) technology in 1995, which reduced NO_x emission by as much as 45% [12]. The DAC technology reduces NO_x, CO and UHC emissions by adopting radially staged fuel strategy to produce a lean combustion stoichiometry and a constant temperature by switching fuel injection in multiple combustion zones based on the power settings. At low power settings, the pilot combustion zone (i.e. outer circumferential annulus) is fuelled and operates to raise the equivalent ratio (~ 0.8) in order to increase the combustion efficiency and reduce CO and UHC [13][14]. At high power settings, both the pilot zone and the main combustion zone (i.e. the inner annulus) are fuelled and operated to maintain equivalent ratios of around 0.6 for both zones, with the objective of achieving lean combustion for NO_x and smoke reduction. At mid-power settings, the full pilot nozzle and part of the main combustion nozzle are fuelled and operated to increase the transition efficiency. The single annular combustor (SAC) technology was previously used especially in the CFM56-5B engines.

History of innovation & improvement



Figure 2-6: CFM56 Engine Evolution

The Core Improvement Programme – **TOW (time-on-wing) upgrade kits** were offered in 2002. This upgrade consist of re-blading the HP compressor using the 3-D technology of the -5B/P and -7, re-blading of the HP turbine rotor with blades of different materials, introduction of new nozzle and shroud materials, and new coatings and improved cooling technology. The upgrade offered a 1% reduction in SFC and 15% reduction of EGT margin [12]. In 2007, the Tech Insertion technology was introduced which became the production configuration for all CFM56-5B engines, offering operators significant improvement in SFC, emissions, and maintenance costs.

Tech Insertion upgrade package for CFM56-5A/-5B incorporates new fan with wide-chord swept blades without snubbers, improved HP turbine rotor blade, redistributed cooling-air holes with extended blade life, TAPS (Twin-annular pre-swirl) combustor chamber, counter-rotating HP/LP turbine, elimination of losses due to leakage with brush seals, and core nozzle replacement with chevron design which has a zig-zag trailing edge. More recently in 2011, the CFM56-5B/3

PIP (performance improvement package) configuration was released, and becoming a new production standards providing 0.5% improvement in fuel efficiency and 1% reduction in maintenance cost.

There exist copious information in literature concerning announcements of these engine upgrade kits purchase order by airlines, their costs and potential benefits claimed by the OEMs [15][16][17].

2.2.3.2 Rolls-Royce Upgrade Programs

Rolls Royce has over the years developed a track record on systematic product enhancement and upgrade offerings for improved efficiency, performance output, reliability and emission reduction in aero engines. The OEM strategy of feeding back advance technology from new variants to previous engines is benefiting in-service engine, as some of these upgrade improvements can be retrofitted during shop visits and overhauls [18]. Trent 700, which is the first engine in the Trent family, has undergone a series of upgrades and modification inspired by newer technology for improved performance. In 2009 the Trent 700EP (enhancement package) was introduced to the market incorporating improved fan-tip clearance, improved blade-tip clearance for HP and IP compressors, HP and IP turbines, turbine case cooling, elliptical leading edge airfoil in the compressor section, IP Turbine NGV re-profile end wall and re-blading LP turbine according to Trent 1000 style. Trent 700EP is the current build standard delivering 1.3% improvement in fuel burn. Some of the improvements are offered as EP retrofit kit giving 1.1% improvement in fuel burn [19].

These retrofit kits include elliptical leading edge IPC/HPC blades and optimized turbine-case cooling. Further upgrade, the Trent 700EP2 introduced in 2015 to achieved additional 1% improvement in fuel burn by incorporating new stator blade in the HPC and IPC, improved nozzle guide vanes (NGV) and better IPT aero-standard flutter bridge [6].

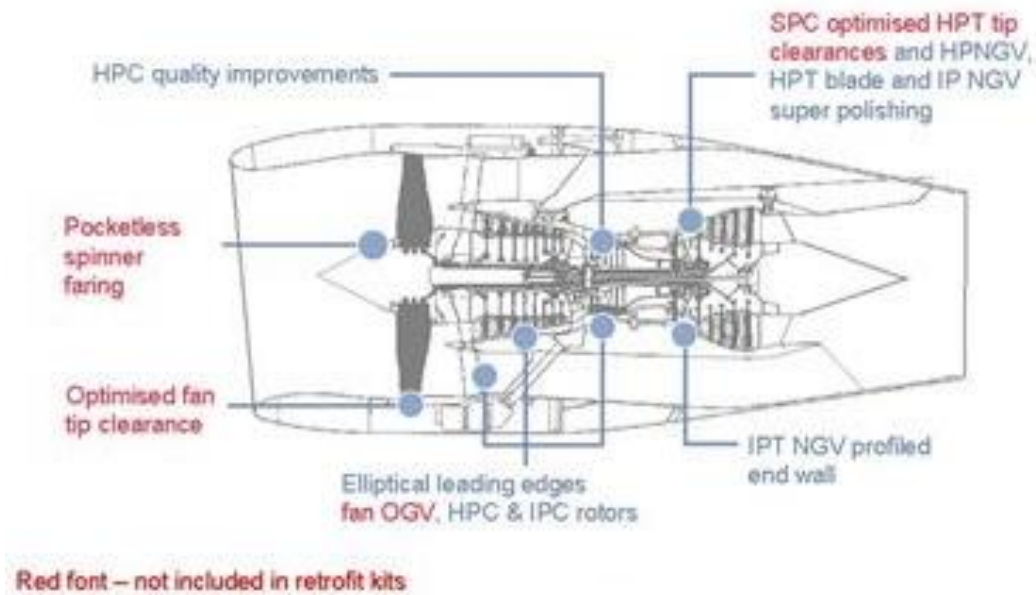


Figure 2-7: Rolls-Royce Trent 700 Upgrade Retrofit Kits

The elliptical leading edge compressor blade with improved efficiency developed for Trent 1000 is now available to Trent 800 and 500 operators as retrofit kit, providing 0.5% and 0.7% improvement in fuel burn respectively which is estimated to provide a corresponding cost savings of \$200,000 per aircraft annually [20].

2.3 High Pressure Turbine

The turbine system is a complex assembly of blades, nozzle guide vanes, disc, turbine shaft, casings and structures (see Figure 2-8). The turbine extracts thermal energy from combustor hot gas stream by expanding the gases to lower pressure and temperatures, and the power is utilized for driving fan propeller, compressor or electric generator. The turbine is continuously exposed to very harsh operating environment of elevated temperature gases and high stress loading. The high shaft rotating speed imposed considerable stresses on the component material and presents difficulty in sealing and cooling of the rotating and stationary component interface [21]. The Increase in turbine means blade speed influences maximum stage efficiency achievable. For a given output, reduction in losses (i.e., reduced gas velocities and deflections) and increase in

turbine disk stresses are proportional to the square of higher mean blade speeds [22].

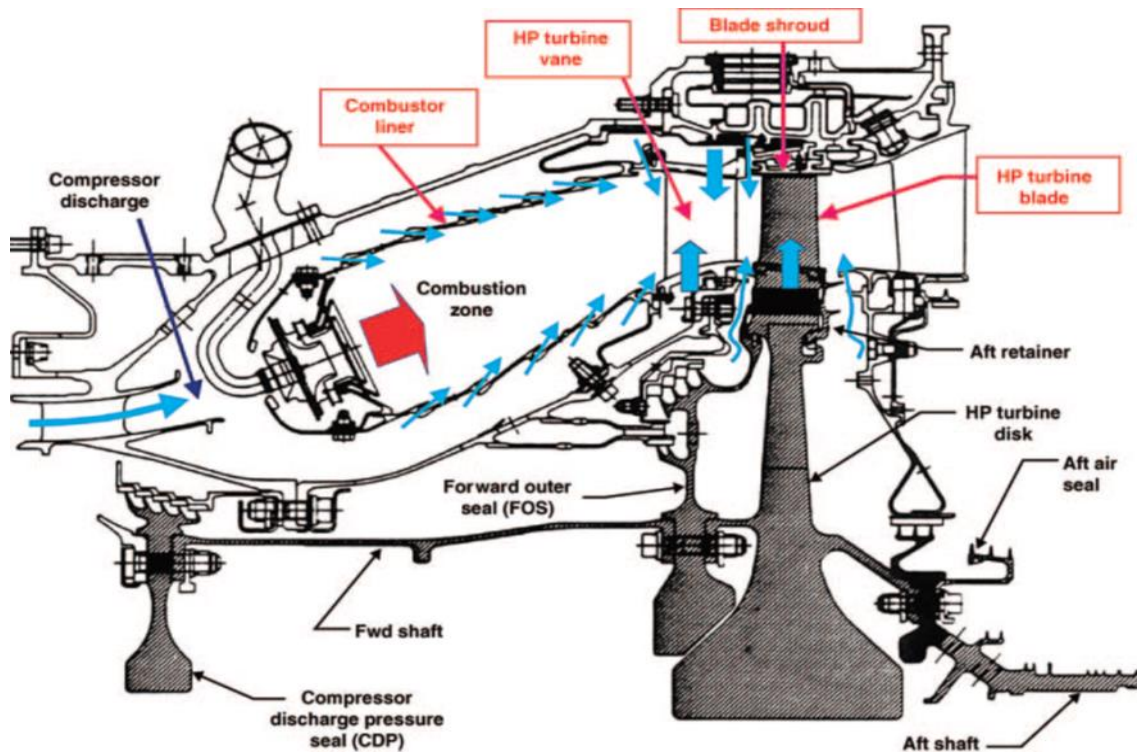


Figure 2-8: Schematic of CFM56 commercial engine combustor and HPT [23]

However, to achieve further increase in turbine efficiency and engine performance improvement, the development of new advanced materials with increase temperature capabilities, high strength and increased creep and corrosion resistances, improved active cooling system for not only rotor blades, but also stator vanes and rotor disk and the use of protective coating (thermal barrier coating) is required. Other methods include minimization of leakages and cooling airflows, optimization of HP turbine blade tip-clearance control and tip-sealing concept throughout the flight cycle, and fully featured 3D design for HP, IP, and LP turbine components.

2.3.1 Key Drivers of Turbine Technology

The continuous development of turbine technology is motivated by the drive to increase cycle peak temperature (TET) for cycle efficiency and fuel burn

improvement within the requirement of maintaining or reducing cooling air consumption [8]. This means minimising parasitic air consumption, which does not contribute to cycle performance such as cooling and leakage flows. Therefore, presenting a turbine design challenge, which can be partly handled by optimising the High-Pressure Turbine (HPT) blade tip sealing and the tip clearance control throughout the flight cycle.

2.3.2 Turbine Blade Cooling

The steady increase in allowable turbine entry temperature (TET) trend for increasing thermal efficiency and fuel burn improvement can largely be attributed to the advances in blade cooling technologies and materials. Modern gas turbine engines operate at peak temperatures in excess of the component material melting temperature limits. This is possible through the implementation of an effective cooling scheme on the hot gas path (HGP) components. The development of cooling technologies has been driven on the basis of obtaining the highest overall cooling effectiveness with the lowest possible penalty (cooling air flow consumption) on the engine cycle performance. The use of compressor air of 20 ~ 30% for cooling HPT presents severe penalty on cycle efficiency unless the engine peak temperature is high enough with sufficient gains to outweigh the losses [23]. The improved performance and high cycle temperature in modern large bypass ratio engines are enabled by material improvements, advance cooling techniques and modern thermal barrier coatings (TBC). These technologies have enabled increased engine life and reliability even within the harshest operating conditions.

There are three main cooling techniques commonly utilize for the cooling of modern gas turbine blades; convection cooling, film cooling and Inpingment cooling [24][25]. They have different airflow consumption characteristics and cooling effectiveness. The coolant fluid used for cooling is the compressor delivery air extracted from the HP compressor, which is then introduced through the internal air cooling holes and channels of the nozzle and first stage rotor blade to reduce blade metal temperature, which in turn improves creep and operational life of the engine [24]. Convection cooling is the simplest cooling system in which

the cooling air extracts heat from the internal walls of the blade geometry as it circulates through its complicated passages and channels. Modern gas turbine however, employs augmented convection cooling system with multiple internal ribbed channels and multiple passes. These multiple passes are designed to increase heat transfer surface area by allowing cooling air to flow through the blade length more than once while the ribbed channel walls are used for enhancing heat transfer through increase in flow turbulence in stagnation points. However, the cooling requirements of high TET engines cannot be met by the maximum cooling effectiveness achievable through convection cooling system due to the inherent limitation of heat transfer from blade geometry through internal circulation of cooling air. Thus, convection cooling is improved by film cooling. In this system, the cooling air used for convection cooling is passed through multiple small holes inclined at an angle to the surface, thus forming a layer of film air insulating the metal surface from the hot gas streams. These changes the boundary layer flow on the blade surface, thus increasing both shear and heat transfers. Over the years researchers have studied many aspects of film cooling with the aim of determining the effect of film hole internal fluid dynamics, interactions with hot gas stream, hole shape, size, orientation, spacing, hole length-to-diameter, blowing strength, density ratio and momentum flux ratio on the performance of film cooling effectiveness.

Impingement cooling is used in more confined regions of the blade geometry such as the leading edge, trailing edge, spanwise lines or some primary locations with high external heat load like local stagnation points [23]. Figure 2-9 shows a typical turbine blade cooling arrangement with three distinct internal cooling passages. A combination of impingement and film cooling are employed on the blade leading edge region, the impingement jet air are delivered to the leading edge through the crossover holes and then the leading edge discharges the air through the showerhead holes to film cooling as depicted in Figure 2-9(b). The blade mid-chord region is cooled by serpentine passages, which consist of radially aligned tabulated channels that are connected by 180° turns. The trailing edge region consists of a pin fin array which supplies a distribution of small axial flow channels

ending in bleed slot [23]. In addition, the blade tip section is designed with dust holes and dedicated coolant holes passages exiting into a tip cavity.

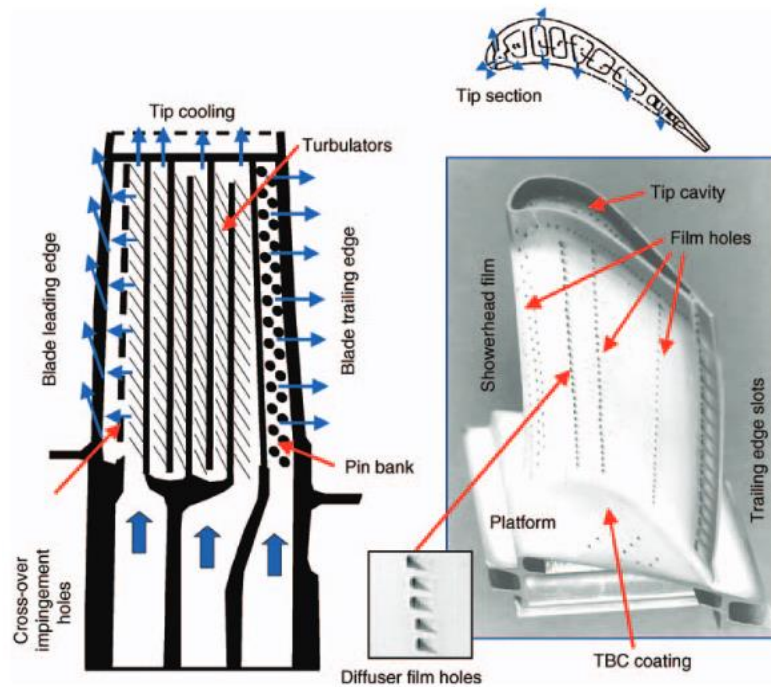


Figure 2-9: Typical turbine blade cooling arrangement: (a) internal flow circuits, and (b) actual blade [23]

Other novel cooling schemes being investigated and developed are transpiration cooling and dual-wall cooling. Transpiration cooling systems produce very high cooling effectiveness by ejecting cooling air through porous wall. It forms a well-defined uniform layer of air insulating the blade metal surface from the hot gas stream. However, the inevitable challenges of blockage of the porous wall might lead to serious reduction of cooling effectiveness and even blade damage [26]. Most demonstration of transpiration cooling are conducted on blades fabricated from woven wire cloth material. Dual-wall cooling is a highly effective semi-transpiration cooling method in which the outer wall and inner wall are cast to form the wall of the blade. Cooling air is forced into the hollow layer between the outer and inner wall through tiny passages. Rolls-Royce has produced blades with dual-wall cooling in CMSX-4 single crystal [26]. Many similar cooling methods such as Transply cooling, Castcool, Lamilloy and Supercool have been developed and demonstrated in Europe and USA.

2.3.3 Thermal Barrier Coatings

The improvement in engine fuel consumption and thrust experienced in modern gas turbine engines due to higher operating overall pressure ratio (OPR) and turbine entry temperature (TET) have led to increased thermal efficiency which in turn led to the reduction in engine specific fuel consumption (SFC). This high OPR and TET achieved have led to CO₂ reduction but simultaneously promoted NO_x formation, which is control with the use of lean burn combustor technology. However, these gains are mainly possible through technological improvements in engine cooling and material innovation. Engine hot section components operates in very demanding conditions, with operating peak temperatures far exceeding the melting point or permissible limit of the superalloy material. Operating under this condition is only achievable through the combined effect of TBCs, convection cooling and film cooling to produce a very efficient cooling experience capable of decreasing metal surface temperature by more than 165⁰C [27].

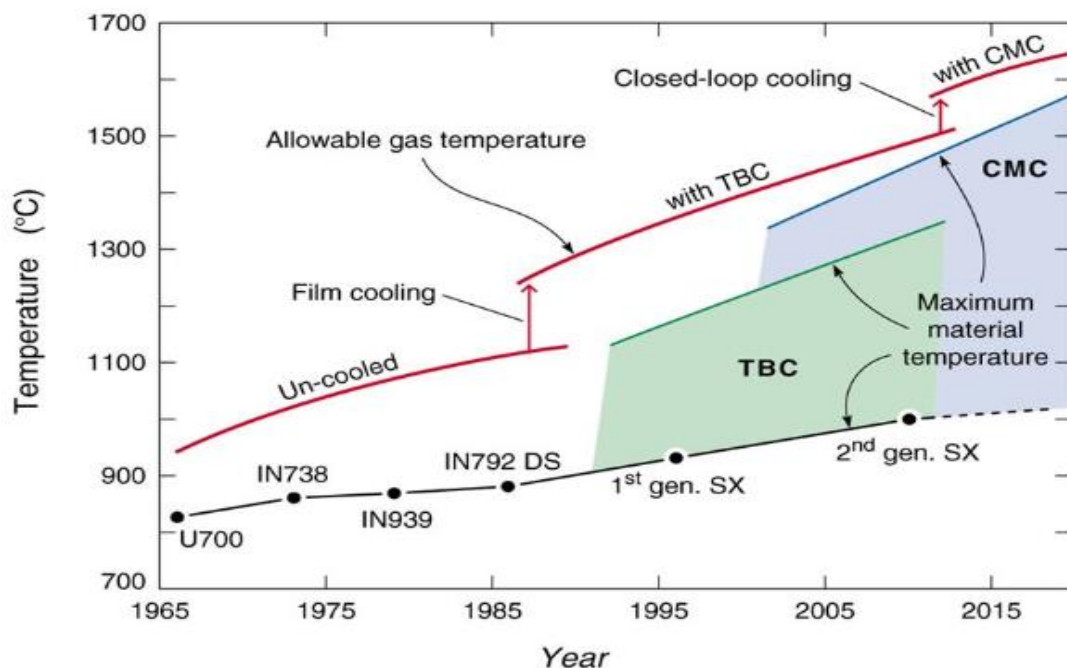


Figure 2-10: Increase in TET and cooling technology advancement [28]

The increase in engine TET over the years can be attributed to the development of efficient cooling methods and advances in material technologies such as TBC and the ceramic matrix composite (CMC) structures, as shown in Figure 2-10.

The figure shows that the increase in TET with convection and film cooling have reaches its peak with further increase in TET possible through the design of new TBCs with ceramic materials and CMCs.

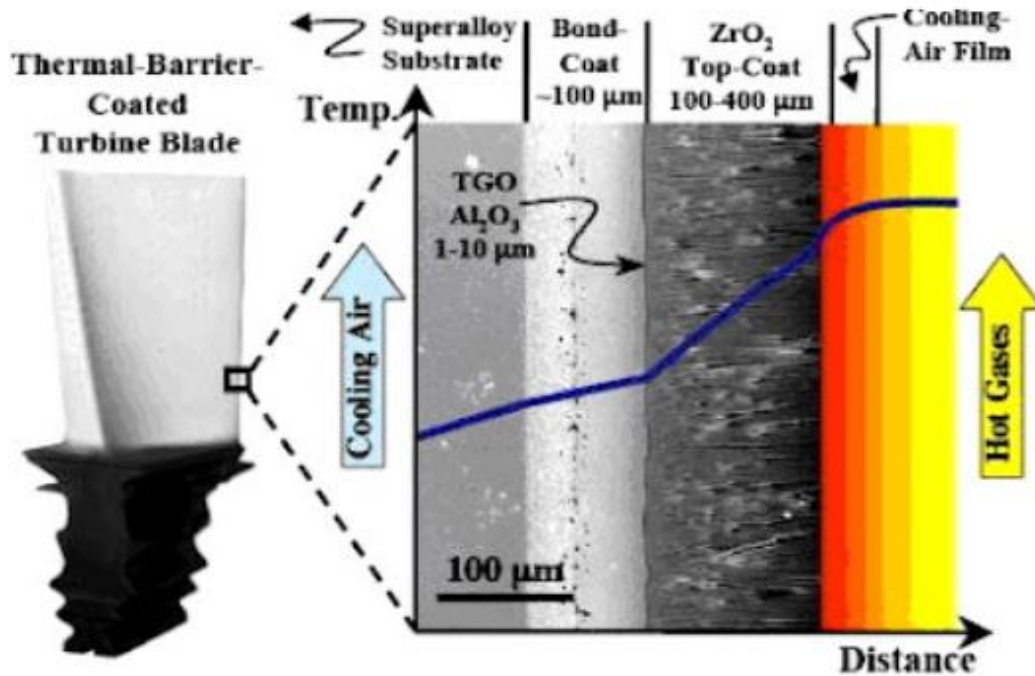


Figure 2-11: Thermal barrier coating structure [29]

TBCs are made of low-thermal conductivity ceramics used as an insulation layer for shielding the turbine blade metal surface from the hot gases streams in the gas path of the engine. Hence, TBC materials are designed to withstand extreme conditions of peak temperatures, cyclic thermal loading and stresses [29]. TBC consist of three layers, the topcoat, bond-coat and TGO layers. Topcoats are the low-thermal conductivity ceramic materials, which directly shield the metallic substrate from the hot gas stream. Bond-coats are metallic adhesive materials used for adhering the topcoat to the metal substrate and serve as an oxidation resistance barrier for the TBC. During operation, the thermally grown oxidation layer is formed as a result of thermal oxidation of the bond-coat at the interface between bond-coat and topcoat. Figure 2-11 shows the different layers of the TBC structure [29].

Substrate: The substrate is the turbine blade metal made of nickel-based alloys. Within the substrate, a temperature gradient is created as the hot gas streams from the combustor flows externally over it while cooling air flows through the internal cooling holes. During high operating temperatures some constituent elements of the substrate alloy diffuses onto the bond-coat layer and can sometimes be found in the TGO and topcoat layers of the TBC. This diffusion between interfaces has a significant influence on TBC failure.

Bond-Coat: This is an oxidation resistance metallic layer made of NiCrAlY or NiCoCrAlY alloys. There are deposited on the substrate through air plasma spray (APS) or EBPVD methods. During peak operating temperature in the engine, bond-coat temperature could reach an excess of 700 °C causing the oxidation of the bond-coat layer and consequent formation of the TGO between bond-coat and the topcoat.

Thermally Grown Oxide (TGO): These are α -Al₂O₃ oxides formed by bond-coat oxidation during high temperature exposure. Bond-coat ideally are designed to ensure the TGO formation is very slow by lowering oxygen ionic diffusion which tend to retard bond-coat oxidation [29][30]. The growth of TGO is seen to develop compression stresses thus, enhancing failure in TBC.

Ceramic TopCoat: The topcoat layer is typically made of Y₂O₃ – stabilized ZrO₂ (YSZ) and its used as a protective shield for the metallic superalloy from the hot gas streams. YSZ is a material that has very low thermal conductivity (~2.3 W/m/K at 1000°C for a fully dense material) and a high thermal expansion coefficient (~11x10⁻⁶ °C⁻¹). These properties give it the ability to reduce stresses due to thermal expansion mismatch between the topcoat and the substrate. Stresses in the microstructure are also removed by including cracks and increased porosity in the topcoat, increasing its elastic modulus and strain tolerance.

2.3.3.1 Methods of TBC Deposition on Surface Substrate

The two most important method used for TBC topcoat deposition on a surface substrates are given as follows:

- o Air-plasma-spray (APS)

- o Electron beam physical-vapour deposition (EBPVD)

These methods produce different characteristics and microstructures with desirable attributes unique to the method employed and each offering different advantages in terms of properties and performance.

2.3.3.1.1 Air-Plasma-Sprayed (APS) TBC

APS method uses an inert gas that is electrically heated to form a plasma jet; the powdered form of the coating materials is then injected into the plasma flow path, where this mixture of the plasma jet and the molten coating material is then sprayed on the surface of the component or part being coated as shown in Figure 2-12. The resultant spray deposited materials are comprised of an assembly of “splats” grain morphology (i.e. 1-5 μ m thick and 200-400 μ m diameter) of rapidly solidifying material to form a brick-wall structure [31]. The solidification process usually results in a chaotic assembly of deposited microstructure with splat-interface and unfilled regions, thus resulting in increase porosity (i.e. of the range 15 to 25 vol % to give low elastic modulus) and low thermal conductivity.

The undulating nature APS TBC at the interface between the substrate and the top-coat, increases its interlock adhesion properties resulting in the out-of-plane stresses responsible for failure of TBC in service [30]. The orientation of the cracks and pores normal to the direction of heat flux help in reducing thermal conductivity of the top-coat of a fully dense material from 2.3 W/m/K to around 0.8-1.7 W/m/K [29]. Because of the defects in the microstructure of APS TBCs, which are manifested in the roughness, and parallel orientation of the interface, they tend to have a much lower thermal conductivity cycle life than EBPVD TBCs. Hence, the reason why APS TBCs are used for less demanding applications such as combustors, after burner, fuel vaporizers and flame handlers in aircraft engines.

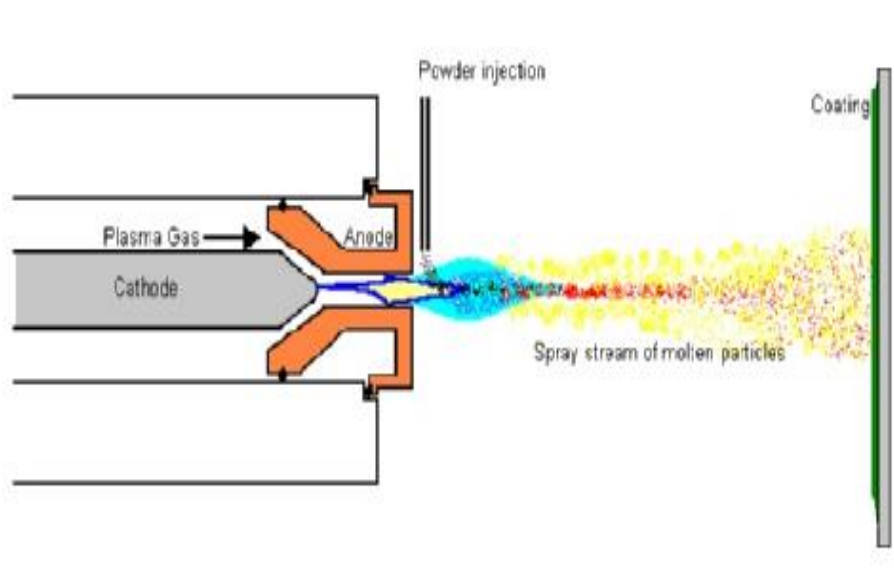


Figure 2-12: Air Plasma Spray [32]

2.3.3.1.2 Electron Beam Physical-Vapour Deposition (EBPVD) TBC

EBPVD method makes use of a beam of highly energetic electrons to vaporise an ingot of coating material, which is then precipitates onto the substrate surface within a vacuum chamber. The ceramic material YSZ EBPVD deposition requires that the substrates be preheated to around 1000°C and positioned in a surrounding vapour cloud, which is then deposited onto the substrates at a deposition rate of $\mu\text{m}/\text{minute}$. During this process a high level strain tolerance EBPVD TBC columnar microstructure is form, with high erosion resistance, smooth surface finishing offering potential aerodynamic advantage.

A typical~ 125 μm thick of EBPVD top-coat materials have the following microstructure [29];

- Presence of thin regions of polycrystalline equiaxed grains (usually 0.5 to 1 μm) at and near the interface of metal and ceramic.

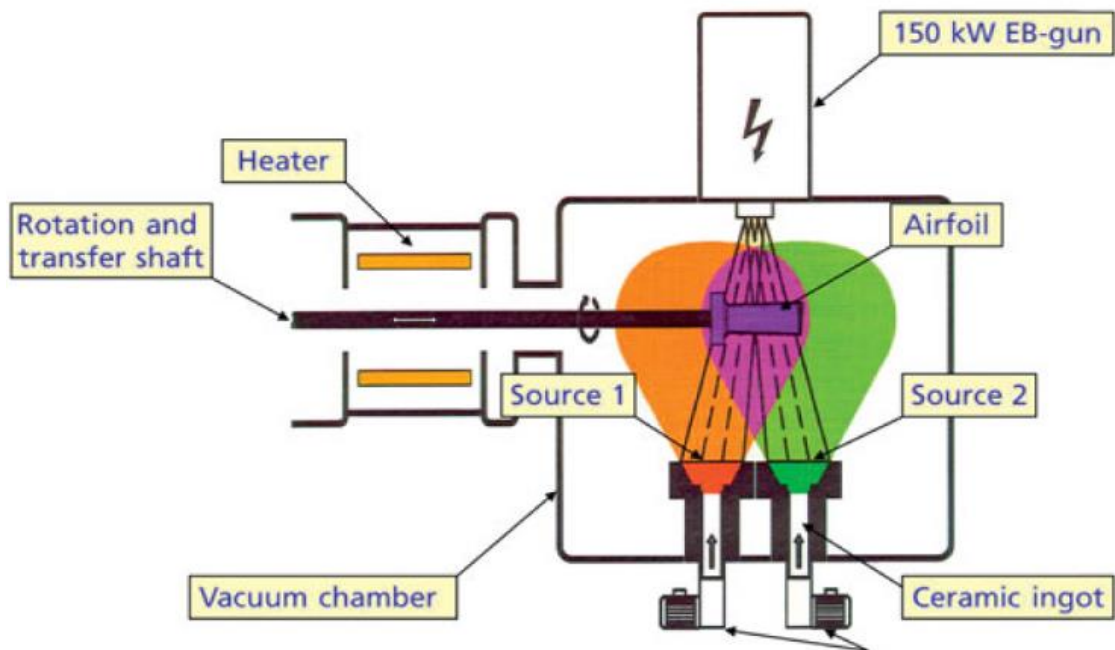


Figure 2-13: Electron-beam physical vapour deposition (EBPVD) process [31]

- Columnar YSZ grains of diameter from 2 to 10 μm growing out of the equiaxed-grain region to the top-coat surface
- Nanometre- scale pores present within the columnar grains.
- Channels that separate the columnar grains, perpendicular to the metal and ceramic interface

The disconnected columns exert “strain tolerance” to the TBC due to their increased mobility at high temperature and accommodating thermal-expansion mismatch stresses. The porosity and cracks helps to reduce the thermal conductivity from ~1.5 to 2.0 W/m/K, but less than that for APS TBCs because of the orientation of channels parallel to the direction of heat flow.

2.3.3.2 TBC Failure Mechanisms

TBCs are design to shield the substrate alloy from high temperature and protect it from oxidation and corrosion. Exposure of TBC to this extreme environment, operational variability and a combination of multiple phenomena leads to failure of TBC. This failure occurs in several ways including spallation, sintering, thermal fatigue and oxidation and corrosion environment [33].

2.3.3.2.1 Spallation

Spallation failure in TBC occurs due to the growth of thermally grown oxide (TGO) within the topcoat and bond-coat layer of TBC during high engine operating temperatures. The constrained volume the TBC tends to restrict the TGO growth thus, resulting in a compressive growth stress during operating high temperatures. However, during cooling process after operation a thermal-expansion mismatch is experienced between the TGO and the bond coat, again inducing high thermal compressive residual stresses in TGO that reached its peak at ambient temperature [29]. The alumina oxide (α -Al₂O₃) TGO formation and growth results in Aluminium element (Al) depletion, which in turn facilitates the formation of a phase change containing spinel oxides which comprises the TBC structural integrity hence, accelerating oxidation process. During sintering progressive roughening of the top-coat/TGO/bond-coat interface, occur as a result of cyclic creep in the bond-coat.

2.3.3.2.2 Sintering

Sintering failure occurs due to changes in TBC structural morphology at high temperature, which leads to reduction in porosity with TGO and reduction of material density in the TBC. This reduction in porosity increases the thermal conductivity of the TBC and further increase in density, which induces increased stresses due to the volumetric constraints of the substrate alloy, which then leads to TBC cracking and eventual failure.

2.4 Material Advancements

Over the past decades, material advancements have played a major role in the development of high performance engines through the achievement of high turbine inlet gas temperature and increased component efficiencies. These advancements has been towards the development of improved materials with increased mechanical strength and resistance to oxidation and corrosion capabilities at elevated temperatures, and the innovation of advanced material processing techniques. Nickel-based superalloys are traditionally used for high temperature components parts of gas turbine engine. The two high temperature components that have driven the development of Nickel-based superalloys over the years are the HP turbine blades and disc. HP turbine blades are exposed to extreme environmental conditions of elevated gas streams temperatures and high speed rotatory motion. This device is forced to withstand these high temperatures in excess of the material melting point and very high stresses due to centrifugal loading, thus subjected to potential failure modes like creep rupture, thermal-fatigue, and oxidation and corrosion attack at the leading edge and tip of the blade [34]. The turbine disc, which receives the transmitted loading from the blade through the dovetail, is subject to damage due to fretting wear, high-stress low-cycle fatigue and low-stress vibration. The only way these components have the capabilities to operate in these harsh conditions is through the integration of improvements in material properties, advance blade cooling designs and the development of protective coatings to control environmental attack.

2.4.1 Manufacturing Techniques

Investment casting:

Turbine blades are usually produced by investment casting process where the molten alloys in the mold is solidified without interventions to control the pattern of freezing, thus producing blades with polycrystalline dendritic microstructure containing equiaxed grains such as IN-713 Cast Alloy. As Alloy chemistry became better understood, increasing the gamma prime γ' volume fraction produced alloy with higher grain strength like IN100 and Rene100 for turbine

blades [34][4]. Alloy designers strive further to increase γ' volume fraction by increasing the concentrates of titanium, aluminium and refractory elements. Increasing these alloying elements increased grain strengthening but leads to decreased alloy castability and increased brittleness. However, the addition of hafnium in the 1970s increased the ductility of the alloy grain boundary structures resulting in improve alloy castability and transverse rupture ductility. This led to the development of many superalloys with different chemical compositions as shown in Table 2-1

Table 2-1: Chemical composition of some turbine blade and disc superalloys, only major alloying elements have been included [34].

Alloy	Composition (percent by weight)										
	Co	Cr	Al	Ti	Nb	Mo	W	Hf	C	Fe	Ni
<i>Blade superalloys</i>											
Mar-M 200 + Hf*	10.0	9.0	5.0	2.0	1.0		12.5	1.8	0.14		bal
Mar-M 247*	10.0	8.4	5.5	1.0		0.6	10.0	1.4	0.15		bal
Rene' 80 H†	9.5	14.0	3.0	4.8		4.0	4.0	0.75	0.08		bal
Rene' N4†	7.5	9.3	3.7	4.2	0.5	1.5	6.0	0.1			bal
<i>Disk superalloys</i>											
Inconel 718‡		19.0	0.5	0.95	5.1	3.0			0.05	18.5	bal
MERL-76§	18.5	12.5	5.0	4.4	1.4	3.2		0.4	0.04		bal
Rene' 95†	8.0	13.0	3.5	2.5	3.5	3.5	3.5		0.05		bal
Rene' 88 DT†	13.0	16.0	2.1	3.7	0.7	4.0	4.0		0.05		bal

*Martin Marietta Corp. †General Electric Co. ‡International Nickel Co. §Pratt & Whitney.

Directional Solidification (DS):

The limitations of grain boundary crack, propagation and subsequent failure of conventional cast superalloys were addressed by the elimination of the grain boundary through directional solidification (DS) process. The DS column grain blades are produced by solidifying an investment casting from the tip towards the root of the blade by systematically altering the temperature changes. In DS process alloys performance are less dependent grain-boundary structure, thus more grain strengthening elements such as B, Zr and Hf which reduces the alloy melting temperature are removed in order to increase their temperature capabilities. The temperature capabilities of superalloys was further enhanced by adding Rhenium which raises the melting point of nickel and prevent dislocation motion by producing ordered clusters in the grain microstructure. The

temperature capabilities of DS superalloys were increased by 14⁰C compare to the conventional Investment casting alloys.

Single Crystal (SC) Casting:

Superalloys high temperature capabilities were further enhanced by completely eliminating the grain-boundary from the microstructure through Single Crystal Casting process. In SC the directionally solidified blade is grown from a single grain of selected orientation [34]. The increased addition of refractory elements to inhibit γ' growth produced more superalloys with increased temperature capabilities such as Rene N5, PWA 1484 and CSMX-4. More modifications for better performance saw the addition of rare earth elements such yttrium to enhance oxidation resistance characteristics. Second generation single crystals alloys have achieve 30-50⁰C increase in temperature capabilities over the first generation alloys. Further increase in turbine blade operating temperature over the years has been an efficient integration of advances in material technologies, advance blade cooling techniques and highly effective protective coating. The cumulative effect of these technologies has increased blade metal temperatures by about 300⁰C over the last 50 years [21]. Figure 2-14 shows the progress in HP turbine blade system (material, cooling and coating) development over the years.

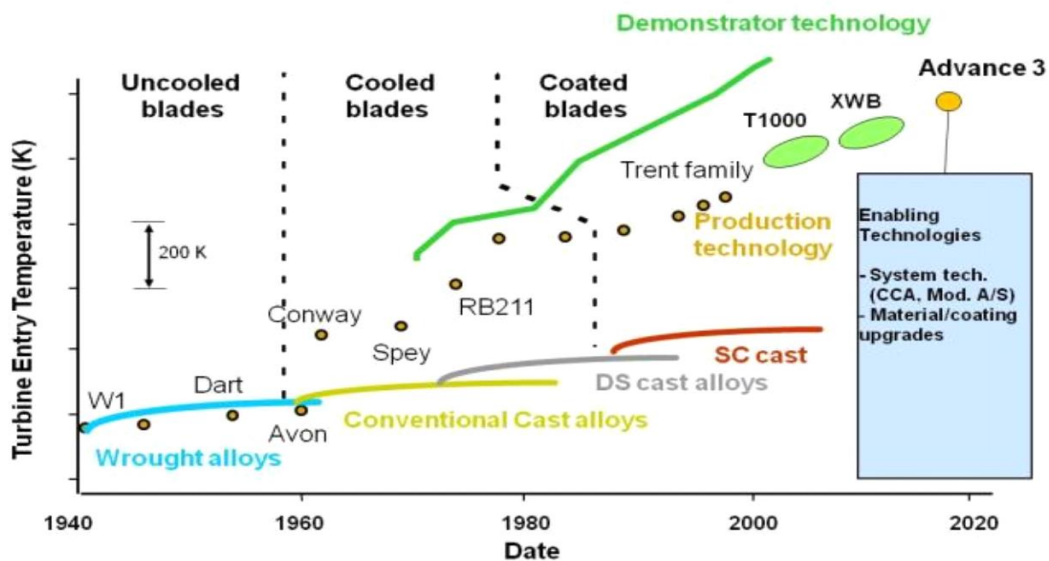


Figure 2-14: Development of HP turbine blade TET capability [21]

Turbine disc manufacture has traditionally been through cast and wrought route. The mechanical integrity criteria of turbine disc to withstand high temperature and high stress loadings led to the development of alloys with very high levels of γ' phase such as Rene'95 and MERL76. However, the high content segregation in the Ingot casting poses potential crack problems during disc forging. The solution is the development of powder processing route. Forging is usually carried out to refine the microstructure of the disc, improve strength, and fatigue life.

Powder Metallurgy Processing:

The powder processing method was design to reduce alloy segregation. In this process, a molten stream of the alloy undergoes atomisation into powder and consequently consolidated by hot isostatic pressing (HIPing) just below the γ' solvus to inhibit grain growth, and then followed by extrusion to dense billets where there are isothermally forged.

2.5 TERA Framework

TERA (Techno-economic, Environmental and Risk Assessment) is a multi-disciplinary optimization framework utilized for modelling gas turbine engines to achieve specific objectives, such fuel burn improvement, emission pollutants or noise level reduction. It has capability for assessing both traditional and novel technologies for “minimum environmental impact and lowest cost of ownership within a variety of emission legislation scenarios, emission taxation policies, fiscal and air traffic management environments” [35].

The approach is an invention of Cranfield University used since the early 1990s to study both traditional and novel engine systems. It takes into account the technical (performance), economics, environmental and risk analysis of the power plants, and have been applied and proven in the field of aviation, industrial, and marine gas turbine studies. Vicente (1994) carried out a study on the ‘effect of bypass ratio on long range subsonic engines’ [36]. The research provided a comparative analysis of two existing aircraft engines – the Rolls-Royce Trent and

General Electric GE90 turbofans – and a hypothetical engine with very high-bypass ratio. The capability of TERA approach to support decision making process was shown by Gayraud (1996) [37]. He performed a study on the ‘Technical and Economic Assessments for Industrial Gas Turbines Selection’, a decision-making support model for industrial gas turbines in the electricity generation market industry. The model analyses the technical and economic performance of powerplant systems to estimate the payback period, discounted cash flow and net present value (NPV) of the investment. TERA was further developed by Whellens M.W (2003) in the study of genetic algorithm based optimization of intercooled recuperated turbofan design [38].

During the VITAL (enVironmenTAlly friendly aero-engine) project between 2005 and 2007 [39], where stakeholders from different companies, manufacturers, organizations and universities were brought together to investigate the impact of new direct-drive, geared and contra-rotating turbofan engine architecture to achieve ACARE (Advisory Council for Aeronautical Research in Europe) goals. The term ‘TERA’ was officially coined when Cranfield University developed the ‘TERA 2020’ architecture for the VITAL project [35] to evaluate the new technologies.

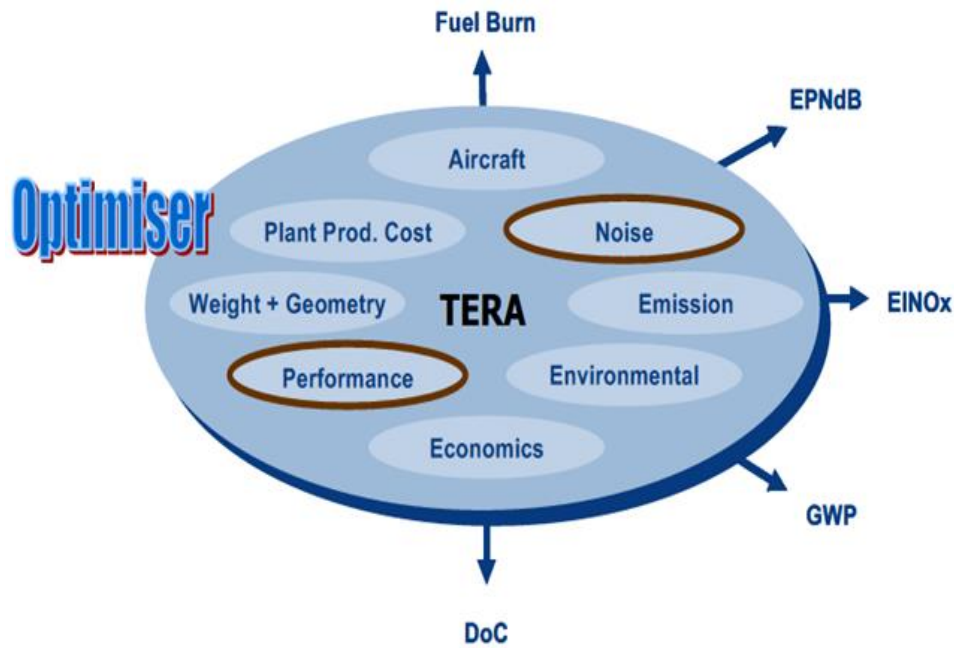


Figure 2-15: TERA Overall Framework [35]

Figure 2-15 shows the typical TERA framework developed for the VITAL project consisting of an integration of the several component modules. Each module is made of an individual model used for performing specific task, such as engine performance model, aircraft performance model engine-life model and economic model. A brief discussion of some of TERA component modules are provided below.

Engine Performance Module: It models and performs gas turbine engine design-point (DP) and off-design point (OD) performance simulations in a Cranfield University's Fortran-based code called TURBOMATCH. The code uses pre-programmed units called BRICKS. Each component of the gas turbine is represented by a brick and identified with unique names such as INTAKE, COMPRE, BURNER, TURBIN, NOZCON, ARITHY and PERFOR [40].

Aircraft Performance Module: This module carries out aircraft geometric, performance and mission modelling and simulation with a Cranfield University's code called HERMES. The code comprises of aircraft aerodynamic and performance models while utilising results of engine simulation from

TURBOMATCH code. The code works by using specific input parameters concerning the aircraft, the mission profile and the engine model and specification, to calculate the aircraft and engine performance throughout the whole mission including each segment of the flight path. The HERMES code was design for passenger jet aircraft in conventional configuration, and assumes standard ISA conditions (with deviation functionalities) and a typical take-off, climb, cruise, landing profile. The HERMES code has been validated against publicly available aircraft performance data within less than 1% deviation in the payload-range diagram [41].

Economic Module: The economic module is executed in HESTIA code, which is divided into three different models: the life prediction model, the economic and the risk model. The life model estimates the engine hot section turbine blade and disc life through creep life, fatigue life and oxidation analysis. Component failure due to creep life is usually a result of the prolong exposure to high temperature. Failure due to creep for in-service fleets is often associated with long-range flight. On the other hand, Fatigue failure is due to cyclic aero thermal stresses imposed on the component during take off, climb, cruise and landing phase. Oxidation failure is due to the oxidation of blade metal surface. TBC that protect the blade form the hot gas streams are usually more susceptible to failure due to oxidation. The effect of TBC oxidation on the engine lifing prediction is generally expected, however this was not considered in this analysis because of the limitation of the code used. The economic model estimates the engine maintenance costs and aircraft direct operating costs utilizing user-defined inputs like engine cost, labour cost per man-hour and maintenance duration. The risk model quantifies the impact of change in costs parameter of the net present costs (NPC) of the engine [42].

Emission Module: The emission module estimates the emission index (EI) for NO_x, CO₂ and unburned hydrocarbons (HC) produced from a gas turbine engine. The calculations are performed with HEPHAESTUS code, a Cranfield University in-house software for assessing the environmental emission performance of different engine combustor designs [39]. It receives engine performance data

from TURBOMATCH to predict the emission index of pollutants used for estimating aircraft landing and take-off (LTO) segment emission.

Plant Production Cost Module: This is a complex module based on a number of factors such as number of production, wages, technology levels, material availability, etc. It estimates the cost of engine production within realistic cost trends.

2.6 Advanced Aircraft Engine Technologies

This section provides an overview of advanced engine technologies with potential to provide additional benefits over conventional gas turbine for aircraft propulsion. Some of these advance technologies may be fed back to develop upgrade variants of existing engine with the promise of performance enhancement and/or economic benefits.

2.6.1 Intercooled, Recuperated and Intercooled and Recuperated Cores

Thermal efficiency of current engines can be improved by increasing the engine overall pressure ratio (OPR) and engine TET. This is however, limited by the compressor material capabilities and HPC exit temperature at take-off [4]. This has led to the introduction of new aero engine cores – Intercooled, Recuperated or Intercooled and Recuperated engine cores. Compression stage intercooling can allow for higher engine OPR within a given HPC exit temperature by increasing the overall engine specific output (i.e., reducing compressor work), which results in better fuel efficiency. On the other hand, some waste heat in the gas turbine exhaust can be utilized for cycle improvement through the recuperated engine core.

Intercooled Core Turbofan Engine: Intercooled core increases the engine specific thrust by cooling compressed air at multiple compressor stages to reduce the overall engine compressor work requirement for a given compressor OPR (see Figure 2-16). However this heat remove from the compressor reduces the HPC exit temperature which must be compensated by increase heating, thus deteriorating the thermal efficiency which in turn increases the specific fuel

consumption (SFC) of the engine [7]. Increasing thermal efficiency of an intercooled cycle is achieved by increasing the engine overall pressure ratio. This increase is usually limited by the engine turbine entry temperature (TET), component materials and HPC exit temperature. For Modern engine where HPC exit temperatures are reaching compressor blade temperature limits, the Intercooled Core engine achieves higher OPR and thermal efficiency compared to conventional engines [43][44]. However, the drawbacks associated with this engine are additional weight introduced by the heat exchanger especially for aircraft application will pay the penalty of additional thrust and increased fuel burn.

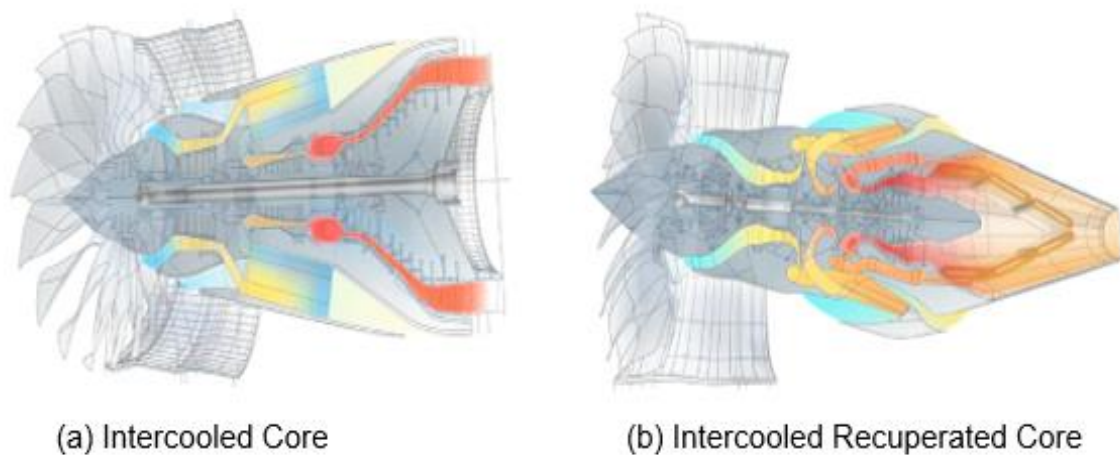


Figure 2-16: Artistic diagram of Intercooled and Intercooled Recuperated Cores Turbofan Engines [45]

Recuperated Core Turbofan Engine: Recuperated engine uses the hot exhaust gas temperature to preheat the compressor exit air before entry into the combustion chamber, so that less fuel would be required to heat the compressed air to a given combustor exit temperature. Therefore improving the overall thermal efficiency of the recuperated engine compared to the conventional engine. This cycle has the potential to improve SFC and NO_x emission of an engine.

Intercooled Recuperated Core Turbofan Engine: Intercooled and recuperated core cycle incorporates both the increased specific thrust output advantage of the

intercooled cycle and the increased thermal efficiency associated with the recuperated to produce a cycle with improved thermal efficiency in comparison with the conventional, intercooled and recuperated cycles [44] [see Figure 2-16]. The cycle higher OPR and exhaust heat recovery potential allows for significant improvement engine fuel efficiency and NO_x emission at landing take-off (LTO) cycle requirement.

Several studies on intercooled recuperated core engine concept have been carried out to quantify the potential benefit of fuel burn improvement. The concept was successfully investigated previously under different European Union funded project such as NEWAC (New Aero engine Core concepts), CLEAN (Component Validator for Environmentally-friendly Aero-Engine) and LEMCOTEC (Low Emissions Core-Engine Technologies) [46][47]. According to Boggia and Rud (2005), a fuel burn reduction of up to 18.7% was achieved for intercooled recuperated core engine compare to the conventional engine, a 1995 technology level. The study investigated a 3-shaft geared engine with intercooled and recuperated core engine, optimized for long-range application, improved fuel burn, NO_x emission reduction and heat exchanger weight prediction. A fuel savings benefit of up to 22% for the intercooled recuperated core engine was reported by Kyprianidis et al (2010) in a study “Assessment of future aero-engine designs with intercooled and intercooled recuperated cores” [48].

2.6.2 Geared Turbofan Engine

The Geared turbofan engine (GTF) is a high bypass-ratio engine developed by Pratt & Whitney (P&W). The geared turbofan (GTF) concept introduces a speed reduction gearbox connecting the shaft of the fan and the low-pressure stage components (booster, LP compressor and LP turbine), as shown in Figure 2-17. The technology enables the fan and the LP-stage components connected by a common shaft to rotate at different optimum speeds. This means the fan can be made to rotate at a lower speed for maximum efficiency and fan noise reduction [44][46]. The lower speed allows for longer fan diameter operating with the same blade tip speed (i.e. ultra-high bypass ration (UHBPR) engine of about 12:1 to 15:1).

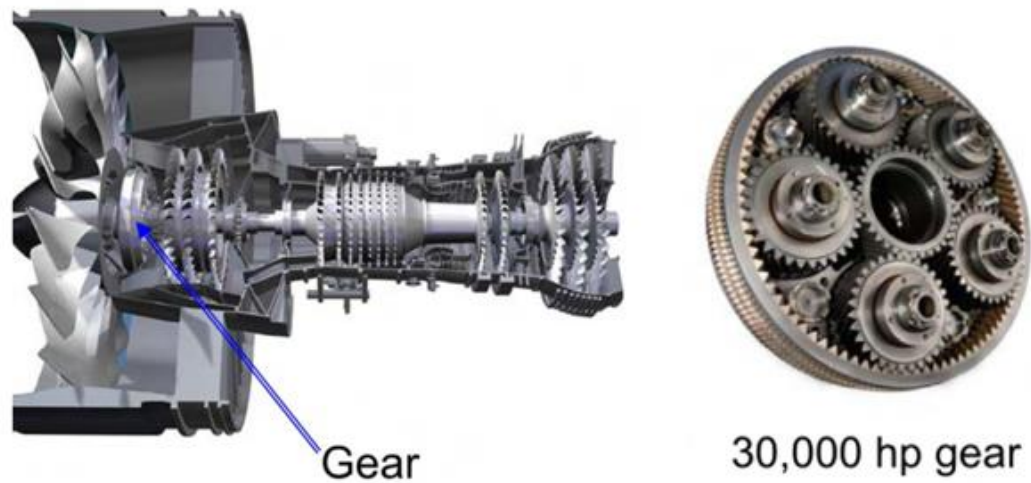


Figure 2-17: Geared Turbofan Architecture [49]

The offers primarily the benefit of fuel burn reduction due to the high bypass ratio, but comes with the associated penalties of weight and cost. However, the GTF is design with 18 fan blades, one-half the number of blades of similar engine size of previous generation [49].

The LP-stage components on the other side of the gearbox can rotate at higher speed, which results in the LP-compressor and LP-turbine with fewer numbers of stages for the same mass flow rating, thus leading to the LP-stage component weight reduction.

2.6.3 Contra-Rotating Turbofan Engine

The contra-rotating engine concept was developed by Snecma in response to the fan and compressor efficiency losses experience in counter-rotating engine. In this configuration, there are two shafts rotating the fan and compressors independently in opposite directions, and then connected at one end of the LP-section to a LP-turbine with counter-rotating blade stages [44][49]. The architecture enables significant increase in bypass ratio, thus providing significant benefit in fuel burn reduction over current generation engines.

2.6.4 Open Rotor Engine

The Open Rotor also known as unducted fan is an engine architecture initiated and extensively tested in the 1980's by General Electric, NASA and other consortium of OEMs in response to the 1973 oil crisis, with an ambitious goal of fuel burn reduction by 50% for narrow body aircraft [50]. Further development was suspended because of the noise concerns and low oil price. However in recent years renewed interest on open rotor configuration have been rekindled due to increased emission regulations, and investigated within the EU projects DREAM and Clean Sky [51].

Unducted fan or open rotor engine configuration are design with fan blades externally mounted on the nacelle. The hot exhaust jets drives two counter-rotating turbines directly coupled to the external fan blades. The engine is provided with large span variable pitch blades to provide the necessary blade angle of attack to meet variable speed and power requirement. These allow for higher BPR and consequent improvement in propulsive efficiency in comparison with the conventional engine.



Figure 2-18: Open Rotor Concept [52]

Chapter Three

Methodology

3. Introduction

This chapter presents an overall methodology of how the research was conducted to achieve the project aims and objectives. Also provided is the description of the various tools utilized for the research and flowcharts highlighting summaries of procedures followed. An overview of the upgrade TERA methodology and its constituent models are further described in this chapter.

3.1 Scope of the Methodology

This research evaluates and quantifies potential engine upgrade benefits from both the manufacturer's and airline owner's (user) perspectives. Four different case studies were analysed in this work: The thermal barrier coating (TBC) upgrade for engine cooling flow reduction, increased engine fan diameter upgrade, thermal barrier coating (TBC) upgrade for increase TET and re-engine upgrade respectively. The first two upgrades were investigated from the manufacturer's perspective and the later from the user's perspective. The general TERA approach was deployed for the evaluation of all the upgrades, but the procedure or method of implementing the upgrade differ with each case study.

3.1.1 Thermal Barrier Coating (TBC) Upgrade TERA Methodology

The TERA approach utilized for investigating the upgrade case study is presented in this subsection. Figure 3-1 shows the TERA-TBC upgrade framework deployed for evaluating the potential benefits of "thermal barrier coating (TBC) upgrade for both the increase TET and engine upgrade cooling flow reduction cases". It consists of an integration of the several component modules. Each module is

made of an individual model used for performing specific task. The TERA-Upgrade is an integration of four modules, as illustrated in Figure 3-1: they are the engine performance model using TURBOMATCH code, aircraft mission and performance model (in HERMES), blade geometry sizing and cooling model in Microsoft Excel, and the engine life prediction and economic model (using HESTIA code).

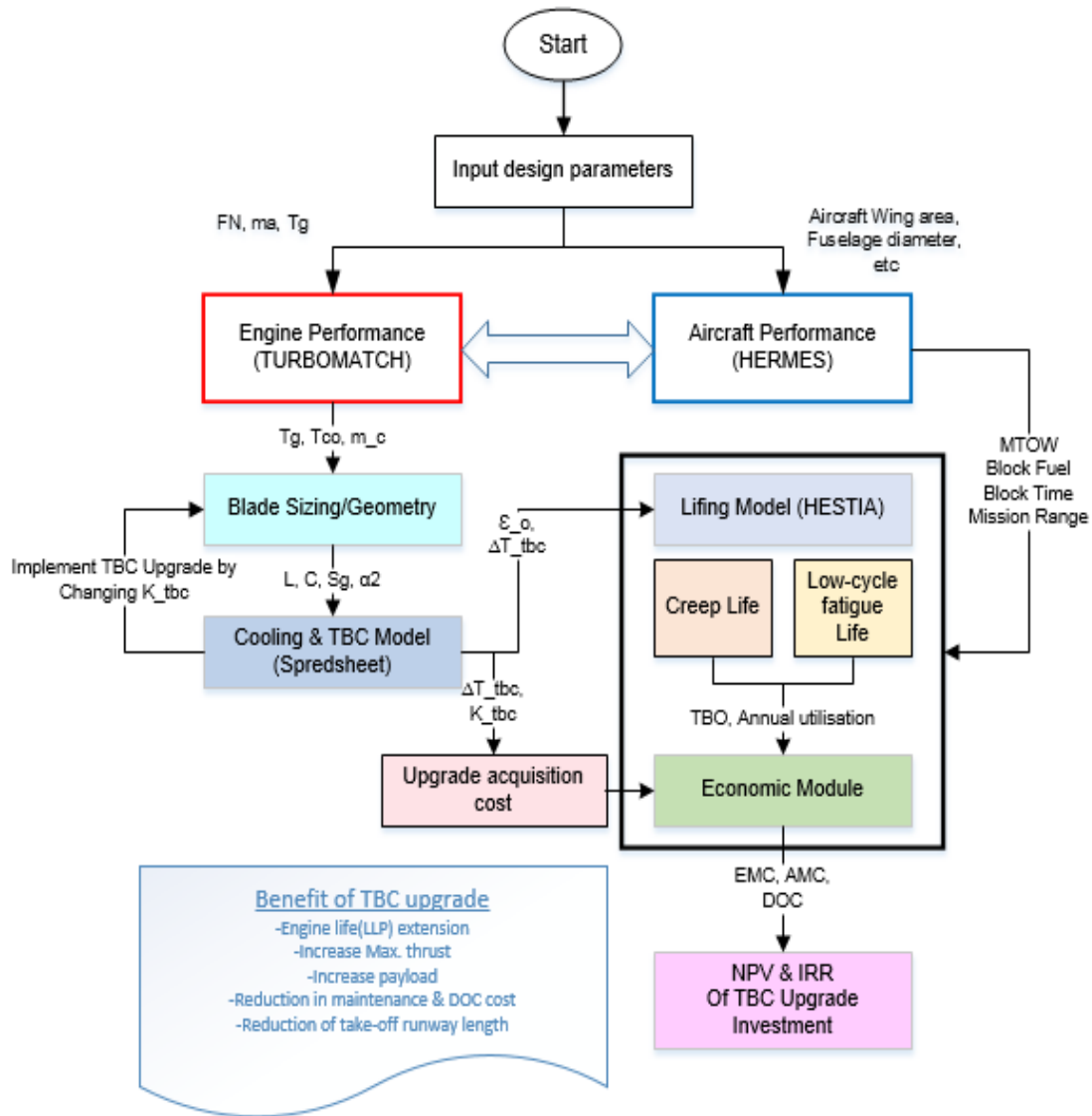


Figure 3-1: Flow chart for TERA of TBC-upgrade Case study

Assumption:

- The TBC upgrade effectiveness is based on the reduction of thermal conductivity of TBC
- TBC case study evaluation is based of the Electron beam physical vapour deposition (EB-PVD) TBC type.
- Estimation of TBC change in temperature is based on the combined effect of cooling systems from theTBC, convention cooling and film cooling.
- The TBC upgrade costs estimation is based on temperature change between TBC.

Limitations: The implication of this assumption is that although simulation results follow a general trend over a range of TBC upgrade, uncertainties due to assumptions could be improved by using industry data.

3.1.2 Increased Engine Fan Diameter Upgrade TERA Methodology

This investigation evaluates the feasibility of engine performance improvement and the potential economic impact via increased engine fan diameter variant. The engine variant is implemented through fan and bypass nozzle components flow path modification without altering the engine core configuration. The increase fan diameter engine variant design is intended as modification upgrade to enhance engine off-design performance through increasing the fan flow capacity proportional to the slight increase in diameter. The TERA procedure utilized for investigating this proposed “increased engine fan diameter upgrade” is presented in Figure 3-2.

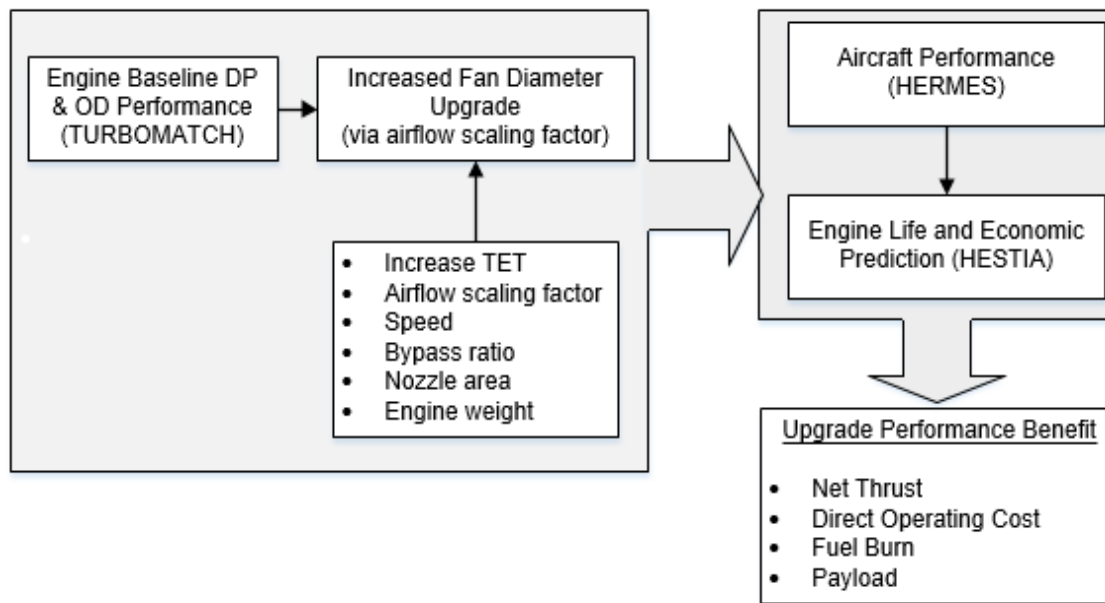


Figure 3-2: TERA for Increased Engine Fan Diameter Upgrade Case study

Assumptions:

- It is assumed that the engine core inlet mass flow is kept constant, the increase inlet mass flow of the Increased engine fan diameter upgrade only increases the bypass mass flow.
- The modification costs was base on Fasching's modification (see page 160).
- The increase inlet mass flow due to increased engine fan diameter upgrade was represented by mass flow scaling factors.
- The engine running line was kept constant by increasing engine TET assuming better component material is adopted.
- The increase drag due to the larger fan diameter was integrated in the simulation by reflecting the higher engine diameter in HESTIA code.

3.2 Engine Performance Module

The engine performance module is the central part of the TERA methodology connecting all other component modules. It simulates gas turbine cycles design point and off-design point performance conditions. As mentioned previously in section 2.6, the engine performance is modelled in TURBOMATCH code. TURBOMATCH was created by MacMillan (1974) in Cranfield University and is a 0-D modular code with pre-programmed bricks representing individual engine components; this enables the assemblage of different bricks such as INTAKE, COMPRE, BURNER, TURBIN, MIXEES and NOZCON to create different type of gas turbine engine cycles. Additional bricks like ARITHY and PERFOR are incorporated to perform the calculations. Each bricks are design to receive inputs and produce outputs. They are connected together in series by an interface called station vector. Each station vector consist of eight variables; fuel to air ratio, mass flow, total pressure, static pressure, total temperature, static temperature, flow velocity and area – uniquely identified by their numbers 1 – 8 in sequential order. Bricks not arranged in series can also be linked together using engine vector as shown in Figure 3-3.

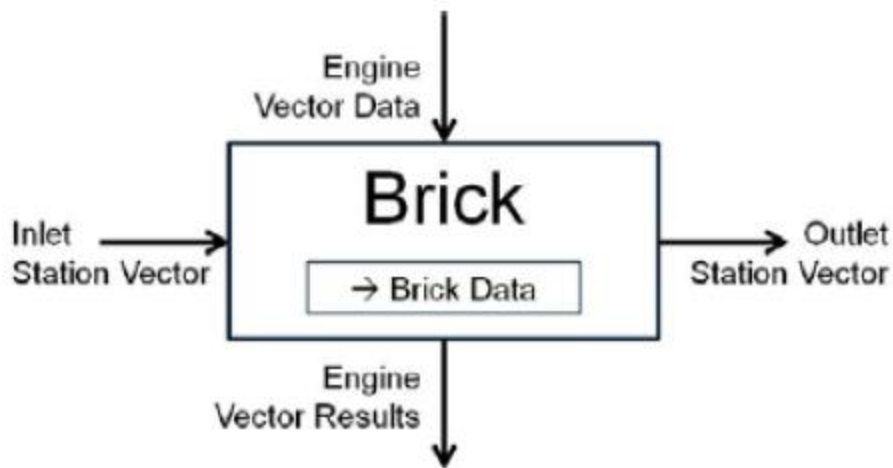


Figure 3-3: Engine brick data flow chart [40]

The TURBOMATCH text input file is use to specify the brick data and engine vector of the engine being created, including the design point TET and inlet mass flow, and then the off-design (OD) conditions investigated. Currently the code is

capable of controlling the engine OD engine behaviour using both the TET and shaft relative rotational speed (PCN) as handle.

In TURBOMATCH, the engine off-design behaviours are modelled by using several pre-defined component maps. There exist five maps for each of the compressor and turbine component, and one default map for each bricks of the combustor, intercooler and nozzle. These maps are based on a default reference map derived experimentally from real measurement of gas turbine engine. The component maps are scaled base on the reference map during design-point calculations, and the performances of the different components are matched iteratively during the off-design operations. It begins by initially guessing several parameters, and then checked the validity of those guesses. These checks are based on the mass flow compatibility, work compatibility, shaft rotational speed and power law [40].

3.3 Aircraft Performance Module

The aircraft performance module is an important TERA module that allows the investigation of engine performance when integrated on an airplane. It enables the calculation of fuel burn over a pre-defined mission range, and can be useful in comparing advanced and conventional aircraft engine.

The aircraft performance module used for this study is called HERMES, a Cranfield University developed in-house code for the integration of aircraft and engine performance simulation [35][41]. Hermes code comprises of aircraft aerodynamic and performance models while utilising results of engine simulation from TURBOMATCH code. The code works by using specific input parameters concerning the aircraft, the mission profile and the engine model and specification, to calculate the aircraft and engine performance throughout the whole mission including each segment of the flight path. The HERMES code was design for passenger jet aircraft in conventional configuration, and assumes standard ISA conditions (with deviation functionalities) and a typical take-off, climb, cruise, landing profile. The HERMES code has been validated against publicly available aircraft performance data within less than 1% deviation in the payload-range diagram [41].

HERMES file structure is grouped into two; the Aircraft and Engine. The aircraft group contains all input/ output files and the executable of Hermes code. The engine group also contain the input/output files and executable of the TURBOMATCH code and TmatchCalls. The TmatchCalls is a code that automatically retrieves engine performance data from TURBOMATCH to be used by HERMES [53].

The executable of TmatchCalls uses information concerning aircraft geometry, the mission and engine specification read from the *GeomMissionEngineSpec.txt* file and the engine off design point read from *Engine-DP.dat* file to generate engine performance data needed for the flight mission in the form of tables stored in *EngPerfData.txt* file. During the execution of Hermes, information from EngPerfData.txt and GeomMissionEngineSpec.txt files are read as input to generate output like *LOGFILE.txt* on the screen, and in the *AircraftFlightPathPerf.txt* and *EngineFlightPathPerf.txt* output files. If a convergence solution is reached, no error will be displayed on the screen (LOGFILE.txt) and the output results will be found in the AircraftFlightPathPerf.txt and EngineFlightPathPerf.txt output files [53].

GeomMissionEngineSpec.txt is the main input file for both the TmatchCalls and Hermes code. It offers the user the means to change values of the input variables. This file has several sections. The major parts are the aircraft geometry and specifications, mission and aircraft weight breakdown, total flight phases (the take-off, climb, main and diversion cruise, descent, hold phase, landing and taxi phases) description, the code tolerance and the TmatchCalls configuration.

In the mission/weight specification data section, the weight breakdown of the aircraft based on the mission specification is required. This can be estimated based of an aircraft conceptual approach presented by Jenkinson and Rhodes (2003) [54]. Aircraft mission in Hermes is defined in two ways; in mission type 1, the total fuel available is specified and code calculates the range of the mission while in mission type 2, the range is specified and the total fuel used in the mission calculated. The fuel used for the diversion mission and contingency fuel is also specified as a percentage of the main mission fuel. However, care should be

taken when specifying mission range, it is the distance covered during climb + cruise + descent, excluding distance covered in diversion mission, as shown in Figure 3-4.

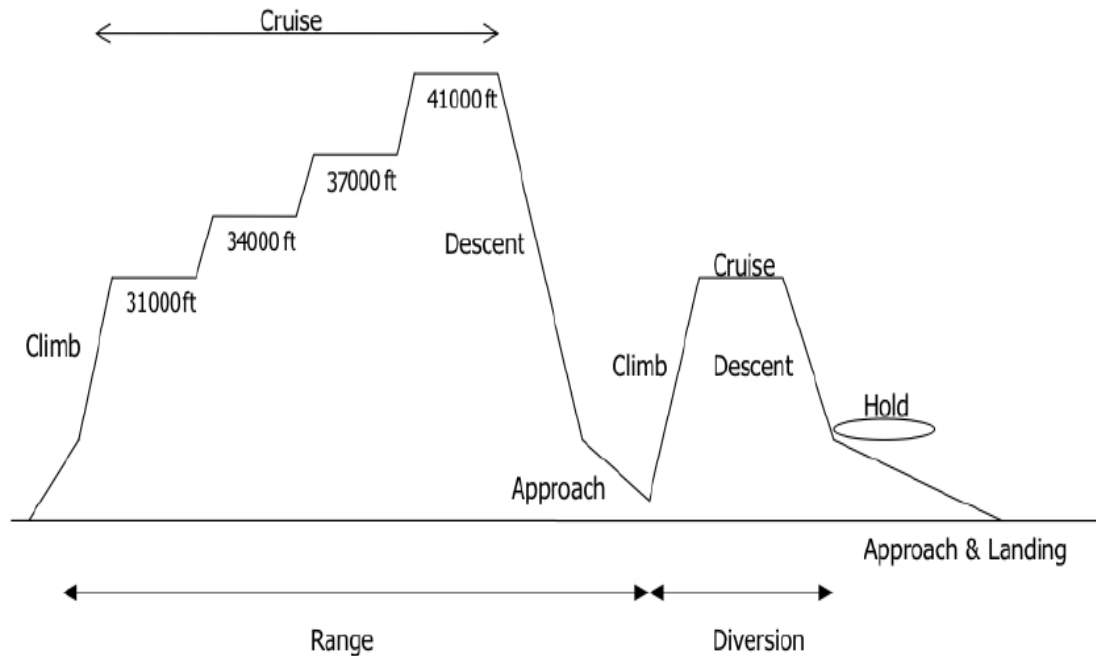


Figure 3-4: A Typical Flight Mission Profile [41]

3.4 Blade Cooling Model

The combined effectiveness of Internal convection and impingement cooling, film cooling and thermal barrier coating (TBC) are widely responsible for the high turbine entry temperatures (TET) and peak thermal efficiencies achieved in modern gas turbine engines. Blade cooling technology has evolved rapidly over the years with designs from simple cooling channels/passages to very complex geometries with intense fluid-surface interactions as discussed in previous chapter. The aim of these technologies is to achieve the highest overall cooling effectiveness with least possible penalties on cycle performance [23][8].

Figure 3-5 shows a typical film-TBC-convective cooling architecture of a gas turbine HP turbine blade. Figure 3-6 illustrates the heat transfer analysis on the cooled airfoil.

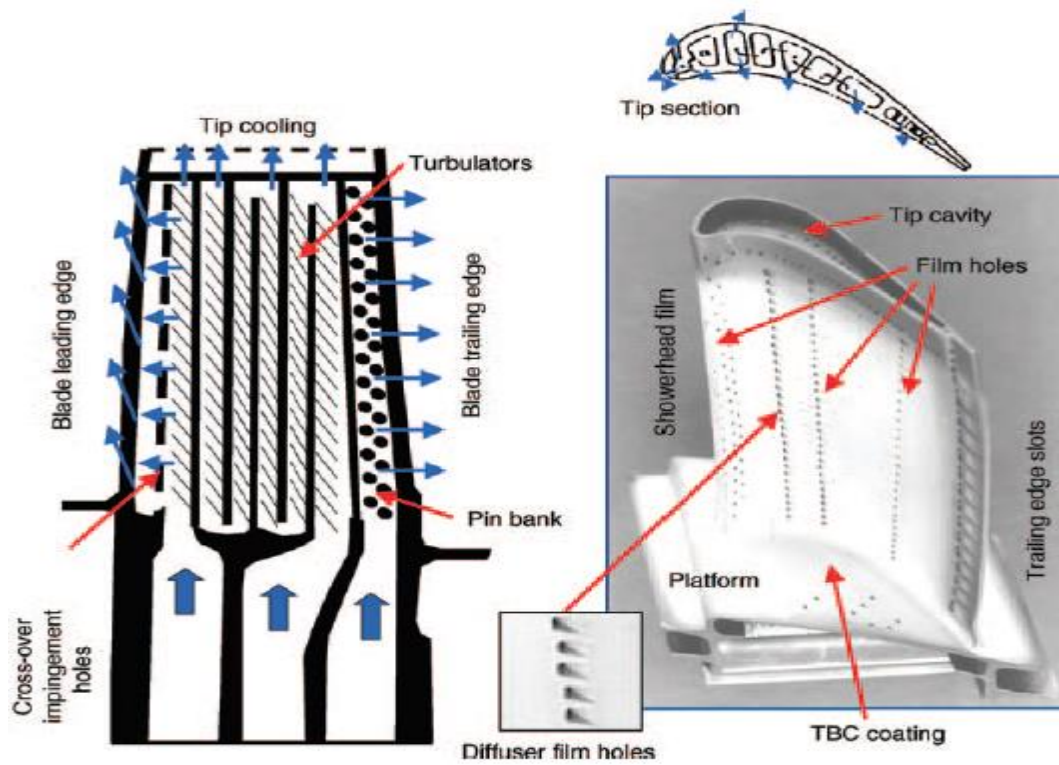


Figure 3-5: Typical Film-TBC-Convection Cooling Architecture [23]

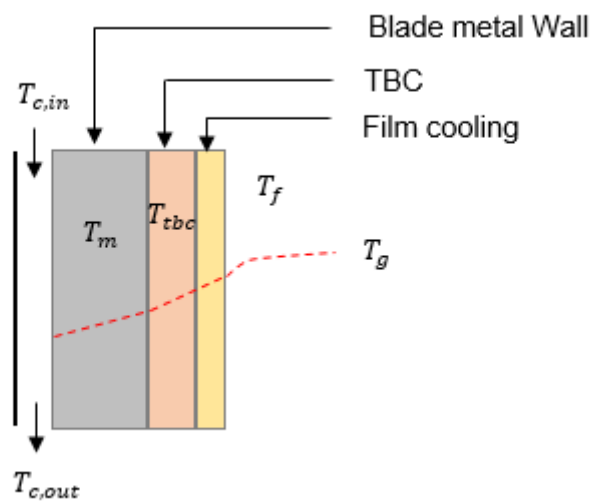


Figure 3-6: Heat Transfer Analysis of Cooled Blade

The thermal parameters widely used to determine the cooling technology of a gas turbine blade-cooling scheme is described by the overall cooling effectiveness, heat load parameter (also called mass flow function), adiabatic film effectiveness and the cooling efficiency, defined as non-dimensional quantities.

The overall cooling effectiveness defines how effectively the coolant removes heat from the system. It ranges from zero value to one, corresponding to no cooling to perfect cooling technology, respectively.

$$\varepsilon_0 = \frac{\varepsilon_f - \varepsilon_f \eta_c + \eta_c m_f^*}{1 - \varepsilon_f \eta_c + \eta_c m_f^*} = \frac{T_g - T_m}{T_g - T_{c,in}} \quad \text{Equation 3-1}$$

The heat load parameter is the ratio of heat flux that can be absorbed by the coolant to the amount of heat imposed on the blade.

$$m_f^* = \frac{\dot{m}_c c_{p,c}}{A_g h_g} = \frac{T_f - T_m}{T_{c,out} - T_{c,in}} \quad \text{Equation 3-2}$$

The adiabatic film effectiveness defines the ratio of heat absorbed through film cooling to the maximum heat the coolant absorbs in the system. It indicates the contribution of film cooling in the overall cooling scheme.

$$\varepsilon_f = \frac{T_g - T_f}{T_g - T_{c,out}} \quad \text{Equation 3-3}$$

Cooling efficiency defines the ratio of actual heat absorbed by the coolant flow to the maximum possible heat that can be absorbed by the coolant. The theoretical maximum would exist if the coolant exit temperature were equal to the metal temperature. Alternatively, cooling efficiency can be expressed as function of coolant mass flow function (heat load parameter) and cooling effectiveness.

$$\eta_c = \frac{T_{c,out} - T_{c,in}}{T_m - T_{c,in}} \quad \text{Equation 3-4}$$

$$\eta_c = \frac{\varepsilon_0}{m^*(1 - \varepsilon_0)} \quad \text{Equation 3-5}$$

The model utilizes augmented convection cooling with multiple internal ribbed channels and passes. The passes increase the heat transfer surface by allowing

coolant flow through the blade length more than once. The ribs facilitate enhanced heat transfer through creating turbulent flow particularly at stagnation points. Film cooling ejects coolant outlet flow through the distributed thin-holes on the surface of the blade creating a uniformly distributed film or layer of coolant air insulating the blade metal from the hot gas stream. Based on the cooling design architecture of the blade, different section has varied cooling flow requirements. The airfoil leading edge stagnation point, trailing edge, pressure side and suction side, all experiences different temperature distribution gradients, hence difference cooling and design requirements.

3.4.1 Convection Cooling

To reduce blade metal temperature via cooling, heat in the blade is transferred to the internal surface and removed by coolant air flowing through the cooling channels/passes. The blade cooling by convection mechanism, assumes that the heat flux from the hot gases to the blade, q_{in} is equal to the heat flux from the blade surface to the coolant flow, q_{out} .

$$h_g S_g L (T_g - T_m) = \dot{m}_c c_{p,c} (T_{c,out} - T_{c,in}) \quad \text{Equation 3-6}$$

Where S_g is the wetted perimeter of the blade outer surface, L , the blade span or height and $\dot{m}_c$ is the amount of coolant flow through a single blade.

Rearranging equation 6 becomes

$$\dot{m}^* = \frac{\dot{m}_c c_{p,c}}{h_g S_g L} = \frac{T_g - T_m}{T_{c,out} - T_{c,in}} \quad \text{Equation 3-7}$$

The cooling technology of the blade is determined by the blade geometric properties, gas properties and the cooling flow characteristics through the blade. The Technology factor, which is an indication of the measure of the cooling system technology, is expressed as:

$$X = \frac{N_p N_c h_c S_c}{h_g S_g} \quad \text{Equation 3-8}$$

Where N_p and N_c is the number of cooling passes and channels in a single blade, respectively. S_c is the wetted perimeter of the blade coolant passage.

3.4.1.1 Heat Transfer Flow Calculation

The heat transfer coefficients for both the coolant flow and the hot gas streams are based on the non-dimensional functions: Nusselt number, N_u , Stanton number, St , Reynolds number, Re , and Prandtl number, Pr .

Nusselt number: It defines the ratio between convective (including both diffusion and advection) and conductive heat transfer across a boundary. On laminar boundary layers, Nusselt number is small and becomes significantly increased due to mixing and increased temperature gradient as the flow transit to turbulent flow.

$$N_u = \frac{hd_h}{K} \quad \text{Equation 3-9}$$

It can be expressed as a function of Reynold and Prandtl number, and varies for the external hot streams and internal coolant flows [55].

$$N_{u,c} = 0.013Re_{e,c}^{0.8} \quad \text{Equation 3-10}$$

$$N_{u,g} = 0.037Re^{0.8}Pr^{0.43} \quad \text{Equation 3-11}$$

Stanton number: It defines the ratio of the convective heat transfer coefficient to the heat capacity of the fluid.

$$St = \frac{h}{\rho V c_p} \quad \text{Equation 3-12}$$

External Stanton number for turbulent flow [56].

$$St_g = 0.285Re_{e,g}^{-0.37}Pr_g^{-2/3} \quad \text{Equation 3-13}$$

Where

$$St_g = \frac{h_g}{c_{p,g}(m_g/A_g)} \quad \text{Equation 3-14}$$

And

$$Re,g = \frac{m_g V}{A_g \mu_g} \quad \text{Equation 3-15}$$

For the internal flows [55].

$$St_c = 0.285 Re_{e,c}^{-0.37} Pr_c^{-2/3} \quad \text{Equation 3-16}$$

Reynolds number: It compares both flow inertia forces and the viscous forces with the fluid, and predicts flow type and patterns associated with it.

$$Re = \frac{\rho V d_h}{\mu} \quad \text{Equation 3-17}$$

Prandtl number: Unlike other numbers, which are properties of specific flow, it is a fluid property. It defines the ratio of momentum to thermal diffusivity.

$$Pr = \frac{\mu c_p}{K} \quad \text{Equation 3-18}$$

3.4.2 Cooling with Thermal Barrier Coating (TBC)

To further lower the blade metal temperature, the airfoil external surface is coated with thermal barrier coating (TBC). The low thermal conductivity ceramic coating offers protection to the blade by shielding the external surface from direct contact with the hot gas streams. The ability at which TBC lowers the blade metal temperature depends on the Biot number of the TBC and blade metal: a function of the hot gas heat transfer coefficient, h_g or Reynolds number, thermal conductivity, and the thickness. Biot number Bi defines the ratio of convective heat transfer from the hot gas streams to the heat transfer by conduction through the TBC or metal. Figure 3-7 shows the thermal model describing the boundary condition and temperature distribution between hot and cold gas side.

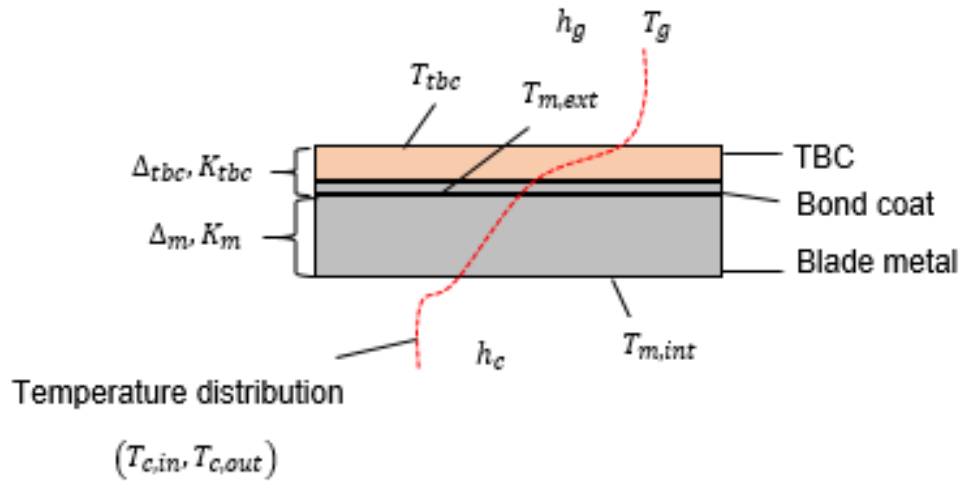


Figure 3-7: Thermal Parameter of blade metal surface with thermal barrier coatings

The overall heat transfer coefficient is:

$$\frac{1}{U_{overall}} = \frac{1}{h_g} + \frac{\Delta_{tbc}}{K_{tbc}} + \frac{\Delta_m}{K_m} + \frac{1}{h_c} \quad \text{Equation 3-19}$$

The TBC layer lowers the effective heat transfer coefficient, U_g , which cause an insulating effect resulting in lower metal temperature. Combining the first three terms of Equation 3-19 and rearranging them gives

$$U_g = \frac{h_g}{1 + \frac{h_g \Delta_{tbc}}{K_{tbc}} + \frac{h_g \Delta_m}{K_m}} \quad \text{Equation 3-20}$$

Where, Biot number of TBC and blade metal are given as:

$$Bi_{tbc} = \frac{h_g \Delta_{tbc}}{K_{tbc}} = \frac{T_{tbc} - T_{m,ext}}{T_f - T_{tbc}} \quad \text{Equation 3-21}$$

$$Bi_m = \frac{h_g \Delta_m}{K_m} = \frac{T_{m,ext} - T_{m,int}}{T_f - T_{tbc}} \quad \text{Equation 3-22}$$

Equation 3-20 clearly shows that the effective heat transfer coefficient decreases with an increase in TBC Biot number, which is achieved by either increasing the thickness or decreasing the thermal conductivity of the TBC coating.

In the presence of TBC, the mass flow function (heat load parameter) becomes:

$$m_f^* = (1 + Bi) \frac{\dot{m}_c c_{p,c}}{h_g S_g L} = \frac{T_f - T_{tbc}}{T_{c,out} - T_{c,in}} \quad \text{Equation 3-23}$$

Film cooling efficiency

$$\varepsilon_f = 1 - \exp \left[-\frac{X}{m_f^*} \right] \quad \text{Equation 3-24}$$

The overall blade cooling effectiveness

$$\varepsilon_0 = \frac{m_f^* \varepsilon_f}{1 + m_f^* \varepsilon_f} \quad \text{Equation 3-25}$$

3.5 Engine Life Prediction and Economic Model – HESTIA

The prediction of gas turbine engine life can be computationally expensive, especially with finite element analysis (FEA) method. However, this work employs a more simplified model to predict the life and consumption rate of Gas turbine HP turbine blade using creep life, low cycle fatigue and oxidation failure analysis. The simulation was implemented in the HESTIA software, an in-house code for life and economic estimation, developed in Cranfield University. The Input parameters required for this model include outputs from previous engine performance, aircraft mission and performance, emission and cooling models as illustrated in Figure 3-1. These include engine peak operating temperature (TET), cooling flow temperature, temperature change across TBC, ΔT_{tbc} and overall cooling effectiveness, ε_0 ; an effect of the combination of convection cooling, film cooling and thermal barrier coating (TBC) systems.

The HESTIA model is a pre-validated tool used for several engine life and economic analysis. It comprise of two main modules: the engine life estimation

and direct operating costs (DOC) modules. The former contain five sub-models to evaluate mechanical stress, thermal, creep life, fatigue life and oxidation life analysis, based on user-defined data (aero-thermal, blade and disc geometry, and material properties) [57]. The model predicts the life of HP turbine blade at the take-off, climb, cruise, descent and reverse-thrust/landing segment of the flight mission. Results from stress and cooling calculations are used in creep and fatigue module to predict HP turbine blade life and time between overhaul (TBO) of the engine. Further details on HESTIA model is found in [58] [59].

3.6 Stress Model

Gas turbine hot path components are designed to operate at extreme environments with high thermal gradient and mechanical loads, inducing high centrifugal and thermal stresses on life limiting parts (LLP) such as turbine blades, vanes and disc [22][59]. During the different phases (taxing, take-off, cruise, landing and manoeuvring) of aircraft mission, variation in thrust or power setting causes the cyclic loading of component materials which might evolve to damage and consequently failure [2]. The stress model evaluates the centrifugal stress acting on the HP turbine blade. The stress is induced by centrifugal loading created by the rotation or inertia of the engine. The model is based on assumptions of constant axial velocity along the blade span and the forces acting at the centre of gravity (CG) of the blade [57]. However, other kind of stresses such as shear stress due to centrifugal untwisting and gas bending moment stress have not been discussed in this work.

3.6.1 Centrifugal Stresses

The centrifugal force acting on the rotating HP turbine blade component is given as [2]:

$$\text{Centrifugal Force} = m * r_{avg} * \omega^2 \quad \text{Equation 3-26}$$

For a given blade mass of:

$$m = \rho * A_{avg} * h \quad \text{Equation 3-27}$$

Therefore, the centrifugal force becomes:

$$\text{Centrifugal Force} = \rho * A_{avg} * h * r_{avg} * \omega^2 \quad \text{Equation 3-28}$$

Where $A_{avg} = (A_1 + A_2)/2$ and $r_{avg} = (r_2^2 - r_1^2)/2$ are the average cross-sectional area and radius between the inner and outer section of the blade.

The maximum centrifugal force acting at the blade root is expressed as:

$$\begin{aligned} \text{Centrifugal force} &= \rho \omega^2 \int_{r_1}^{r_2} A r dr \\ &= \frac{1}{2} \rho \omega^2 A_{avg} (r_2^2 - r_1^2) = 2\pi N^2 \rho A_{avg} \end{aligned} \quad \text{Equation 3-29}$$

Therefore, the maximum centrifugal stress is expressed as:

$$\text{Centrifugal force} = \frac{1}{2} \rho \omega^2 (r_2^2 - r_1^2) = 2\pi N^2 \rho A_{avg} \quad \text{Equation 3-30}$$

3.6.2 Blade Stress Module in HESTIA

HESTIA calculates the maximum stress acting on the HP turbine blade according to the procedures presented in Figure 3-8. The detail steps and subroutines can be found in [58].

3.7 Creep Life Analysis

The creep life for the HP turbine blade was predicted using the Larson-Miller Parameter (LMP) method and the Miner's cumulative creep law. The LMP predicts the damage by creep on the component per cycle and the time to failure for a fixed operating condition based on Arrhenius equation [60]. The material used for CEUP56 engine model HP-turbine blade is Rene N5. N5 is a nickel-based superalloy with excellent creep-failure strength, good ductility at elevated temperature and superior corrosion resistance [60][33].

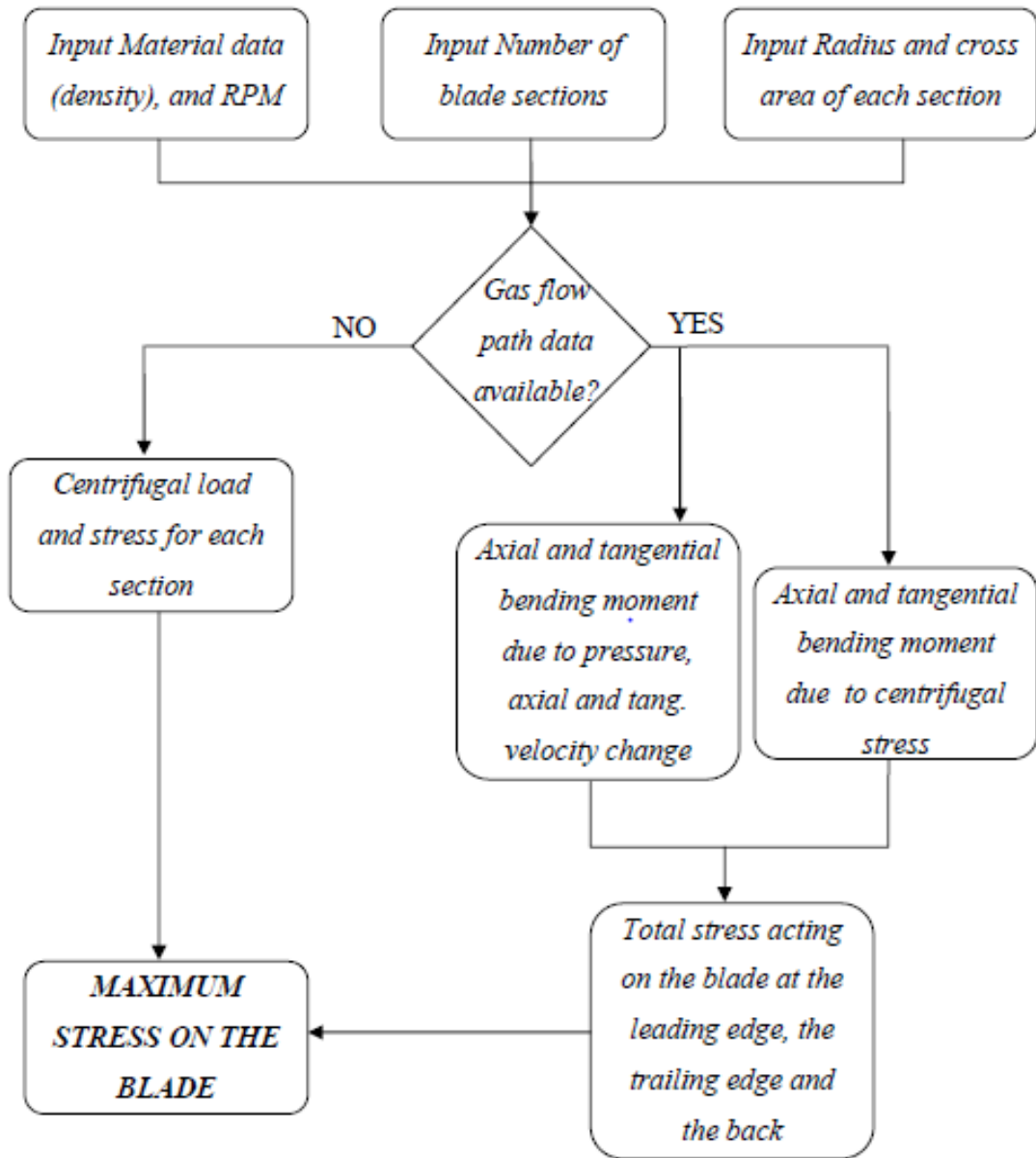


Figure 3-8: Blade stress calculation subroutine in HESTIA [58]

Given the estimated value of the stress, the Larson-Miller Parameter (LMP) can then be obtained from the LMP plot for Rene N5 as shown in Figure 3-9. The time to rupture t_r by creep can be estimated using the Equation 3-31.

$$LMP = \frac{T}{1000} (\log t_r + C) \quad \text{Equation 3-31}$$

Rearranging the equation, we have

$$t_r = 10^{\left(\frac{1000LMP}{T}\right) - C}$$

Equation 3-32

Where T = Metal operating temperature (K)

t_r = Time to rupture (hours)

C = A constant typically equal to 20 (i.e. the intercept of $\log(t_r)$ with the inverse temperature $1/T$).

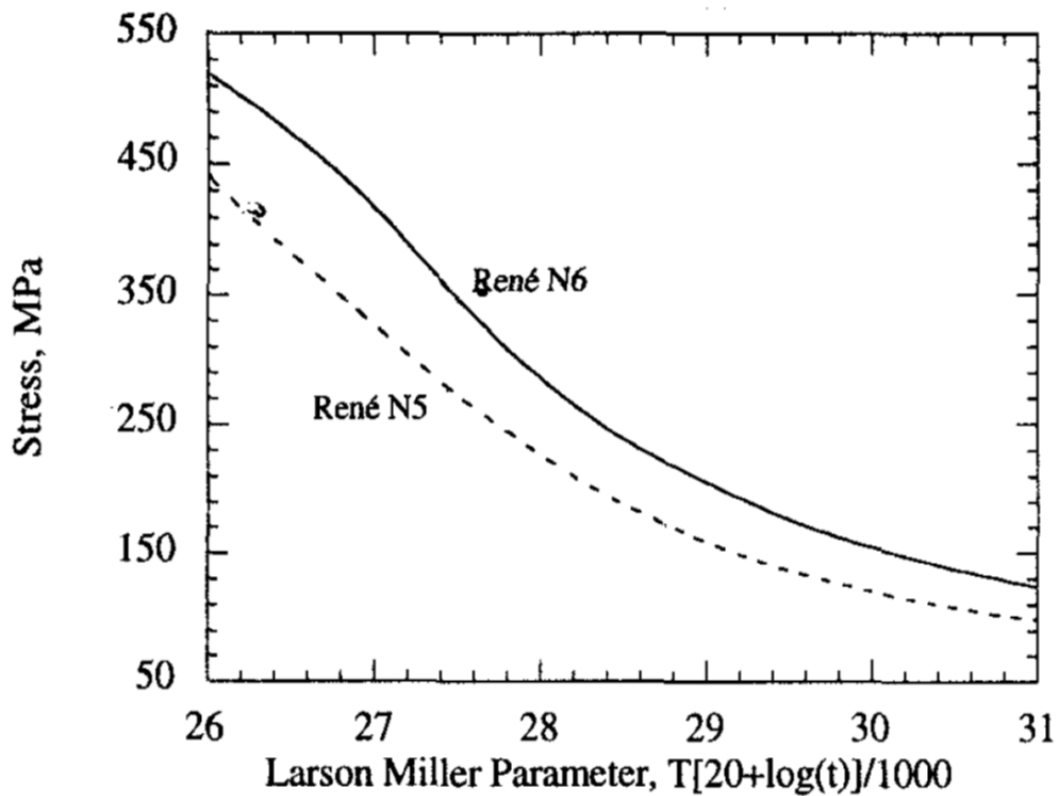


Figure 3-9: Larson-Miller Parameter Plot of Rene N5 [61]

Even though the stresses and metal temperature can be estimated at different sections of the blade (1D-thermal analysis), for simplicity this study assumes a uniform metal temperature from root to tip along the blade span (0D-thermal analysis). The impact of creep damage on each segment of the flight phase (take-off, climb, cruise, descent, and landing) and the Cumulative creep per flight cycle was estimated using the Miner's Law which equates the sum of life fraction to unity [62]:

$$\sum_{i=1}^n \left(\frac{t_r}{T_{total}} \right) = 1$$

Equation 3-33

3.7.1 Creep Life Module in HESTIA

HESTIA predicts the engine creep life at different flight segment of take-off, climb, cruise, descent and landing with typically different engine operating conditions such as temperature (TET), RPM and stresses. The main parameters that influence the component creep life are TET and time spent during each flight segment. Figure 3-10 represent the module structure for creep life estimation within HESTIA [58].

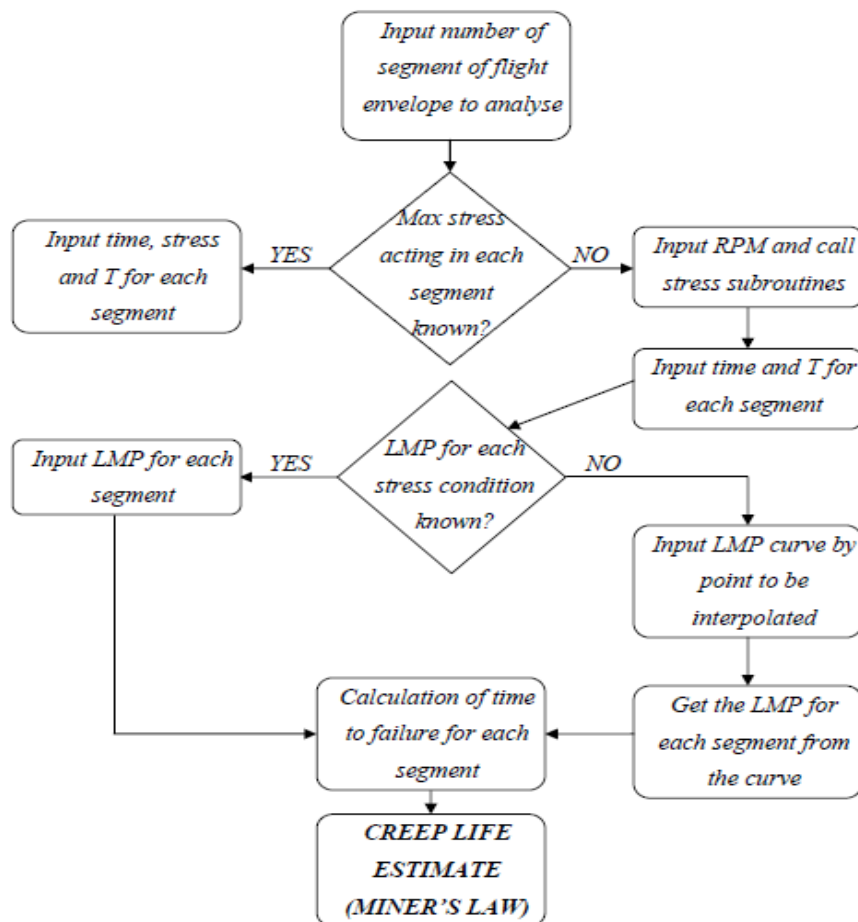


Figure 3-10: Creep life estimation subroutine in HESTIA [58]

3.8 Low Cycle Fatigue (LCF) Life Analysis

Manson estimation LCF life by plotting a logarithmic graph of inelastic strain range $\Delta\varepsilon_T$ (i.e., sum of elastic and plastic components) against the number of cycles to failure N_f . This plot showed a linear relationship between total inelastic strain range and cycle life to failure [2][63][64]. Thus, the total inelastic strain range is:

$$\varepsilon_T = \varepsilon_e + \varepsilon_p \quad \text{Equation 3-34}$$

According Basquin, the elastic strain component in terms of true elastic strain amplitude is expressed as:

$$\varepsilon_e = \frac{\sigma_a}{E} = \frac{\sigma'_f}{E} (2N_f)^b \quad \text{Equation 3-35}$$

Where: ε_e is elastic strain component, σ_a is the cycle stress amplitude, σ'_f fatigue strength coefficient, N_f number of cycle to failure and b is fatigue strength exponent.

The plastic strain component was modelled by Manson and Coffin (1950):

$$\varepsilon_p = \varepsilon'_f (2N_f)^c \quad \text{Equation 3-36}$$

Where: ε_p is the plastic strain component, ε'_f fatigue ductility coefficient and c is the fatigue ductility exponent.

Thus, total inelastic strain (which is sum of elastic and plastic strains presented in the strain-life curve), can be written as:

$$\varepsilon_T = \frac{\Delta\varepsilon}{2} = \frac{\sigma'_f}{E} (2N_f)^b + \varepsilon'_f (2N_f)^c \quad \text{Equation 3-37}$$

The life at which elastic strain equates plastic strain is called the transition life, $2N_t$ (see Figure 3-11). Beyond this point, the effect of elastic strain dominates fatigue life while below the transition life the plastic strain influence dominates the fatigue life.

The fatigue strength, σ'_f/E determines fatigue performance in high cycle fatigue lives while the fatigue ductility, ϵ'_f determines fatigue performance in low cycle fatigue lives.

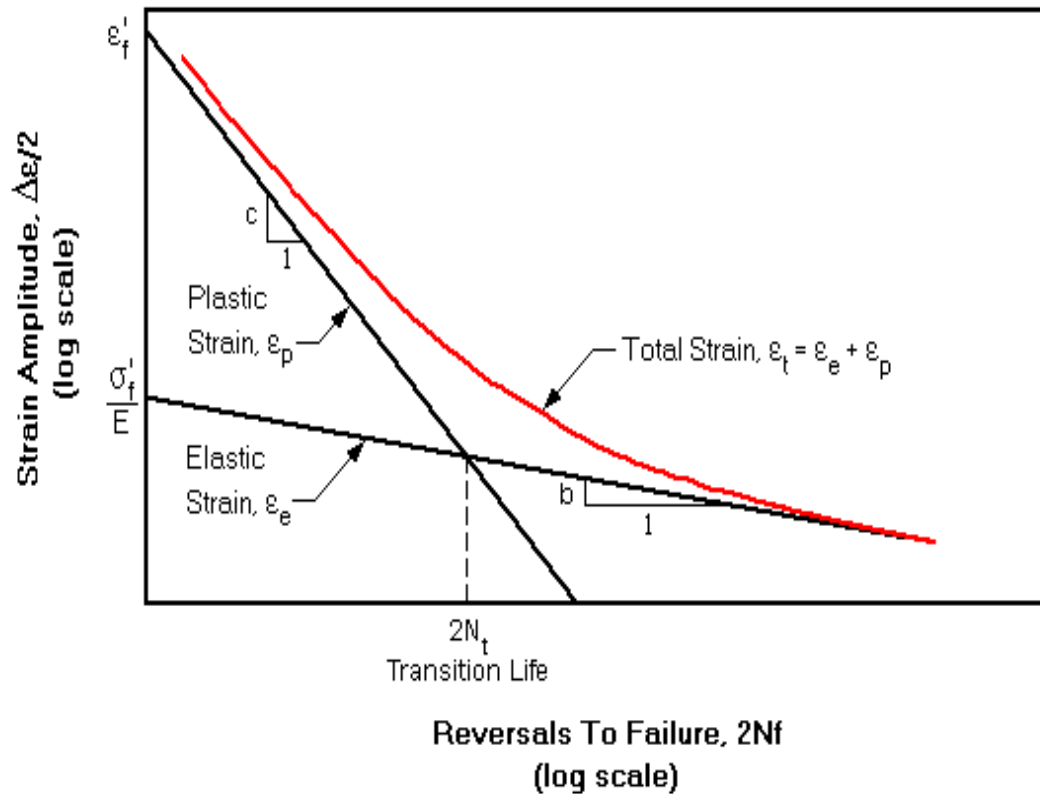


Figure 3-11: Strain-Life Curve

The fatigue properties required to use the low cycle fatigue model are as follows:

1. Cycle strength coefficient, K'
2. Cyclic strain hardening exponent, n'
3. Fatigue strength coefficient, σ'_f
4. Fatigue strength exponent, b
5. Fatigue ductility coefficient, ϵ'_f
6. Fatigue ductility exponent, c

Where the constants K' and n' can be obtained from curve fitting of cycle stress-strain data, but in the absence of experimental data the constants can be defined by the following relations:

$$K' = \frac{\sigma_f'}{(\varepsilon_f)^n} \quad \text{And} \quad n' = \frac{b}{c}$$

Where: σ_f' is the true fracture strength, b varies between -0.05 to -0.12 for most metals while c also for most metal varies between -0.5 and -0.7. For metals c varies between -0.7 to -0.5 from low to high value of ductility [59].

3.8.1 Low Cycle Fatigue (LCF) Module in HESTIA

The HESTIA program predicts the low cycle fatigue life of an engine component by making use of the Coffin-Manson rule, Neuber method and impact of cyclic loading. The life estimation is a strain-method, based on the ability of the turbine blade material to withstand cyclic loading (start-stop cycle during flight mission cycle) at engine peak temperatures. The model was created and validated by [58]. The structure of the low cycle fatigue module is shown in Figure 3-12.

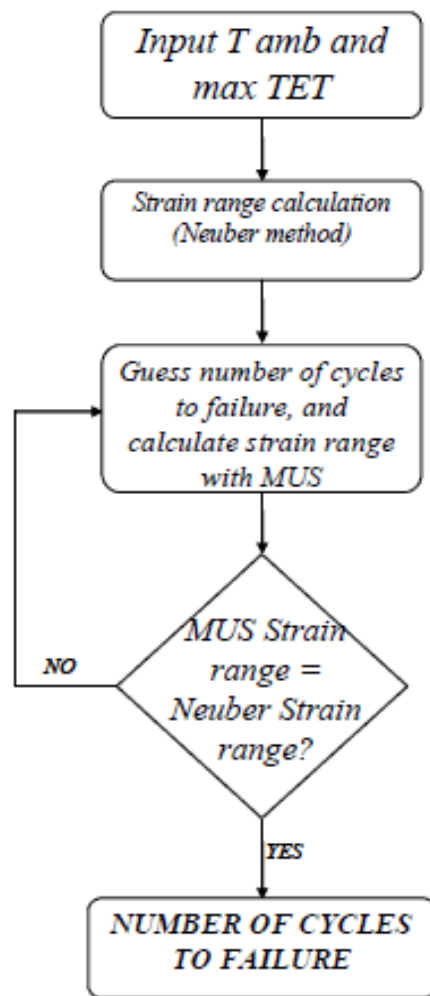


Figure 3-12: Low cycle fatigue subroutine in HESTIA [58]

3.9 Time between Overhaul

The HESTIA program compares the values of the creep and fatigue life of the HP turbine blade component calculated previously and selects the lowest as the limiting life of the engine. The blade oxidation life on the HP turbine is neglected, although smaller than the others is not considered as an engine life-limiting factor. This life estimated is a function of the engine operating time and number of mission flight cycles defined by the mission profile. A Weibull life is then predicted by applying the Weibull analyses module to extend the life prediction capabilities of the engine components.

General theory Weibull distribution:

Weibull distribution is widely used for lifing prediction of hot gas path engine components due to failure. Its popularity is attributed to its flexibility and ability to mimic the characteristics of different probability distributions such as the normal and exponential distributions. The function is defined by three parameters; the scale parameter, α , the shape parameter, β (also known as Weibull slope), and the location parameter, γ . The probability density function (PDF) for Weibull distribution is expressed as:

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x - \gamma}{\alpha} \right)^{(\beta-1)} \exp \left[- \left(\frac{x - \gamma}{\alpha} \right)^\beta \right] \quad \text{Equation 3-38}$$

Where, $\alpha > 0$, $\beta > 0$ and $\gamma (-\infty < \gamma < \infty)$.

Weibull cumulative distribution function (CDF) is written as:

$$F(x) = 1 - \exp \left[- \left(\frac{x - \gamma}{\alpha} \right)^\beta \right] \quad \text{Equation 3-39}$$

The Reliability of the engine/component is written as:

$$R(x) = \exp \left[- \left(\frac{x - \gamma}{\alpha} \right)^\beta \right] = \exp \left[- \left(\frac{x - \gamma}{MTBF} \right)^\beta \right] \quad \text{Equation 3-40}$$

Where, MTBF is the mean time between failures.

It can also be said that, Reliability = [1 – Cumulative distribution function (CDF)].

Weibull distribution can also be defined by only two parameters; a case where the location parameter is zero ($\gamma = 0$). Its application is widely seen in probabilistic fracture mechanics and fatigue analysis. The probability density function (PDF) is written as:

$$f(x) = \frac{\beta}{\alpha} \left(\frac{x}{\alpha} \right)^{(\beta-1)} \exp \left[- \left(\frac{x}{\alpha} \right)^\beta \right] \quad \text{Equation 3-41}$$

And the cumulative distribution function (CDF) expressed as:

$$F(x) = 1 - \exp \left[- \left(\frac{x}{\alpha} \right)^\beta \right] \quad \text{Equation 3-42}$$

The Weibull parameters control the size, shape and the location in time of the PDF, (i.e., it affects the shape, reliability, and failure rate characteristics of the distribution). The scale parameter, α , defines where the bulk occurrences lies on the distribution, the shape parameter, β , dictates the shape of the distribution curve, and the location parameter, γ , determines the location of the PDF in terms of time [59]. As mentioned earlier, Weibull distribution versatility is due to its ability to mimic the behaviour of other distributions during failure or life prediction of engine components.

For a two-parameter Weibull distribution, the rate of failure decreases over time when the shape parameter, $\beta < 1$. This implies that components with initial defects would fail early and the failure rate decrease over time as they are extracted out from the sample or population. This stage is known as the infantile or early mortality stage. When $\beta = 1$, the failure rate is constant over time, suggesting that components failure occurs at random event, thus, mimicking the behaviour of exponential distribution. Finally, when $\beta > 1$, then the failure rate increases with time, indicating a more likely behaviour with many common parts. This stage is known as “wear out” stage, and the Weibull distribution mimic’s the normal distribution at $\beta = 3.5$, the log-normal distribution at $\beta = 2.5$, and the Rayleigh distribution at $\beta = 2$ [65].

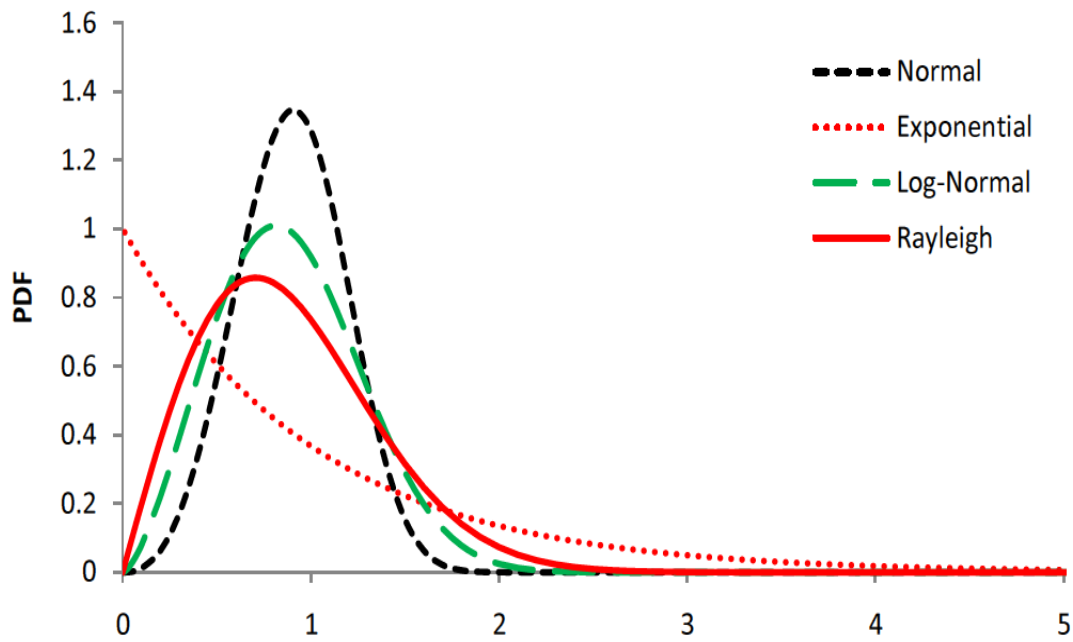


Figure 3-13: Weibull distribution flexibility to mimic other common distributions
[65]

Figure 3-13 represent Weibull distribution, and shows it flexibility due to its ability to mimic the characteristics of different distributions, which represents the various stages of the life cycle of an engine component.

The relationship between the mean value and standard deviation of the random variable x within the two- parameter Weibull distribution is expressed as:

$$\mu(x) = \alpha \Gamma\left(1 + \frac{1}{\beta}\right) \quad \text{Equation 3-43}$$

$$\sigma(x) = \alpha \left\{ \Gamma\left(1 + \frac{1}{\beta}\right) - \left[\Gamma\left(1 + \frac{1}{\beta}\right) \right]^2 \right\}^{1/2} \quad \text{Equation 3-44}$$

Where Γ is the gamma function.

From the density function of five (5) gas turbine engine components with high failure risk: combustor, life limited parts (LLP), High pressure compressor (HPC),

High pressure turbine (HPT) and General breakdowns as presented in Figure 3-14, the HPT have the highest value therefore the most critical component .

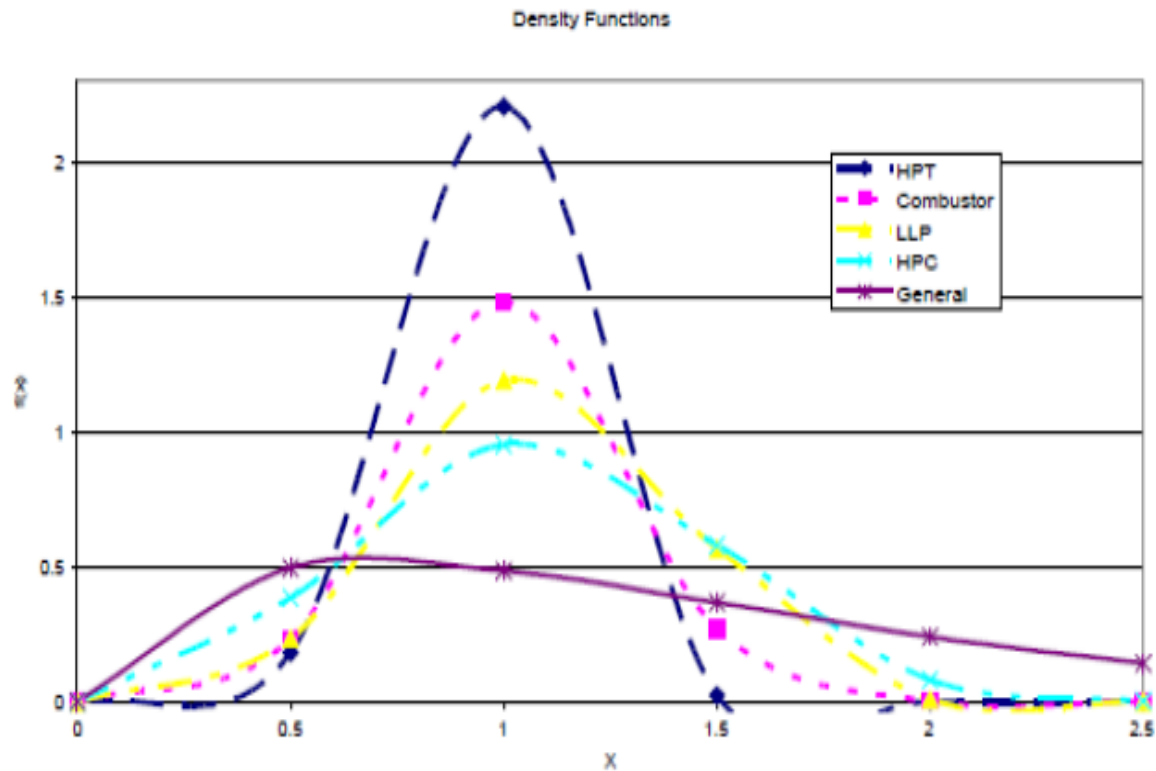


Figure 3-14: Dendity function of gas turbine critical components [59]

3.10 Economic Analyses Module in HESTIA

The economic submodule in the HESTIA program predicts the direct operating costs (DOC) and the maintenance costs of the aircraft based on a pre-defined flight mission. The DOC is calculated based on three costs categories: flight related costs, standing charges and direct maintenance costs [54][66]. Figure 3-15 shows the HESTIA main costs component for direct operating costs (DOC) calculation [67].

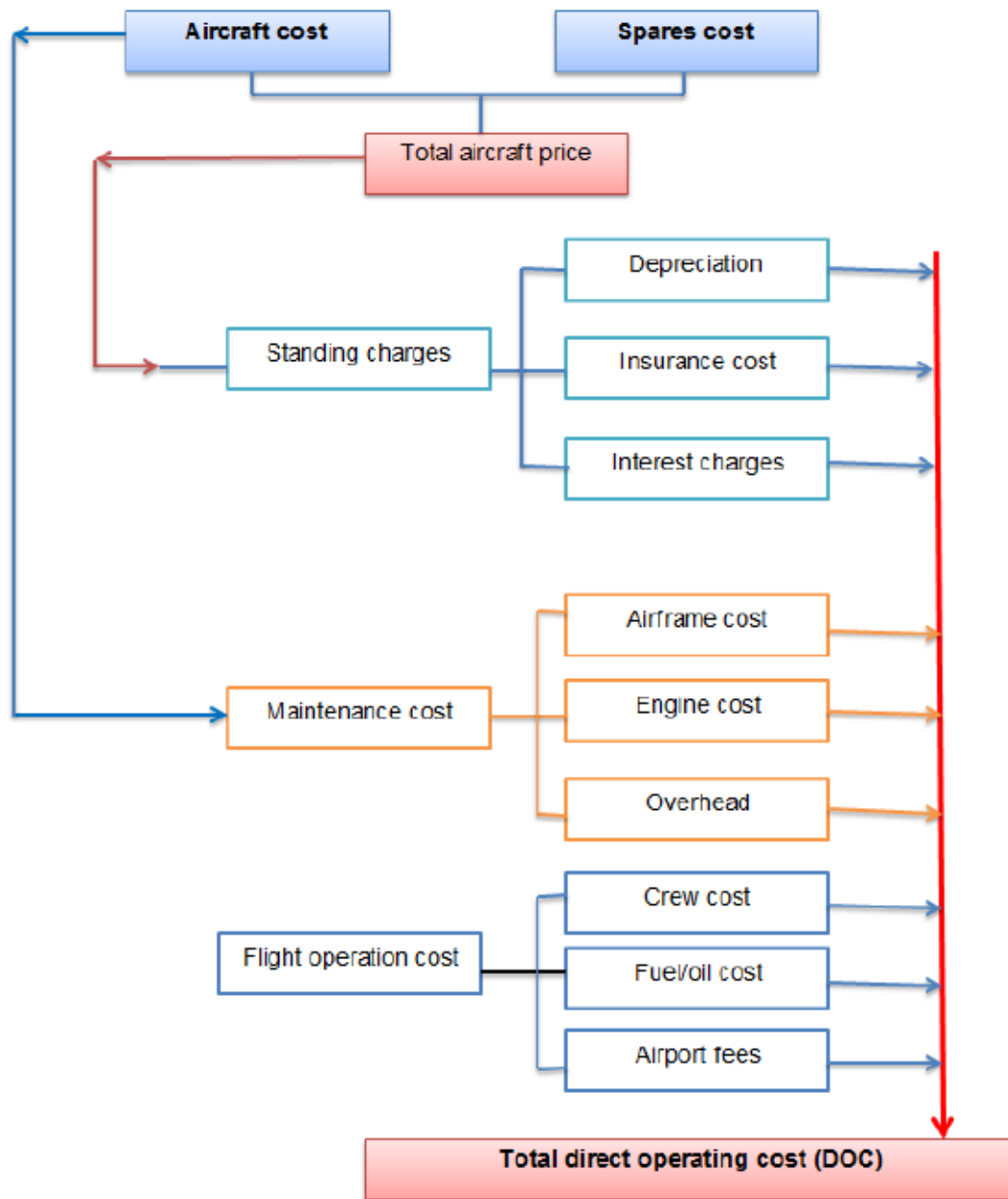


Figure 3-15: Direct operating costs components [67]

3.10.1 Standing Charges

Standing charges are costs incurred during the aircraft business operations, but not directly linked to a flight mission. There are regarded as overheads, and comprise of the aircraft depreciation or lease costs, insurance costs and interest charges on loans or cost of capital [54].

-Depreciation: This cost is mainly influenced by the total investment cost of the aircraft (which comprises the acquisition cost of aircraft including engine and the price of aircraft and engine spares). Other parameters of interest in computing depreciation cost are the depreciation period and aircraft residual value. For example, the depreciation period (DP) over the aircraft useful life of 30 years may be assumed to be 10% or 15% residual value (RV). The aircraft price (AP) is computed as the sum of aircraft factory price and some allocation of capital for spares (airframe and engine spares). The depreciation costs may be estimated from the equation [68].

$$Depreciation = APP \frac{(1 - RV)}{DP} \quad \text{Equation 3-45}$$

Where APP is the airplane purchase price, RV is residual value and DP is the depreciation period.

-Interest and Insurance costs on investment: Although these costs are largely based on the aircraft price (i.e., including engine and spares), there can vary greatly between aircrafts since there are influenced by global economic and environmental dynamics. Insurance companies asking fee varies depending on the nature of the business, area of operation and level of security policy adopted. However, an annual reference rate of 6% and 0.5 % respectively has been assumed for this work.

3.10.2 Flight Related Costs

This cost comprises of all costs incurred during the flight mission, and consists of crew expenses, fuel costs, airport fees (landing and navigational charges) and potentially any taxation charges for Noise or NOx emission.

The crew expenses cover the costs of salaries for flight crew and cabin crew members, and are essentially a function of aircraft block time, number of passengers, wages of crews per block hour and annual crew utilisation [59][69]. The number of crew members for an aircraft is determined by airworthiness standards and labour union agreement [54].

Fuel costs represent the total amount of fuel consumed and it is a function of fuel price and aircraft engine fuel consumption characteristics. Fuel cost represents one of the most important parameter that significantly influence aircraft design. Over the years, several advance design and components have been developed with the primary goal of improving fuel economy. HESTIA reads the user-defined fuel price to calculate the total mission fuel costs. Airport fees consist of the airplane landing fees, navigational fees and ground handling charges.

Airplane landing fees: The cost of airplane landing fees is hardly constant but vary from airport-to-airport based on many prevailing factors, such as operator class (Part 135 or 121), taxed or subsidies airports (e.g. FAA subsidies airports in USA while airports in Canada are not subsidized but are taxed in form of ground rent), aircraft home airport, airplane weight, number of seats, time in the day, airport congestion etc. Usually in congested airports, landing slots are charge premium price to airlines based on supply and demand and in less congested airports lower charges because of low demand.

Landing fees can also be used to attract more flights to the airport by keeping the fees low. In some airports, the fees encompass additional airport services such as gates and check-in facilities while in others different fees are charged for individual services.

For this study, landing fees is calculated as a function of the airplane maximum take-off weight (MTOW). It is estimated in HESTIA based on the correlation provided in Raskhom [70].

$$C_{aplf} = X_{aplf} * MTOW \quad \text{Equation 3-46}$$

Where X_{aplf} is the landing fees cost factor

Airplane navigation fees: Airplane cost of navigation fees are charged per airplane per flight. This fee varies from route-to-route and country-to-country. It can be expressed as a function of block range (RBL) and maximum take-off weight (MTOW).

$$C_{cnf} = \frac{RBL}{5} * sqr\left(\frac{MTOW}{50000}\right) \quad \text{Equation 3-47}$$

Airplane Ground handling charges: The fees and quality of ground handling services provided at an airport is based on the handler's pricing which is usually market-determined through competitive bidding and optimum cost-effective service delivery. However, in monopolistic situation handlers may have sought excessive charges not reflecting the level of service and market price. These abusive charges may impact airline costs negatively. The ground handling charges is estimated as a function of the number of passenger (NP).

$$C_{ghc} = X_{ghc} * NP \quad \text{Equation 3-48}$$

3.10.3 Maintenance Costs

Maintenance costs is a very important component of aircraft direct operating cost (DOC) [71].

The maintenance cost of an aircraft is made up of the airframe and engine components [54]. Each component of the maintenance costs comprise of the labour and material costs aspect. The engine maintenance costs was estimated using the equations developed by Roskam et al [70] and modified by Pascovici [59].

Engine maintenance cost:

$$EngMC = LabourC + MaterialC \quad \text{Equation 3-49}$$

The labour component of the maintenance costs is

$$LabourC = \left[24.8 * \frac{TET}{TBO} + 0.936 \right] * LREng \quad \text{Equation 3-50}$$

And the material component of the maintenance costs as

$$MaterialC = [2.5E - 05 * Engine Price * ESPPF] / KHEM \quad \text{Equation 3-51}$$

The engine TBO factor

$$KHEM = 0.021 * \frac{TBO}{100} + 0.769 \quad \text{Equation 3-52}$$

Where *LREng* is the labour rate per man-hour (€/hr) and *ESPPF* is a material cost factor.

3.10.4 Total Investment Costs

The total investment cost is the sum of the airplane price, engine price and the airplane and engine spares cost.

The total investment cost is estimated by Equation 3-53

$$\begin{aligned} Total Investment Cost \\ = Engine Price + Spare Cost \end{aligned} \quad \text{Equation 3-53}$$

The engine Price is estimated by the Equation 3-54

$$\begin{aligned} Engine Price = Engine Prod. Cost \\ * \left[1 + \frac{Downtime}{(TBO + Downtime)} \right] \end{aligned} \quad \text{Equation 3-54}$$

TBO is the time between overhaul in hours while the **Downtime** refers to the period in hours used for engine overhaul per year.

The cost of spare engine is calculated by

Cost of Spare Engine

Equation 3-55

$$= \text{Engine Prod. Cost} * \left(\frac{\text{Downtime}}{(\text{TBO} + \text{Downtime})} \right)$$

The cost of airframe is given by

Cost of Airframe

Equation 3-56

$$\begin{aligned} &= \text{Airframe price} \\ &- (\text{Number of Engine} * \text{Engine Price}) \end{aligned}$$

Thus, the total cost of spare parts is sum of 30 percent of engine price and 10 percent of airframe price.

$$\begin{aligned} \text{Spare Cost} = & [(0.3 * \text{Number of Engine} * \text{Engine Price}) \\ & + (0.1 * \text{Airframe Price})] \end{aligned}$$

Equation 3-57

3.11 Weight Estimation Module

The aircraft engine weight has a significant effect on the total aircraft weight and performance of the aircraft systems. The propulsion system (Engine) weight is significantly influenced by parameters such as Bypass ratio (BPR), Turbine entry temperature (TET), Overall pressure ratio (OPR) and year of engine manufacture [72]. To predict the engine weight, a semi-empirical correlation proposed by Gerend [73] has been adopted and implemented for this study to analyse the Increased Fan Diameter upgrade. Gerend's model dates back to 1970 and it is based on statistical correlation developed from a large engine database. To reduce cumulative prediction error from extrapolation in this study, the Gerend's model was slightly modified by using a reference engine of 1985 turbofan (GE CF6-80C2) instead of 1962 turbojet originally used by Gerend. The equations below present the mass of the propulsion system (Engine) which is a function of air mass flow and several correction factors. The air mass flow for this study is defined from the design point condition. Table 3-1 shows the engine parameters

used in Gerend's model, the coefficients on the first column representing the correlation factors and the second column illustrating the variables derived from Gerend's corresponding graphs.

$$WT = \left(\frac{WT}{W_o} \right)_{ref} W_o \cdot KENG \cdot [K_{gg} \cdot KHP + (1 - K_{gg}) \cdot KLP] \quad \text{Equation 3-58}$$

Where,

WT Total engine weight

$\left(\frac{WT}{W_o} \right)_{ref}$ The ratio of reference engine weight to the air mass flow

W_o The air mass flow of the simulated engine

K_{gg} The ratio of core engine weight to total weight

KENG = The correlation factor related to the entire engine

$$= [KBPR][KY][KLIFE][KM][KDUCT]$$

KHP = The correlation factor related to the engine core

$$= [KT_4][KR_p][KW_e]$$

KLP = The correlation factor related to the engine fan

$$= [KW_o]$$

Table 3-1: Reference Engine Weight Model

Coefficient		Variable	
$\left(\frac{WT}{W_o}\right)_{ref}$	14	1962 turbojet	
W_o [Kg/s]	736	Take-off Condition	
KBPR	0.45	BPR	5.15
KY	0.45	Year	
KLIFE	1.07	Long Life	
KM	1	Subsonic	
KDUCT	1	Short Duct	
KENG	0.21668		
KT_4	1.3	ΔCOT [F]	800
KR_p	1.45	OPR	31.5
KW_e	1.1	W_e [Kg/s]	154.4
KHP	2.0735		
KLP	1.6	KWo	1.6
K_{gg}	0.41	BPR	5.15
Weight	4326.7	Predicted	
Weight	4386.2	Actual	
Error	1.36%		

Using the GE CF6-80C2 engine (1985 turbofan) as the reference for this study, the model correction factor coefficients for predicting the engine weight was calculated using the correction factors presented in Table 3-2 .

Table 3-2: Coefficient of Correction Factor for Engine Weight Model

Weight Model Coefficients	
$\left(\frac{WT}{W_o}\right)_{ref}$	$4386.2/279.5 = 15.693$
KBPR	$KBPR = 28.98 - 28.32(BPR)^{0.004664}$
KY	0.56
KLIFE	1.07 for long life civil turbofan
KM	1.0 for subsonic civil turbofan
KDUCT	1.0 for short cowl
KT_4	1.7
KR_p	$1 + (OPR - OPR_{ref})/36.14$
KW_e	$0.9939(CoreMassFlow/Reference)^{0.2106}$
KWo	$(W_o/W_{o_{ref}})^{0.3}$
K_{gg}	$K_{gg} = 0.00843(BPR)^2 - 0.1526(BPR)$ $+ 0.9494$

Although several engine weight estimation methods have been developed over the years, which can be broadly categorized into whole engine-based methods and component-based methods [76][78][80][82][84], the Gerend's model was deployed for this analysis because it was considered fairly simplified, computationally convenient and reasonable suitable for this preliminary feasible study on the increased engine fan diameter upgrade. However, the author acknowledge that a more advanced weight code could be use for a more robust study of this proposed upgrade or general engine weight analysis.

Chapter Four

Baseline Performance Models

4. Introduction

4.1 Performance Model of CEUP56Type Engine

The engine model is a mature two-spool turbofan engine in the 120KN thrust class. The model code-named 'CEUP56' (Cranfield Engine Upgrade Project) is inspired by the CFM56-7 engine, an established powerplant and a likely recipient of an upgrade offer. The choice is arbitrary but relevant. The engine performance model was developed and simulated in TURBOMATCH the Cranfield University gas turbine model used for design-point, off design and transient performance calculations of gas turbine engines [74]. The code uses pre-programmed units called BRICKS. Each component of the gas turbine is considered as a brick, identified with unique names such as INTAKE, COMPRE, BURNER, TURBIN, NOZCON, ARITHY and PERFOR. A brick is characterized by the inlet station vector, outlet station vector, block data, engine vector data and engine vector results. The output result of one brick is the input data for another.

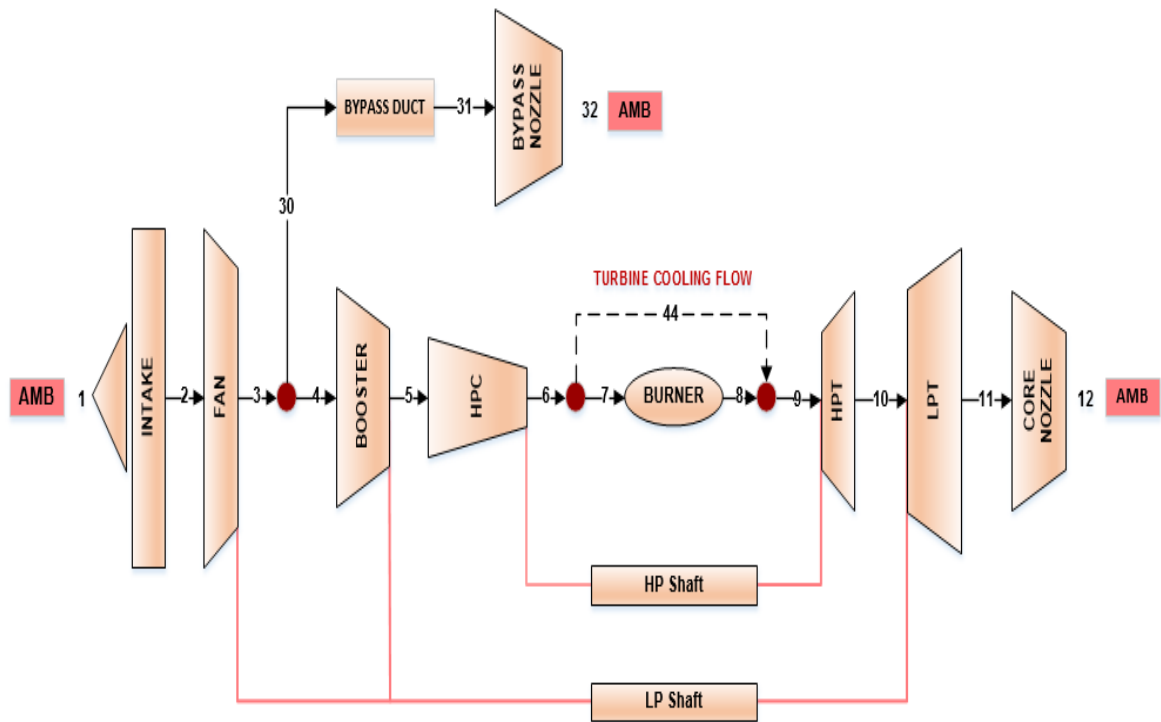


Figure 4-1: Schematic diagram for CEUP56 engine model

The combination of different bricks calculates the engine performance parameters such as thrust, specific fuel consumption, and so on. TURBOMATCH has been validated several times for powerplants when detailed engine data existed. Given the estimative nature of the present exercise, verification was carried out with public data.

The engine configuration is 1-stage Fan, 3-stage Booster (LPC), 9-stage HPC, 1-stage HPT and 4-stage LPT. The combustion chamber is a single annular combustor with an option for dual annular combustor (DAC). The schematic diagram of the two-spool, separate exhaust, high bypass turbofan engine incorporating a booster compressor, is shown in Figure 4-1.

4.1.1 Design Point (DP) Simulation of CEUP56 Engine

Design point performance is very crucial in an engine design process, it is that point where the engine configuration, component design and cycle parameters are optimized [7]. Often defined by the operating condition of the engine flight

phase it spends most of its time on. For aero-engine, the cruise condition is usually selected because it is usually the flight segment with the longest duration and hence, of significant importance in terms of flight mission fuel burn. However, for this work the top-of-climb (TOC) operating condition (10668m, M0.80, ISA+10) was chosen as the design point calculation. This is because more information of CFM56-7B27 engine at top-of-climb condition was found in public domain [12][75] therefore avoiding too many initial assumptions. Even so, assumptions were made for some parameter values not found in public domain such as component efficiencies, component pressure ratio and turbine entry temperature.

Table 4-1: Engine Design Parameters

<u>Design point data</u>	<u>Unit</u>	<u>Value</u>
Design point Altitude	[m]	10,668
Take-off thrust	[KN]	121.47
Take-off Mass flow	[Kg/s]	357.18
Take-off fuel flow	[Kg/s]	1.09
Take-off TET	[K]	1620
Take-off BPR	[-]	5.1
Top-of-Climb Net Thrust	[KN]	26.51
Cruise SFC	[mg/Ns]	17.108
Top-of-Climb TET	[K]	1477
Top-of-Climb Mass flow	[Kg/s]	144.29
Cruise Flight Mach No.	[-]	0.8
Fan Pressure ratio	[-]	1.8
Booster Pressure ratio	[-]	1.85
Overall Pressure ratio	[-]	32.8
Compressor Isentropic efficiencies	[-]	0.87
Turbine Isentropic efficiencies	[-]	0.91
Combustion Fractional Pressure Loss	[-]	0.05
HPT Bleeds	[%]	10

Table 4-2: Engine Model Verification

<u>Parameter</u>	<u>Real Data</u>	<u>Simulated Data</u>	<u>Error [%]</u>
Take-off Thrust [KN]	121.44	121.47	0.02
Top-of-Climb Thrust [KN]	26.51	26.51	0.00
Peak Cruise Thrust [KN]	24.376	24.361	0.06
Cruise SFC [mg/Ns]	17.06	16.88	1.06
Take-off Mass Flow [Kg/s]	355.0	357.18	0.61

This reverse engineering process is called adaptation and although there may be inaccuracies in the data the overall outcome is a very realistic representation of the engine. This model is considered very appropriate for the investigation that follows. The design point parameters for this engine are presented in Table 4-1. It is worth noting that the author's choice of flight phase for the DP calculation was based on availability of sufficient public information. Several iterations were carried out to match the design-point of top of climb condition with other off-design conditions such as take-off, cruise, descent, approach and landing. The simulation was performed by iterating TET, component pressure ratios and component efficiencies of the engine. Table 4-2 presents model verification through comparison between the engine real value from public domain and simulated value. The error value shows the degree of accuracy of the simulation; however, the author has considered the accuracy reasonably sufficient for this work although better accuracy can be gotten by further iterations.

The outputs of the engine simulations indicate the general performance of the engine in terms of net and gross thrust, specific fuel consumption (SFC), fuel flow and other thermodynamic and operational parameters of the different components. Some engine performance output parameters are used as inputs in other models. The gas temperature at HPT inlet and outlet, temperature of cooling air, and the rotational speed of engine core are employed in cooling and life estimation models.

4.1.2 Compressor Map Characteristics of CEUP56 Engine

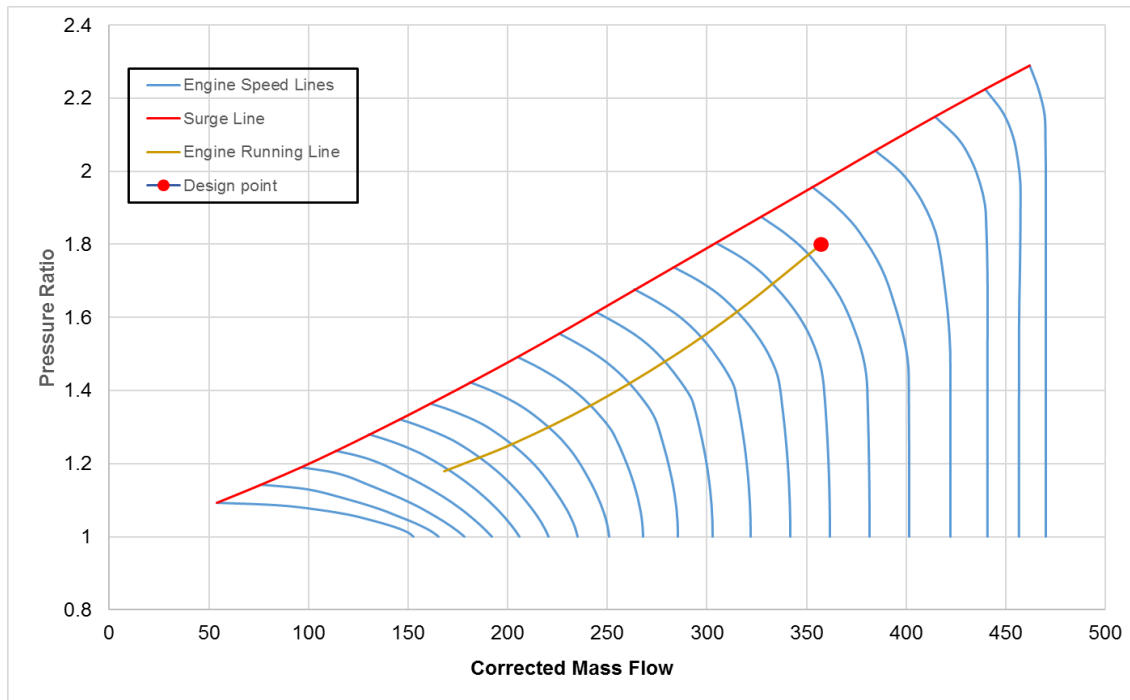


Figure 4-2: CEUP56 Engine Model LP Compressor Map

Figure 4-2 presents the Fan compressor map of CEUP56 engine model, showing the engine design point, running line, speed line and compressor surge line.

The CEUP56 fan map was created in TURBOMATCH base on the zero-dimensional (0D) fan modelling method. 0D fan modelling is evaluated with either the single fan map or the two fan map methods. Using the single fan map models the fan by assuming the averaging of aero-thermodynamic properties across the radial and circumferential direction. Thus not capturing the effect of blade speed variation from hub to tip, work input variation across the blade span, viscous flow effect across the hub and tip region, distortion and other losses. This may introduce some inaccuracies in the simulation outcomes relative to real life data, especially for thrust and SFC. However, the two-fan maps model provides a more realistic modelling by treating the fan as two separate components mounted on the same shaft. Essentially splitting the fan into two distinctive regions, the inner and outer fan regions that are describe by two fan characteristic maps. One map

characterises the flow to the bypass section and the other map the flow to the core fan section, more accurately representing the capabilities to alter the properties (i.e. pressure ratio, efficiency and corrected mass flow) of the bypass and core section. Throughout this study, the single fan map was deployed because the version of TURBOMATCH software used had capability for representing fan through the single fan map. However, results obtain are very realistic and the method considered suitable for this study.

4.1.3 Off-Design Point (OD) Simulation of CEUP56 Engine

After establishing the design point (DP) performance which sets the geometry of the engine, the off-design performance is simulated to evaluate the engine behaviour at different operating environmental conditions during the different flight phase of the aircraft missions (altitudes above sea level, varying flight Mach number and ISA temperature deviation). The effect of varying flight altitude, Mach number, and TET on engine net thrust and SFC was investigated.

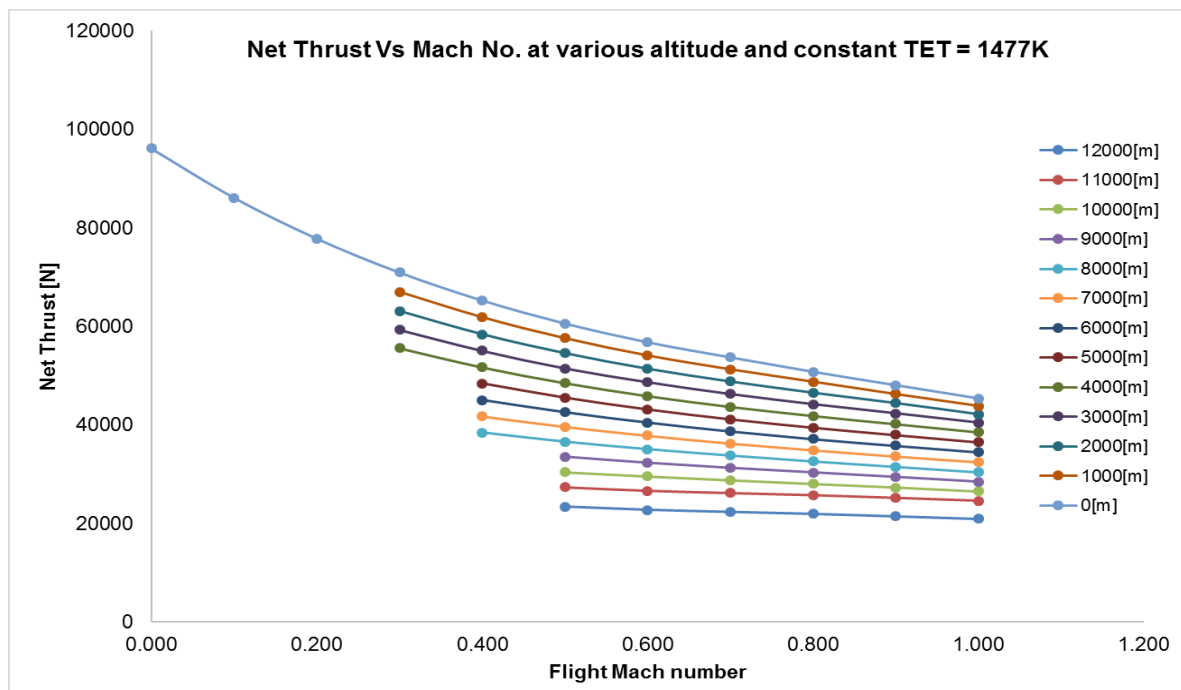


Figure 4-3: Net Thrust versus Altitude at various Mach number

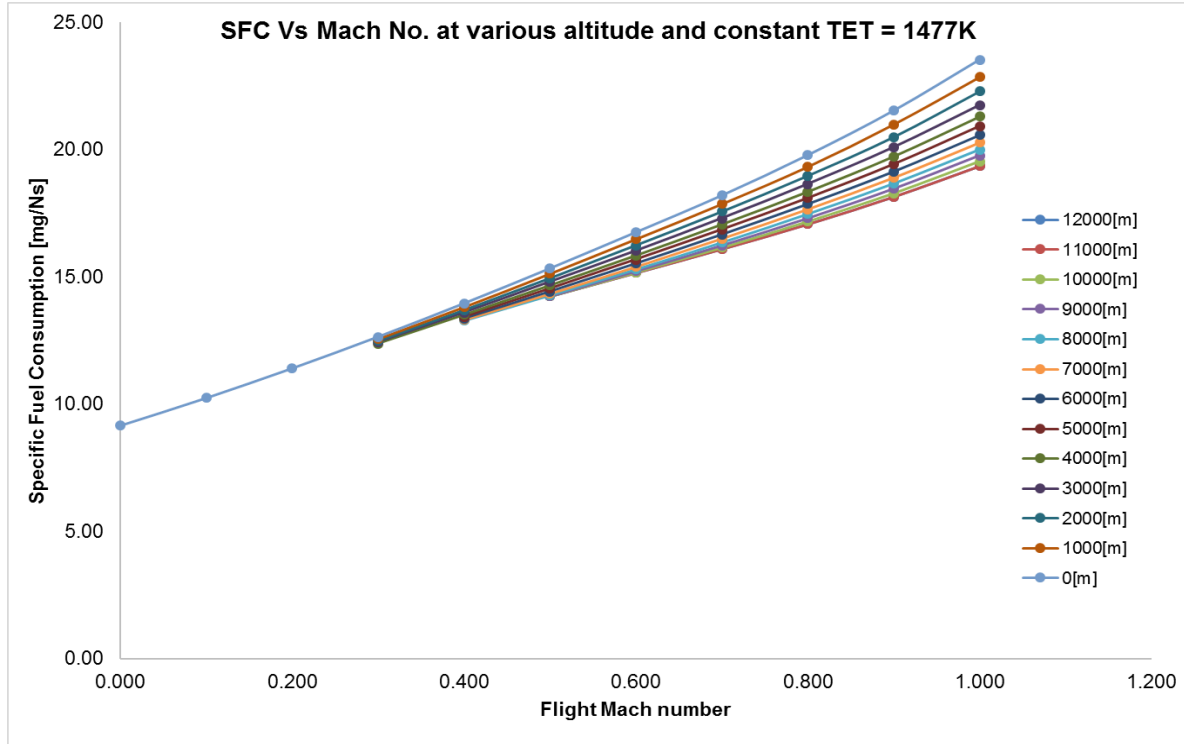


Figure 4-4: SFC versus Altitude at various Mach number

Figure 4-3 and Figure 4-4 shows the effect of Mach number on engine net thrust and SFC respectively at different flight altitude. Generally, the ambient temperature decreases as the altitude increase from 15⁰C at sea level to -56.5⁰C at 11000m above, and then remains constant. Consequently, the ambient pressure and air density decreases with altitude resulting in mass flow reduction. This decrease in mass flow causes the reduction of net thrust with altitude as present in Figure 4-3. As compressor entry temperature T_1 decreases proportionally to the ambient temperature, the non-dimensional rotational speed $N/\sqrt{T_1}$ ($N = \text{constant}$) tend to increase raising the engine pressure ratio, TET, and specific thrust which opposes the fall in net thrust. Figure 4-4 shows a drop in SFC with altitude as Mach number decreases because of the need for higher engine pressure ratio and TET to maintain the required thrust, thus benefiting the thermal efficiency increase but penalysing the propulsive efficiency of the engine.

The effect of thermal efficiency rise is dominated by the drop in propulsive efficiency, thus the SFC decreases in accordance with the formula.

$$\text{SFC} = \frac{V_o}{\eta_{th}\eta_{prop}\text{FHV}} \quad \text{Equation 4-1}$$

Aircraft flight velocity (Mach number) has very important effects on the performance of the engine. Three major factors affect the performance of the engine as the flight velocity changes, these factors are; momentum drag, ram compression and ram temperature rise [2][77]. As the flight, speed increases the rise in momentum drag decrease the net thrust of the engine according to the formula $F_N = W(V_j - V_o) + A_N(P_j - P_o)$. The amount of momentum imparted on the fluid was also affected causing the flight velocity to accelerate faster than the jet velocity, which results in the increase in propulsive efficiency according to the formula $\eta_{prop} = 2 / \left(1 + \frac{V_j}{V_o}\right)$.

Ram compression increases the engine inlet pressure, which results in the rise in air density and mass flow rate. The nozzle pressure ratio is also increased leading to the increase in gross thrust. Ram temperature rise in the other hand, increases the compressor inlet temperature hence decreasing the non-dimensional shaft speed $N/\sqrt{T_1}$ (= constant), net thrust and the thermal efficiency of the engine. Since the engine is a turbofan which operates at lower jet velocities, effect of momentum drag is dominant at lower altitude causing the decrease in net thrust [77]. As the flight, altitude increases as shown in Figure 4-3 the air density falls due to decrease in ambient temperature, and the ram compression and ram temperature effect dominates and reduce the drop in net thrust.

The variation of SFC with increasing Mach number at different flight altitudes is shown in Figure 4-4. The SFC is observed to increase as the flight Mach number increases; this is because the ram compression causes the increase in air mass flow, which would require more amount of fuel to be burn therefore increasing the SFC. Increasing Mach number would increases both gross thrust and momentum

drag, but the momentum drag component rise faster than the gross thrust as the flight altitude increases resulting in reduced net thrust, hence requires increase in fuel burn to balance the needed thrust. At lower altitude, ram temperature rise effect, causes a decrease in the non-dimensional shaft speed $N/\sqrt{T_1}$ and the temperature ratio $TET/\sqrt{T_1}$ therefore require increase fuel burn to balance the drop in net thrust. This account for the high SFC at lower altitude as the flight Mach number increases as shown in Figure 4-4.

The day temperature has significant effect on the engine performance since the aircraft is constantly moving from regions of hot temperature to regions of cold temperatures and svisce versa. As an engine moves from a standard day ISA (International Standard Atmosphere) temperature to as hot day ISA temperature, the work required by the compressor increases since it is easier to compressor cold air than a hot air. For an engine operating at constant TET, the non-dimensional rotational speed $N/\sqrt{T_1}$ decreases as well as the spressure ratio and temperature ratio. This leads to decrease in thermal efficiency and a consequent reduction in net thrust as shown in Figure 4-5.

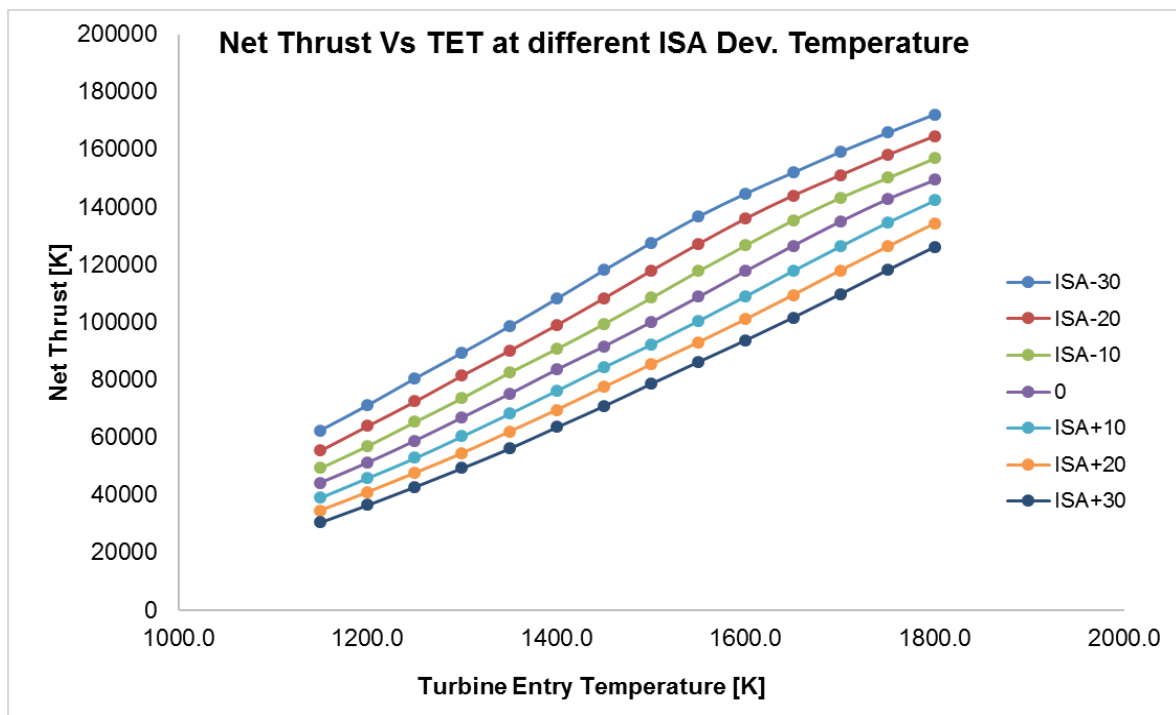


Figure 4-5: Net Thrust Vs TET at different ISA Dev. Temperature

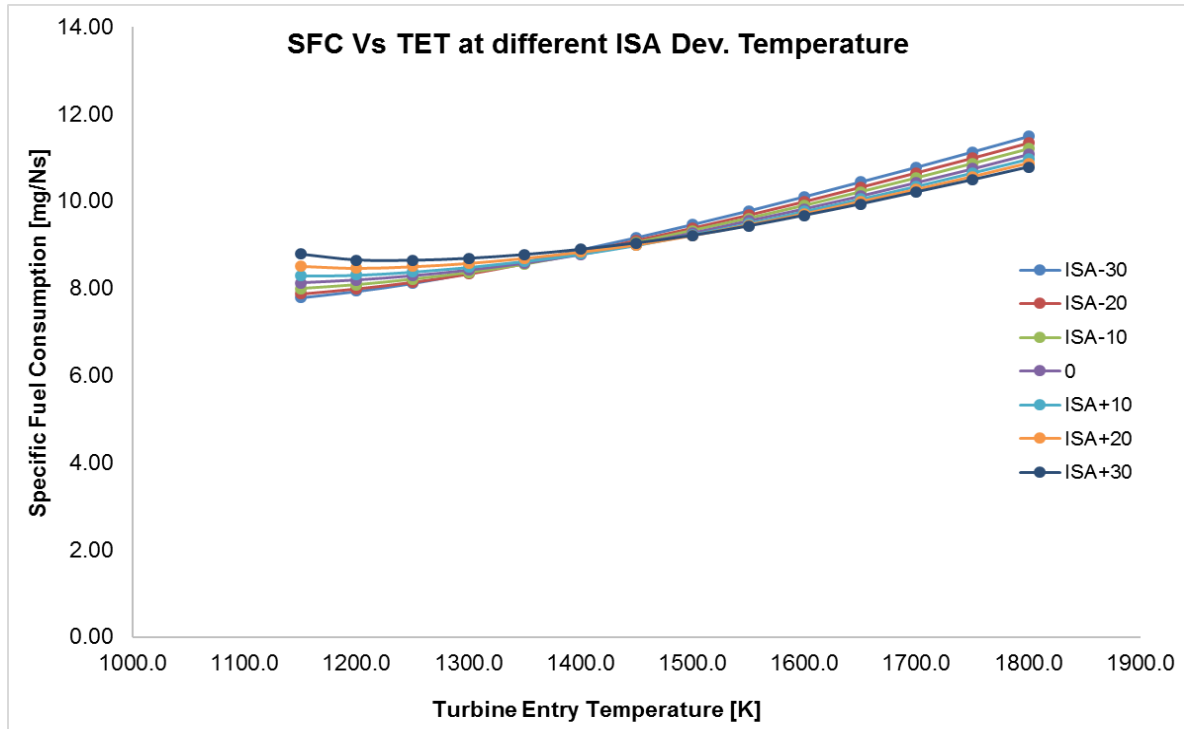


Figure 4-6: SFC Vs TET at different ISA Dev. Temperature

4.2 Performance Model of CEUP6-80Type Engine

The baseline engine deployed for the implementation of the ODIFD (off design increased fan diameter) upgrade is based on a high bypass two spool turbofan engine in the 310 KN thrust class. The engine model was inspired by the CF6-80E1 engine configuration, which consist of a single-stage fan and 4-stage booster (LP compressor) connected to the same shaft driven by 5-stage LP turbine, and the 14-stage HP compressor is dsriven by 2-stage HP turbine. The combustion chamber is incorporated with a single annular combustor, rolled ring construction and film cooling. The pictorial diagram of the engine is illustrated in Figure 4-7.



Figure 4-7: Diagram of CF6-80E1 engine [79]

4.2.1 Design Point (DP) Simulation of CEUP6-80 Engine

The engine design-point performance computation was simulated at standard sea-level take-off condition (i.e., ISA+10) in TURBOMATCH using engine design parameters obtained from the public domain [12] as presented in Table 4-3. The simulation was performed by iterating TET, component pressure ratios and component efficiencies of the engine. Table 4-4 shows the model verification through comparison between the engine real value from public domain and simulated value. The error value shows the degree of accuracy of the simulation; however, the author has considered the accuracy reasonably sufficient for this work although better accuracy can be achieved by further iteration.

Table 4-3: CEUP6-80 Engine Design Parameters

<u>Design point data</u>	<u>Unit</u>	<u>Value</u>
Design point Altitude	[m]	0.0
Take-off thrust	[KN]	310.46
Take-off Mass flow	[Kg/s]	873.6
Take-off fuel flow	[Kg/s]	1.09
Take-off TET	[K]	1699
Take-off BPR	[-]	5.3
Cruise Net Thrust	[KN]	50.441
Cruise SFC	[mg/Ns]	15.848
Cruise TET	[K]	1405
Cruise Mass flow	[Kg/s]	353.762
Cruise Flight Mach No.	[-]	0.82
Fan Pressure ratio	[-]	1.7
Booster Pressure ratio	[-]	2.4
Overall Pressure ratio	[-]	34.8
Compressor Isentropic efficiencies	[-]	0.85
Turbine Isentropic efficiencies	[-]	0.92
Combustion Fractional Pressure Loss	[-]	0.05
HPT Bleeds	[%]	10

Table 4-4: CEUP6-80 Engine Model Verification

<u>Parameter</u>	<u>Real Data</u>	<u>Simulated Data</u>	<u>Error [%]</u>
Take-off Thrust [KN]	310.46	310.94	0.155
Peak Cruise Thrust [KN]	50.40	50.441	0.08
Take-off SFC [mg/Ns]	9.327	9.3437	0.179
Take-off Mass Flow [Kg/s]	873.6	873.6	0.00

4.2.2 Off-Design Point (OD) Simulation of CEUP6-80 Engine

The off-design performance of CEUP6-80 engine was evaluated at different operating and environmental conditions during the different flight phase of the aircraft missions (such as different operating altitudes above sea level, varying flight Mach number and ISA temperature deviation). The effect of varying the

flight altitude, Mach number and TET on engine net thrust and SFC are presented in appendix A.1.

4.3 Performance Model of CEUP772B-60Type Engine

The engine model is a high bypass three-spool turbofan engine in the 310KN thrust class. The models code-name ‘CEUP772B-60’ (Cranfield Engine Upgrade Project) is inspired by the Trent 772B-60 engine, an established powerplant with over 40 million in-service hours [12]. The engine configuration shown in Figure 4.6, consist of a 1-stage low pressure (LP) wide-chord fan, 8-stage IPC, 6-stage HPC, 4-stage LPT, 1-stage IPT and 1-stage HPT incorporated with 24 fuel injector single annular combustion chamber.

4.3.1 Design Point (DP) Simulation of CEUP772B-60 Engine

The engine design point (DP) performance model was created and simulated in TURBOMATCH based on the design parameters from public domain presented in Table 4-5. The accuracy of the model is checked by comparing the result with real engine data as shown in Table 4-6. The deviation between these values is below 1% except for the take-off mass flow rate, which has a higher margin of

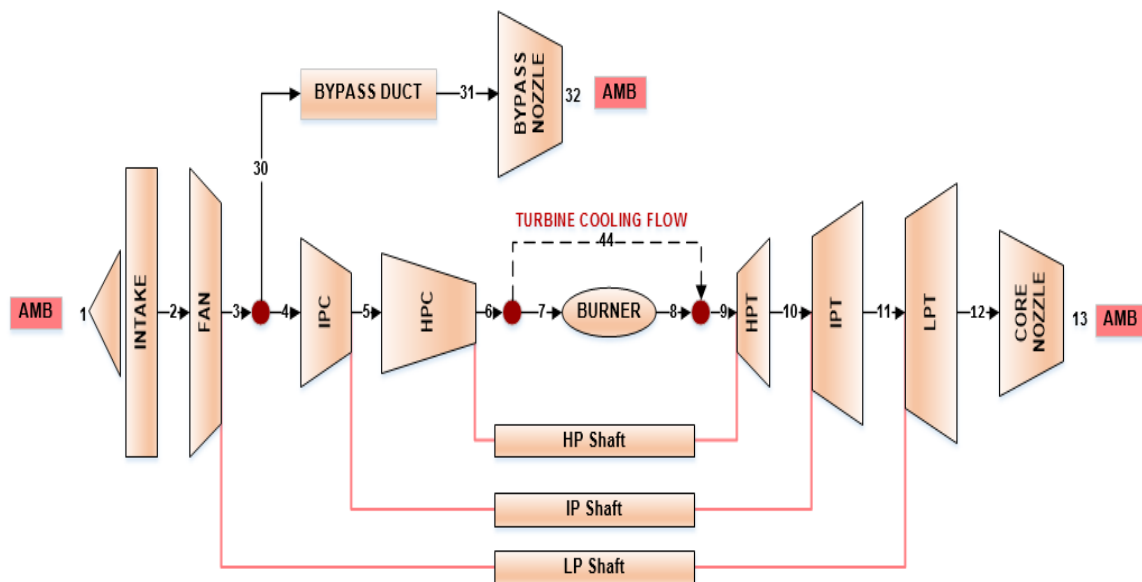


Figure 4-8: Schematic diagram of CEUP772B-60 Engine Model

Table 4-5: CEUP772B-60 Engine Model Design Parameters

<u>Design point data</u>	<u>Unit</u>	<u>Value</u>
Design point Altitude	[m]	10,668
Take-off thrust	[kN]	316.586
Take-off Mass flow	[Kg/s]	886.856
Take-off fuel flow	[Kg/s]	3.0247
Take-off TET	[K]	1638
Take-off BPR	[-]	5.03
Cruise Net Thrust	[kN]	53.513
Cruise SFC	[mg/Ns]	15.896
Cruise TET	[K]	1368
Cruise Mass flow	[Kg/s]	333.9
Cruise Flight Mach No.	[-]	0.82
Fan Pressure ratio	[-]	1.8
ICP Pressure ratio	[-]	6.031
Overall Pressure ratio	[-]	35.5
Compressor Isentropic efficiencies	[-]	0.91
Turbine Isentropic efficiencies	[-]	0.92
Combustion Fractional Pressure Loss	[-]	0.05
HPT Bleeds	[%]	10

Table 4-6: CEUP772B-60 Engine Model Verification

<u>Parameter</u>	<u>Real Data</u>	<u>Simulated Data</u>	<u>Error [%]</u>
Take-off Thrust [kN]s	316.30	316.59	0.09
Cruise Thrust [kN]	53.51	53.51	0.01
Cruise SFC [mg/Ns]	15.86	15.90	0.23
Take-off Mass Flow [Kg/s]	921.00	886.86	3.71

3.707%. It is in the author's opinion that this error can be improved by further iteration of assumed parameters, but because of time constraint and its negligible effect on the performance of upgraded engines, it was considered sufficient for the work. The off-design performance of the engine follows the same trend as the CEUP56 and CEUP6-80 above and the impact of fligsht altitude, Mach

number and ISA temperature deviation on net thrust and SFC is shown in appendix A2.

4.4 Aircraft Performance Modellings

The performance simulation of the aircraft model was carried out in HERMES software; a Fortran-based code developed in Cranfield University for the simulation of an integrated aircraft-engine system performance. HERMES consists of aircraft aerodynamic and performance models while utilising results of engine simulation from TURBOMATCH code. The software works by using specified input data concerning the aircraft, the mission profile and the engine specification, to calculate the aircraft and engine performance throughout the entire mission including each segment of the flight path. Its file structure is grouped into the aircraft and engine group, with each group containing all input/output files and the executables of HERMES code and TURBOMATCH code respectively. A TmatchCalls routine is also embedded as part of the code to automatically retrieve engine performance data from TURBOMATCH to be used in HERMES

The aircraft model utilises engine weight, dimension and performance parameters as input data to predict the block fuel of a given payload-range requirements for the total flight mission profile and have the capability of simulating different aircraft types both existing and conceptual [41][81].

The user defines the mission profile and specifies the climb schedule, cruise speed, altitude (including any step cruise requirements) and descent schedule of the aircraft [41]. The simulation results include among others the fuel used during the mission, distance covered, duration and SFC of engine at different phase of the mission.

4.4.1 Aircraft Weight Categorization

The HERMES performs aircraft performance calculation using the aircraft weight, dimensions (aircraft Wing, Tail, fin, fuselage, and engine geometries) and engine performance characteristics. The certified weight and dimensions for an aircraft can be obtained from the aircraft manufacturer's documents such as Aircraft flight

manual (AFM) and Aircraft weight & Balance manual (AWBM). Figure 4-9 and Figure 4-10 presents a typical aircraft weight build up and categorization [54][83].

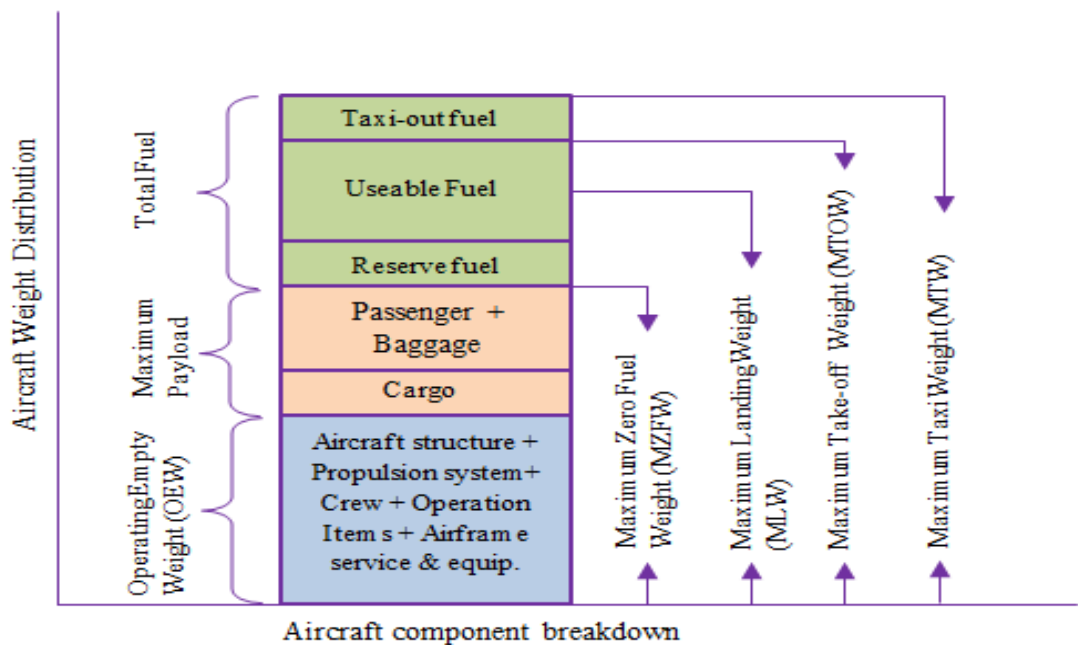


Figure 4-9: Aircraft Weight Build-up [83]

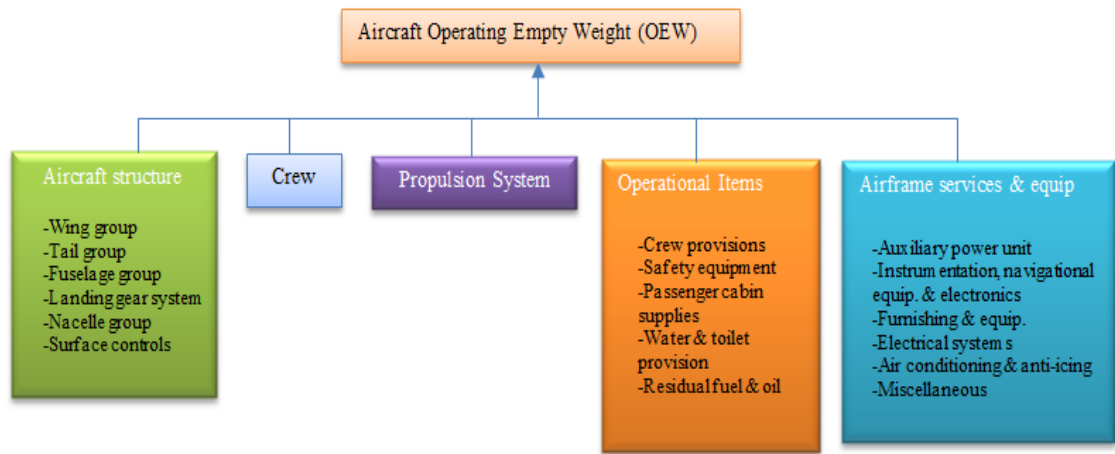


Figure 4-10: Aircraft Operating Empty Weight (OEW) Component Breakdown [83]

Maximum Taxi Weight (MTW): This is the maximum weight of the aircraft for ground manoeuvre as limited by airplane strength and airworthiness requirements. (It includes fuel weight for taxiing to the point of take-off).

$$MTW = MTOW + \text{Taxi-out fuel}$$

Maximum Take-off Weight (MTOW): This is the weight of the aircraft at the point where take-off starts. It is also limited by the airplane strength and airworthiness directives. $MTOW = MZFW + (\text{Reserve fuel} + \text{Useable fuel})$

Maximum Landing Weight (MLW): This is the maximum weight of the aircraft at landing; it is also certified for airplane strength and airworthiness requirement. $MLW = MZFW + (\text{Reserve fuel} + \text{Fuel added but not used})$

Maximum Zero-Fuel Weight (MZFW): It is the maximum aircraft weight permitted before any useable and reserve fuel is added to it. The MZFW is certified based on the airplane strength and airworthiness directives.

$$MZFW = \text{Maximum Payload} + \text{OEW (Operating Empty Weight)}$$

4.4.2 Aircraft Model

The aircraft models deployed for the investigations in this project are the representative prediction of a short-range narrowbody Boeing 737-900 and long-range widebody Airbus A330-200 aircrafts code-name 'Cranboe B737 and Cranbus A330', respectively. The airplane models were created and performance simulations carried out in HERMES with design parameters obtained from public domain [85][86] as shown in Table 4-7. The Cranboe B737 is a twin-engine with a MTOW (without winglet version) of 74,389Kg and 177-passenger two-class seating arrangement. The Cranbus A330 has a MTOW of 230,000Kg in a 247 seats at 105Kg per pax + baggage.

Table 4-7: Aircraft Model Specification

<u>Design Parameters</u>	<u>Units</u>	<u>Cranboe B737</u>	<u>Cranbus A330</u>
Maximum Take-off Weight (MTOW)	Kg	74,389.00	230,000.00
Maximum Zero Fuel Weight (MZFW)	Kg	62,733.68	180,726.24
Operating Empty Weight (OEW)	Kg	40,966.68	120,496.00
Airframe Weight	Kg	36,234.88	111,000.00
Maximum Landing Weight (MLW)	Kg	66,361.00	180,000.00
Thrust per Engine	KN	121.47	316.586
Maximum Fuel Capacity	Kg	20,894.00	71,818.43
Fuselage Length	m	40.67	65.60
Fuselage Diameter	m	3.76	5.64
Wing Span	m	34.32	60.30
Aspect Ratio	-	9.4	10.1
Cruise Altitude	m	10,668.00	10,668.00
Passenger Capacity (3-class seating)	pax	177	283
Maximum Operating Mach Number	-	0.80	0.82

4.4.3 Payload-Range Diagram

In order to verify the accuracy of the aircraft models created using HERMES, the payload-range diagram of the aircraft-engine system was prepared and compared with published data from Boeing and Airbus [86][85]. The payload-range diagram defines the aircraft-operating envelope using three main range-points. These are the maximum payload range, maximum fuel range and the ferry range. Maximum payload range defines the maximum range that can be flown by the aircraft when carrying maximum payload (Max Payload = MZFW – OEW). The maximum fuel range and the ferry range are the maximum range the aircraft can fly at full fuel remainder payload and full (maximum) fuel zero payload respectively. Figure 4-11 and Figure 4-12 shows a typical payload-range diagram for the Cranboe B737 and Cranbus A330 airplanes respectively, for a cruise altitude of 35,000/39,000ft (10,668/11,887m), cruise Mach number of 0.8, temperature deviation ISA + 10°C, 10% contingency fuel, 200nm (370Km) diversion and 30 minutes hold at 1,500ft. The diagrams show a reasonable

correlation of the airplanes model with the Airbus and Boeing data at different range, with a maximum deviation of less than 2%. However, It is worth noting that the maximum fuel range was not included in Figure 4-12 for the CEUP6-80 engine and Cranbus A330 aircraft combination since the Airbus airport planning data [85] the model is compared with did not provide that detail.

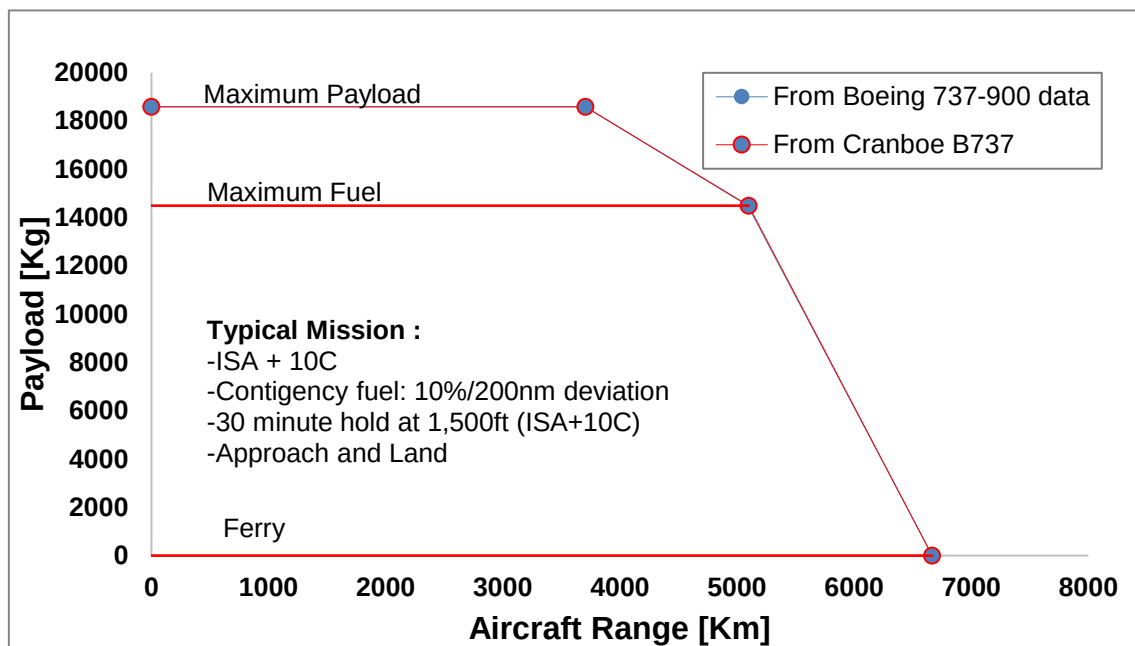


Figure 4-11: Payload-Range diagram for Boeing 737 and Cranboe B737 Aircraft Models

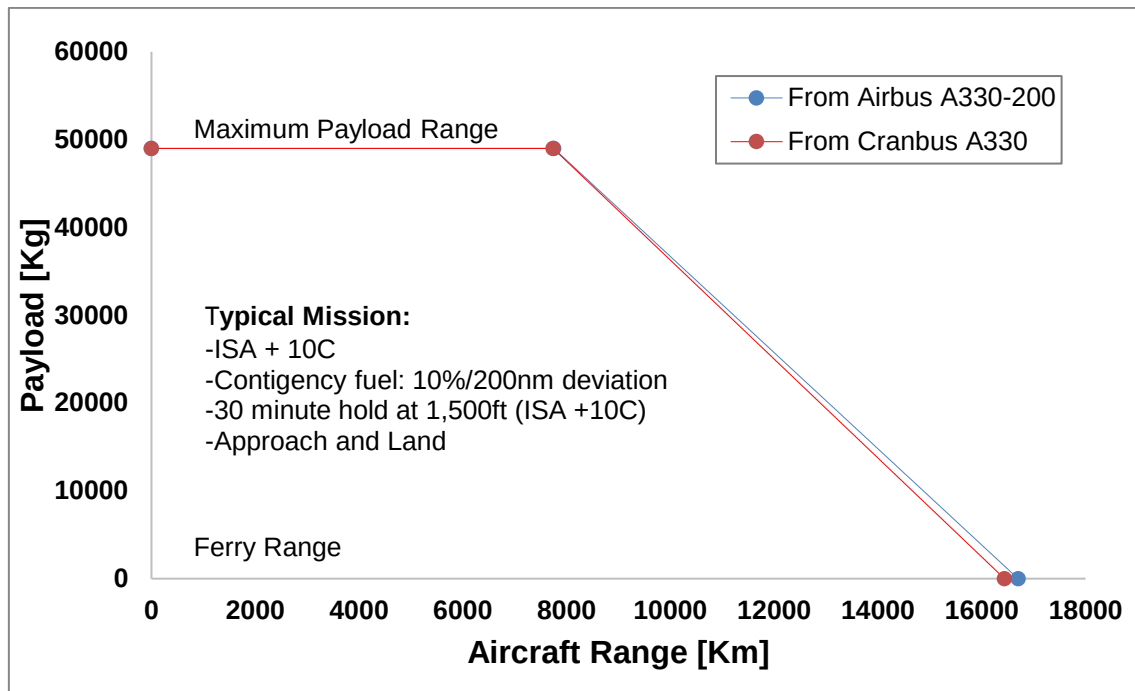


Figure 4-12: Payload-Range diagram for Airbus A330-200 and Cranbus A330 Aircraft Models

Chapter Five

TERA of Aircraft Engine Upgrade from User's Perspective

5. Introduction

This chapter presents a TERA (Techno-economic Environmental Risk Assessment) assessment of the potential performance and economic benefits of engine technology upgrade as a viable investment option for existing airline operators. The primary emphasis is placed on the “Thermal barrier coating” upgrade Case study: an evaluation performed from the perspective of the airline owner (or User). Thermal barrier coating improvement was offered for the overhaul life extension of an ageing civil aircraft engine. The upgrade was evaluated for this original intention, in addition, the potential for higher thrust, which enables increase payload, reduced runway length requirement, or possible aircraft range extension. To represent the upgrade, six hypothetical TBC options are assumed. Lower thermal conductivity ($K_{\text{tbc}} = 1.62, 1.44, 1.26, 1.08, 0.9$ and 0.72W/mK) is assumed to represent improved TBC effectiveness. The effect of this upgrade was examined on the CEUP56 turbofan engine modelled in TURBOMATCH and the Canboe B737 aircraft model simulated in HERMES. The results show quantitative estimates of upgrade effectiveness and the relationship with engine-aircraft performance parameters.

5.1 Brief Background

Aircraft engine operators with ageing and mid-life assets are frequently offered upgrades to deliver benefits. Some upgrades are mandatory: airworthiness directives (AD) to address safety while others are optional (service bulletins – SB) to meet specific operational demands, such as a fuel-burn improvement, performance enhancement and/or engine life extension. During shop-visits these

upgrades could be implemented to improve economics and/or to address a wide range of issues [51]. For example, improved thermal barrier coatings may be implemented as a retrofit to improve the maintenance costs by reducing turbine blade metal temperatures. Alternatively, a coating could be used to improve performance keeping the same metal temperatures. Many, especially smaller operators, lack the analytical tools to carry out an effective cost-benefit analysis for upgrades they may be offered. The work described in this chapter aims to fill this gap and outlines a method to carry out a quantitative evaluation of the performance outcomes and alternative uses of aircraft engine upgrades. This was achieved via the careful adaptation and assembly of a collection of a wide range of technical models.

Example: a hypothetical TBC upgrade

To illustrate the use of the method, the technical component of the TERA is adapted and deployed. As an example, a hypothetical high-pressure turbine (HPT) thermal barrier coating (TBC) upgrade is examined. TBCs are widely used to protect engine parts from the heat of the gas stream. A TBC reduces the metal temperature of many engine components. TBCs deployed alongside advanced cooling systems have been reported to achieve satisfactory operation in gas temperatures in excess of 250°C above the superalloy melting temperature [87][29]. They are designed to withstand high temperatures and cyclic thermal loading and stresses. Given the benefits they deliver, TBCs are continuously upgraded as a result of intensive research and development investments [88][89][90].

5.2 Method Description

As stated, the objective of the investigation is to identify and quantify the benefits of a TBC upgrade on aircraft engine performance with respect to life extension, payload improvement, range extension (increase fuel economy) and shorter take-off length distance.

The Techno-economic Environmental Risk Assessment (TERA) has been adapted to investigate and quantify the potential performance outcomes for aircraft engine through investment in thermal barrier coating (TBC) upgrades. The TERA tool is a multidisciplinary evaluation framework that provides very valuable insights into performance analysis and limitations of competing technologies. The framework is an efficient coupling of several modules such as performance, economics, environmental and risk analysis modules. The TERA methodology adapted for this TBC upgrade assessment study was presented in Figure 3-1. It comprises aircraft performance, engine performance, blade sizing/geometry, cooling/TBC upgrade, component lifing and economic model.

The quantitative analysis of the impact of TBC upgrades on engine performance and the potential for operational flexibility to evaluate benefits was investigated, using six hypothetical TBC upgrade options with different values of thermal conductivity, ($K_{\text{tbc}} = 1.8, 1.62, 1.44, 1.26, 1.08, 0.9$, and 0.72 W/mK for a $200 \mu\text{m}$ thick EB-PVD type. The K_{tbc} -values represent improvement in TBC technology, from baseline or commercially available technology ($K_{\text{tbc}}=1.8 \text{ W/mK}$) to advanced future technology ($K_{\text{tbc}}=0.72 \text{ W/mK}$), examined as concepts or prototypes in research laboratories [89].

The integration phase uses results from these models to estimate the benefits of the upgrade in terms of engine life-extension, increasing thrust, payload improvement and economic impact associated with the operational flexibility due to TBC upgrade.

5.3 Result Analysis

5.3.1 Blade cooling and TBC Upgrade

A simple and approximate blade cooling model comprising a combination of convection, film cooling and TBC inclusion was developed in accordance with empirical equations discussed in chapter 3. The model utilized parameters from the blade sizing and engine performance models, film cooling efficiency, ε_f blade metal Biot number, Bi_m and TBC thermal conductivity, K_{tbc} as shown in Table 5-1, to predict the blade metal temperature, T_m , temperature change across TBC, ΔT_{tbc} and overall cooling effectiveness, ε_0 of the engine. To estimate the impact of TBC upgrade on the engine, a parametric analysis of the different TBC upgrade options was implemented through the cooling model by correspondingly varying the TBC K_{tbc} -values ($K_{tbc} = 1.8, 1.62, 1.44, 1.26, 1.08, 0.9$, and 0.72W/mK) representing TBC upgrade options.

Table 5-1: Cooling and blade sizing parameters

<u>Parameter description</u>		<u>Values</u>
Gas stream temperature[K]	T_g	1620
Coolant inlet temperature[K]	$T_{c,in}$	818.36
Adiabatic film efficiency	ε_f	0.5
TBC thermal conductivity[W/m2/K]	K_{tbc}	1.8
TBC thickness[m]	Δ_{tbc}	0.0002
Metal Biot number	Bi_{met}	0.2
Mean diameter[m]		0.65178
Blade chord [m]		0.02196
Height to chord ratio		1.45
LE/TE radius		1.5474
Inlet annular area [m ²]		0.1079
Stagger angle [deg]		35
Flow coefficient		0.28
Stage loading		1.56

Figure 5-1 shows that as TBC K_{tbc} -values decreases at constant thickness the overall cooling effectiveness and temperature change across TBC increases. The impact of varying the film cooling efficiency, ε_f and TBC thickness, Δ_{tbc} on the blade cooling performance is also illustrated. The TBC insulating effect by lowering the effective heat transfer coefficient, U_g through the decrease in TBC K_{tbc} -values and consequent increase of TBC Biot number is shown in Figure 5-2.

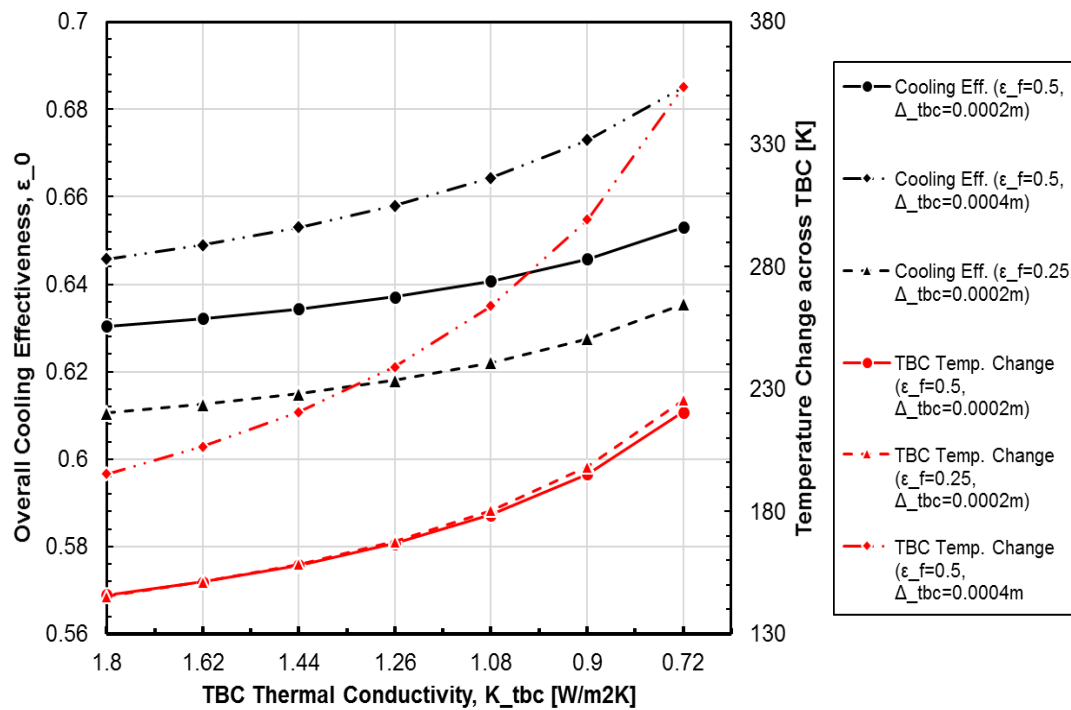


Figure 5-1: Effect of thermal conductivity, TBC thickness and film efficiency on Overall Cooling Effectiveness

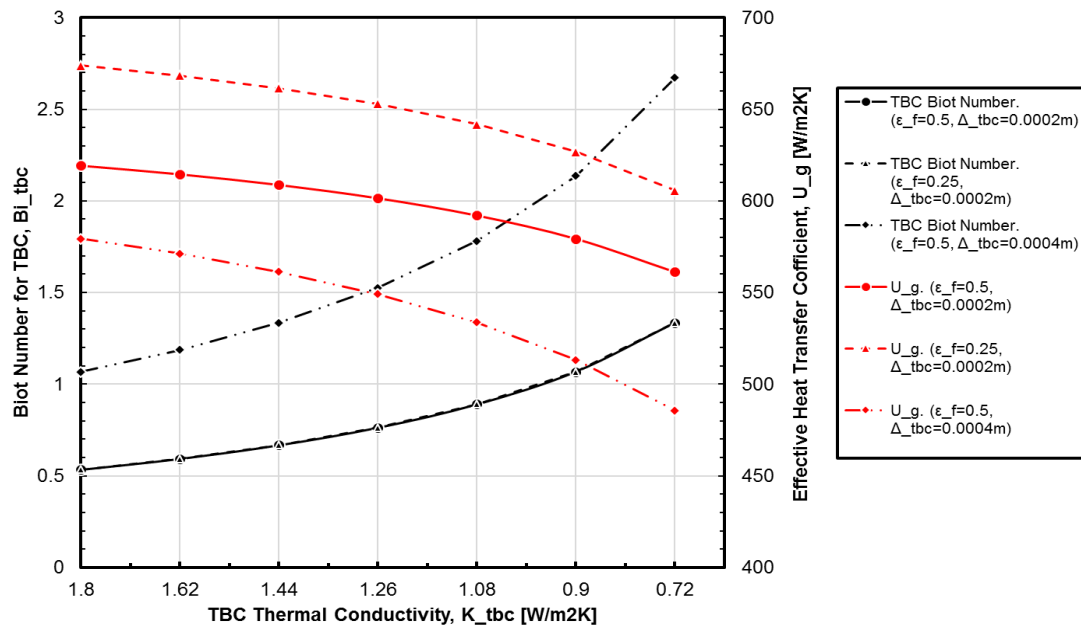


Figure 5-2: Effect of TBC thermal conductivity and Effective heat transfer coefficient on TBC Biot Number

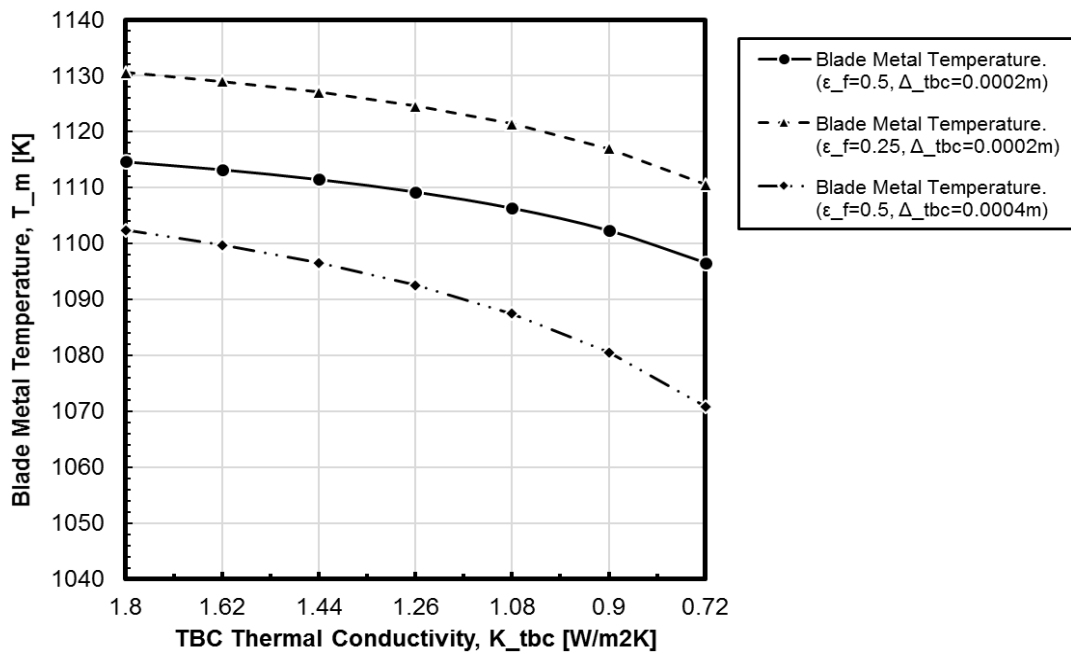


Figure 5-3: Effect of TBC thermal conductivity, TBC thickness and film cooling on blade metal temperature

Figure 5-3 presents the combined effect of the cooling and TBC upgrade (increased TBC effectiveness) through decrease in K_{tbc} -value on the HP turbine blade metal temperature. The figure also illustrates the effect of increased TBC thickness and reduced film cooling efficiency on the blade metal temperature. Since TBC lowers engine HPT blade metal temperature by shielding the component material from the hot path gas stream, thereby increasing the operating life of the blade. As TBC effectiveness increases the temperature change across TBC, ΔT_{tbc} increases as well as the overall cooling effectiveness, ε_o , hence resulting in the drop of blade metal temperature and a corresponding rise in engine life or time between overhaul (TBO). Therefore, Increase TBC effectiveness can allow increased engine operating temperature without any significant change in engine life.

Figure 5-4 shows the effect of increased TBC effectiveness on the temperature change across TBC, ΔT_{tbc} at different thermal load or engine operating peak temperature (TET). The trend reveals that ΔT_{tbc} increases with decreasing TBC K_{tbc} -value, from ΔT_{tbc} (145.878K) at $K_{tbc}=1.8\text{W/mK}$ (baseline) up to 220.729K at $K_{tbc}=0.72\text{W/mK}$ (TBC upgrade Type-F) for the baseline engine TET of 1620K. As thermal load increases the ΔT_{tbc} also increases, an effect attributed to the increased cooling airflow due the rise in engine mass flow associated with the increase in TET. Similarly, Figure 5-5 presents the corresponding response of the overall cooling effectiveness to TBC upgrade at different thermal loads (TET). The overall cooling effectiveness increases with TBC effectiveness but deteriorate rapidly with increase thermal load (TET). This is due to the high temperature coolant air (compressor exit air) which adversely affects the cooling benefit.

The increase in ΔT_{tbc} and ε_o due to decreasing K_{tbc} -values (higher TBC effectiveness) results in a reduction in blade metal temperature as shown in Figure 5-6. The increasing drop in blade metal temperature across the TBC upgrade was a result of the increasing ΔT_{tbc} and ε_o with rising TBC effectiveness.

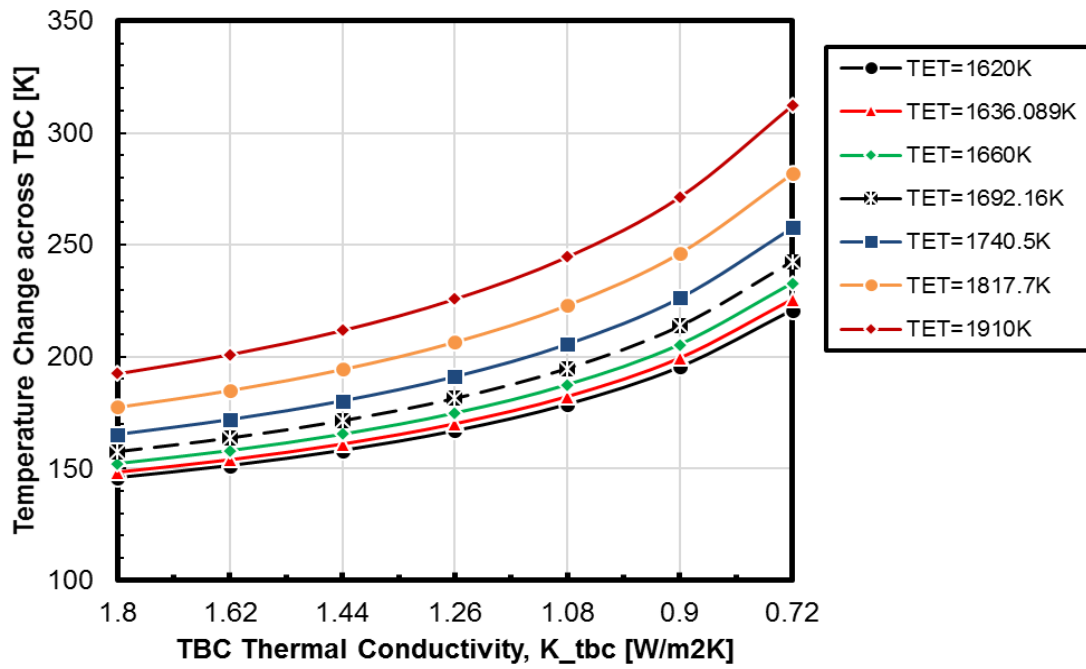


Figure 5-4: Effect of TBC thermal conductivity on temperature change across TBC at different TET

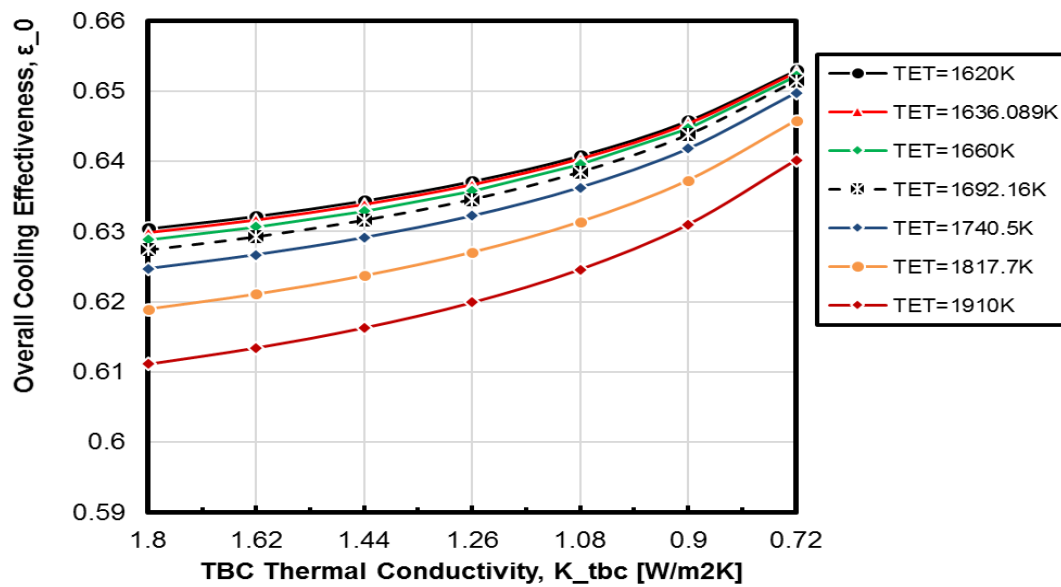


Figure 5-5: Effect of TBC thermal conductivity on Overall cooling effectiveness at different TET

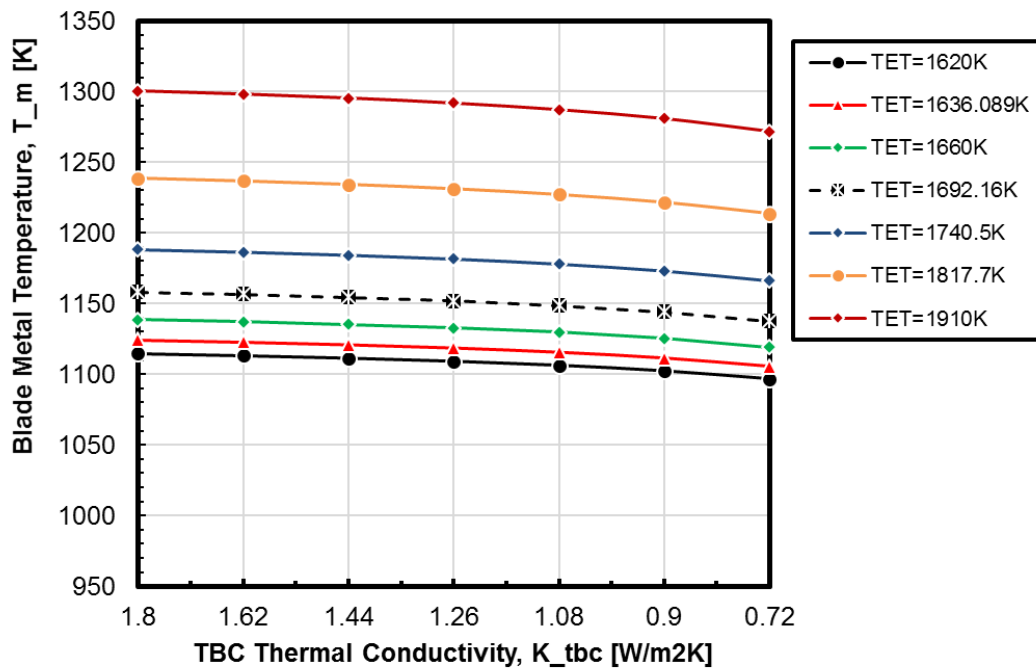


Figure 5-6: Effect of TBC thermal conductivity on Blade metal temperature at different TET

As TBC upgrade effectiveness increases the heat reaching the blade metal is reduced therefore lowering the cooling airflow temperature injected into the cooling film resulting in a more effective overall film cooling system. The blade metal temperature increases with higher engine peak operating temperature (TET) as shown in Figure 5-6. It is worth mentioning that the TET (1620K, 1636.089K, 1660K, 1692.16K, 1740.50K, 1817.70K and 1910K) presented in this figures have been iteratively chosen to maintain a constant engine life (TBO) scenario of about 25000 hours for all the upgrades, from baseline to Type-F upgrade respectively, in order to show the operational flexibility TBC upgrade investment offers. The operational flexibility the TBC upgrade offers to an airline, particularly provides the leverage to explore different business operating strategy by using the benefit derived from TBC, for example, the increase thrust increases the capacity of aircraft to carry additional payload (in terms of more cargo or passengers) and also enhance flight in regions of high ambient temperatures. The benefit of shortened take-off distance aircraft capacity with TBC upgrade

provides opportunity for airlines to widen their operating route-network, connecting airports with shorter runway length.

5.3.2 Engine Life Extension from TBC Upgrade

The engine-life extension potential of TBC upgrade is reported in this section. The engine life is considered in this work as the time between overhaul (TBO) of the engine, which is the life limiting part (LLP) failure mode with the lowest value. For the average mission profile for this study as described in previous section, the engine life (TBO) limited by the low-cycle fatigue life of HPT is observe to increase with increased TBC upgrade effectiveness. Figure 5-7 shows the impact of TBC upgrade on the life (TBO) of the engine at constant cooling mass flow and Table 5-2 representing the actual life extension associated with each upgrade technology in both operating hours and percentage increase relative to baseline engine life (TBO) of 25,864 hours. The results show that investment in TBC upgrade options can extend engine operational life by an additional 1,220 to 14,855 hours or by 4.5 to 36.5% increase in engine life respectively, relative to baseline engine life.

Table 5-2: Engine Life Extension (TBO)

TBC-Type	K-Value [W/m ² K]	Δ Life [hrs]	Δ Life [%]
Baseline	1.80	(25,864.54)	
Type-A	1.62	1,220.17	4.5%
Type-B	1.44	2,758.76	9.6%
Type-C	1.26	4,740.27	15.5%
Type-D	1.08	7,337.96	22.1%
Type-E	0.90	10,743.49	29.3%
Type-F	0.72	14,855.19	36.5%

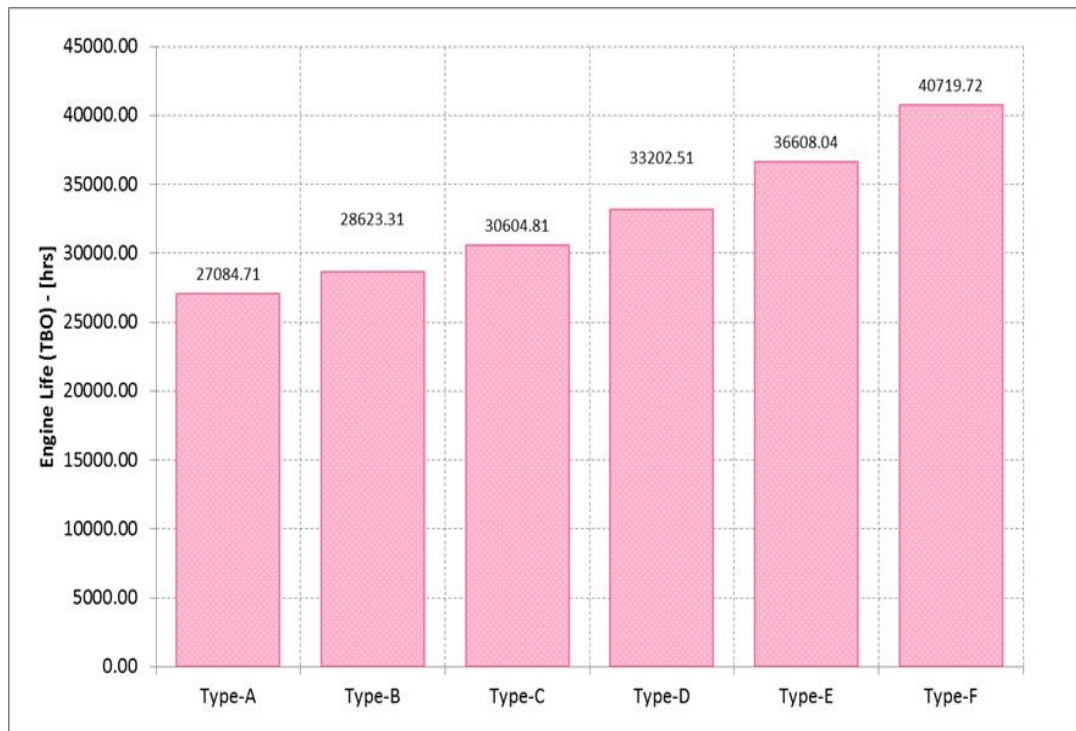


Figure 5-7: Effect of TBC Improvement on Engine Life Extension

This can offer airline operators significant cost savings through reduction in engine maintenance cost and cost of ownership. It is particularly important to commercial airlines operating within the hot and near-desert environment where component degradation is a severe challenge.

The TBC upgrade also provides opportunity for operational flexibility for engine performance improvement. The benefits of additional life gained can be traded-off to increase the maximum engine operating temperature at take-off conditions without compromising the original life of the engine. Figure 5-8 shows the maximum possible increase in engine TET for each TBC upgrade while maintaining a constant baseline engine life and the corresponding increase in take-off thrust produced. Table 5-3 shows that an approximately 290K increase in engine maximum TET and a corresponding 31.4% increase in Thrust could be achieved without sacrificing any engine life; this increase corresponded with the TBC Type-F upgrade

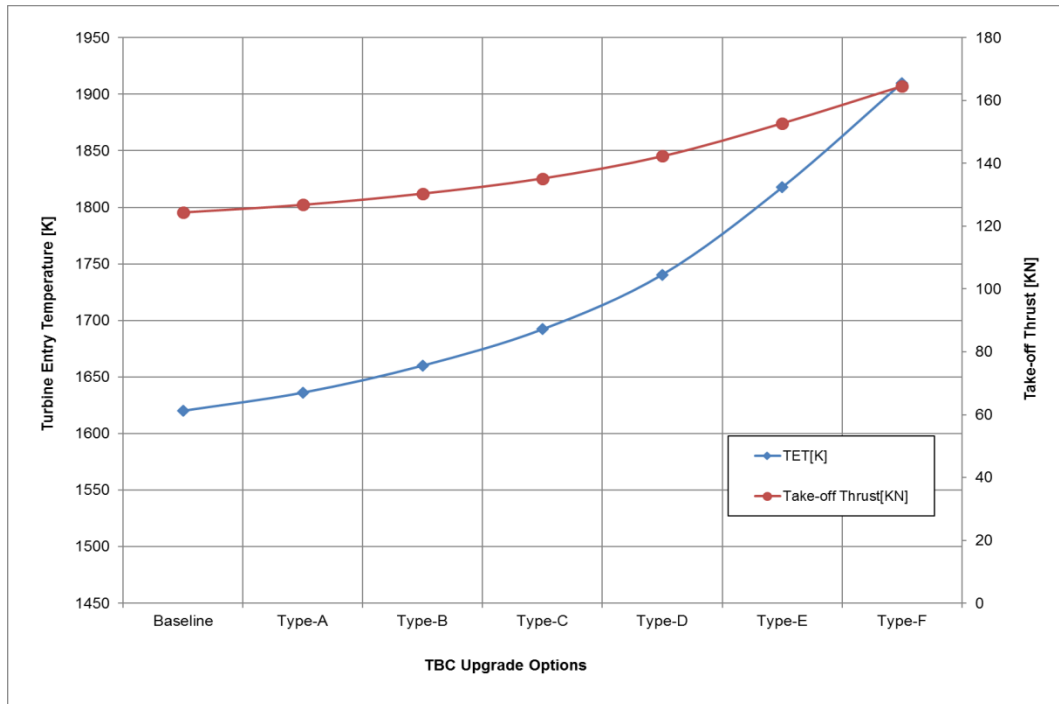


Figure 5-8: Effect of TBC Improvement on TET and Take-off thrust

Table 5-3: Performance Improvement

TBC-Type	Δ TET [K]	Thrust [KN]	Δ Thrust [%]
Baseline	(1620.00)	(124.37)	
Type-A	16.09	126.80	1.96%
Type-B	40.00	130.36	4.82%
Type-C	72.16	135.18	8.70%
Type-D	120.50	142.27	14.39%
Type-E	191.70	152.74	22.81%
Type-F	290.00	164.57	31.40%

5.3.3 Payload Improvement

In addition to the engine-life extension and performance improvement potential of TBC upgrade, increase in engine payload capability is another possible outcome with very attractive economic benefits. The higher take-off thrust

achieved by increasing the engine peak operating temperature (TET), presents the opportunity to carry extra payload within the same aircraft take-off length.

The higher TET was attainable by maintaining the original blade metal temperature (i.e., sacrificing the extra engine life gained) from the TBC upgrade. The additional thrust allows the aircraft to carry extra payload (in terms of carrying additional cargo or passengers), therefore generating additional income per flight. This however, comes with the penalty of additional costs on fuel, emissions and direct operating cost (DOC). The business case is centred on the attractiveness that the income generated per flight due to extra passengers far outweighs the additional operating cost incurred. Figure 5-8 shows the effect of TBC upgrade on increase thrust and the maximum additional payload the engine can carry at constant take-off length. The maximum thrust improvement of 31.40% realised can be utilised to carry an extra payload of about 3485Kg, and correspond to the deployment of the TBC Type-F upgrade technology. It is worth noting that this additional payload (3485Kg) increases the total payload beyond the structurally certified limit allowable for the airplane type considered for this analysis. However, the value is used since the interest here is assessing of the impact of TBC upgrade on engine performance enhancement.

The increased engine payload capability gained allows for carrying more passengers, cargo or fuel. Detail investigation of the economic benefits accrued through any of this routes, may practically require extensive modification/redesign of the aircraft, weight recertification and costs implication to accommodate the additional passengers, cargo containers or an auxiliary fuel tank to maximize the potential benefits. However, the author did not consider this evaluation as it's beyond the scope of this thesis, but rather made a simplified assumption to explore the potential economic benefit for increasing engine payload capability without considering the airframe structural limitations or weight certifications. For carrying extra passengers, Figure 5-10 presents the additional passengers associated with each TBC upgrade. The total weight allocated per passenger is shown in Table 5-4, and the benefit of increase thrust can also be

utilised for carrying the same baseline payload in environment with higher ambient temperatures.

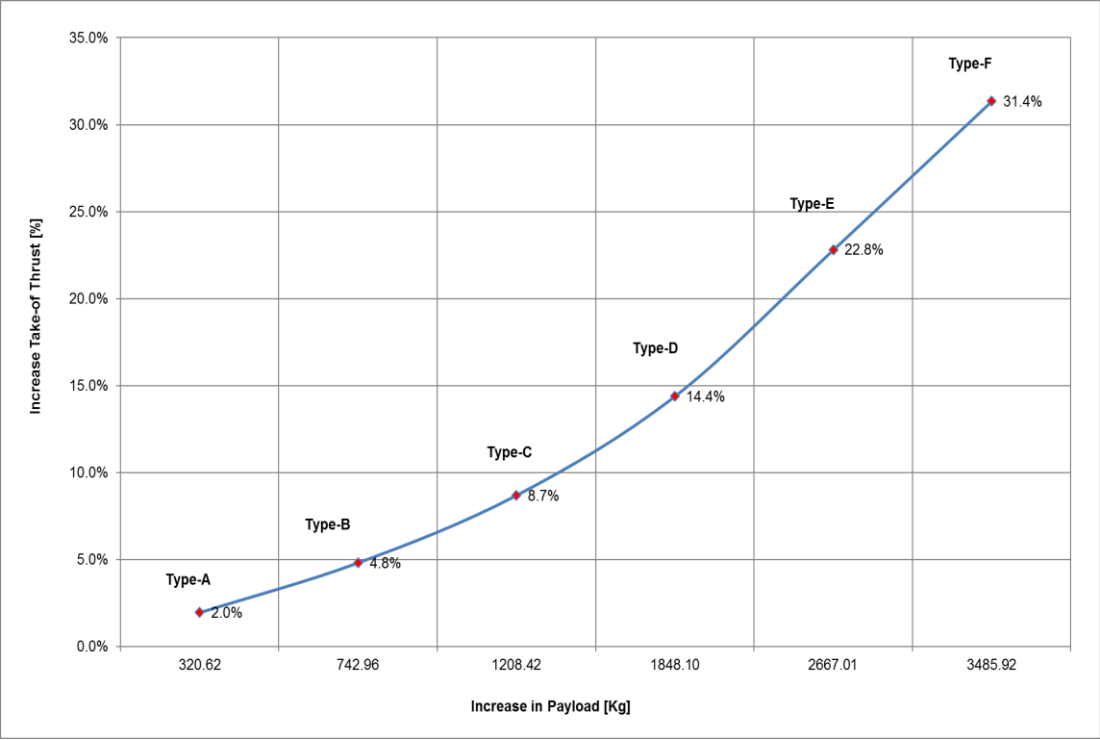


Figure 5-9: Effect of TBC Improvement on Increase Payload and Take-off thrust

Table 5-4: Payload Category [91]

Payload Category	
Passenger	75Kg
Luggage	21Kg
Hand Luggage	9Kg
Total	105Kg

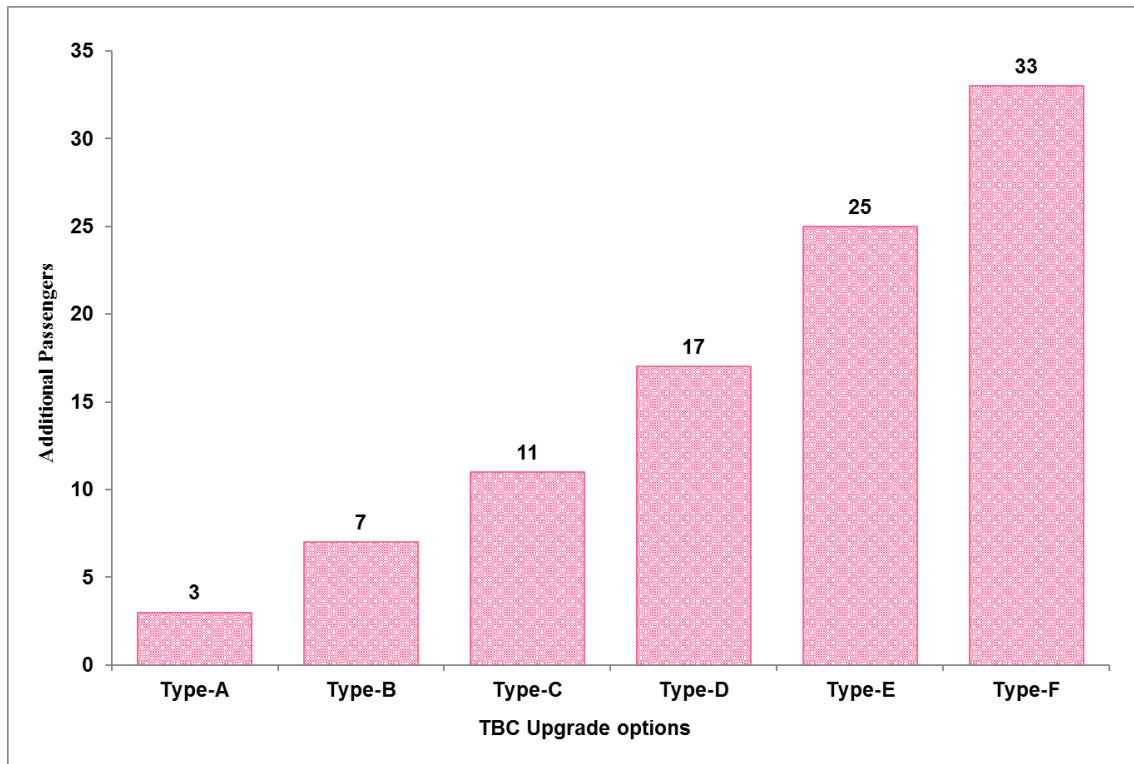


Figure 5-10: Effect of TBC Improvement on additional passenger capacity

5.3.4 Runway Length Reduction

The balance of field length (BFL) normally defines the runway distance requirement for an airplane to take-off. “FAR take-off field length” is the Federal Aviation Administration (FAA) field length specifications for all FAR 25 certified aircraft. It specifies a 35-ft {10.7-m} obstacle clearance threshold and requires the aircraft to meet the minimum BFL or be 15% greater than all-engines-operating obstacle clearance take-off distance. BFL is computed using correlations presented in Raymer et al [92]. The balance of field length (BFL) requirement for the aircraft reduces as the maximum take-off thrust for a constant aircraft weight and ambient conditions increases. The effect of TBC upgrade on take-off thrust improvement and the BFL reduction shown in Figure 5-11 above. As TBC effectiveness increases from Type-A to Type-F upgrade the thrust increased with the corresponding reduction in BFL from 1.739Km to 1.494Km. It is worth stating

however, that the BFL value presented here corresponds to simulation results for the specified aircraft mission payload and range defined earlier, which is below the full payload-range capacity of this aircraft class. Benefit of lower BFL capability to airlines is the ability of aircrafts to take-off/land from airports with shorter runways, therefore creating the potential for increased utilization of flight network.

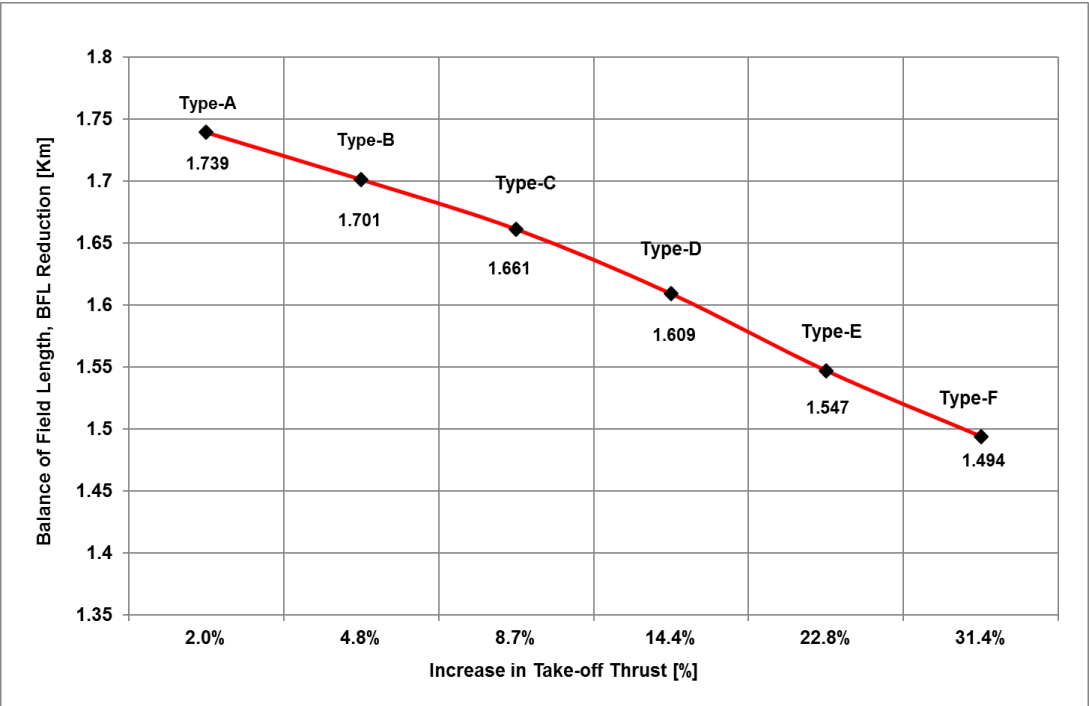


Figure 5-11: Effect of TBC Improvement on BFL

5.3.5 Mission Range Extension

The payload-range diagram defines the operational envelope of an airplane-engine system. A unique tool that characterizes the fuel requirements for a predefined range and take-off weight of the aircraft

Figure 5-12 shows the payload-range diagram for the aircraft model used in this work and its industry resemblance, Boeing 737-900. The model is verify against

public available literature (maximum payload range, maximum fuel range and ferry range values) within an error margin of 1% as shown in Table 5-5.

As discussed previously, the TBC upgrade offers opportunity for increased payload. This additional payload capability allows for aircraft range extension when the extra payload is the weight of additional fuel carried. In civil aircraft, this additional fuel load is accommodated by introducing several auxiliary fuels tanks on the wing and tail structure of the airplane. Figure 5-13 and Figure 5-14 illustrates the potential fuel increase and corresponding range extension associated with each TBC technology. For the same baseline payload (passenger load), the potential fuel increase and the corresponding range-extension associated with each TBC upgrade as shown in Table 5-6, grows from the 320.615Kg fuel increase with 109.11Km range increase for the Type-A upgrade to 3485.9Kg fuel increase and 1154.92Km range associated with the Type-F TBC upgrade.

Table 5-5: Variations in Thrust and Payload with respect to baseline

Parameter	Simulation Value	Real Value	Error [%]
Max. Payload Range [Km]	3705.36	3704	+0.04%
Max. Fuel Range [Km]	5100.92	5093	+0.16%
Ferry Range [Km]	6667.62	6667	+0.01%

Table 5-6: Range Extension due to TBC Improvement

TBC-Type	TET [K]	Δ Fuel [Kg]	Δ Range [Km]
Type-A	1636.09	320.62	109.11
Type-B	1660.00	742.96	251.86
Type-C	1692.16	1208.42	404.50
Type-D	1740.50	1848.10	621.12
Type-E	1817.70	2667.01	886.74
Type-F	1910.00	3485.92	1154.92

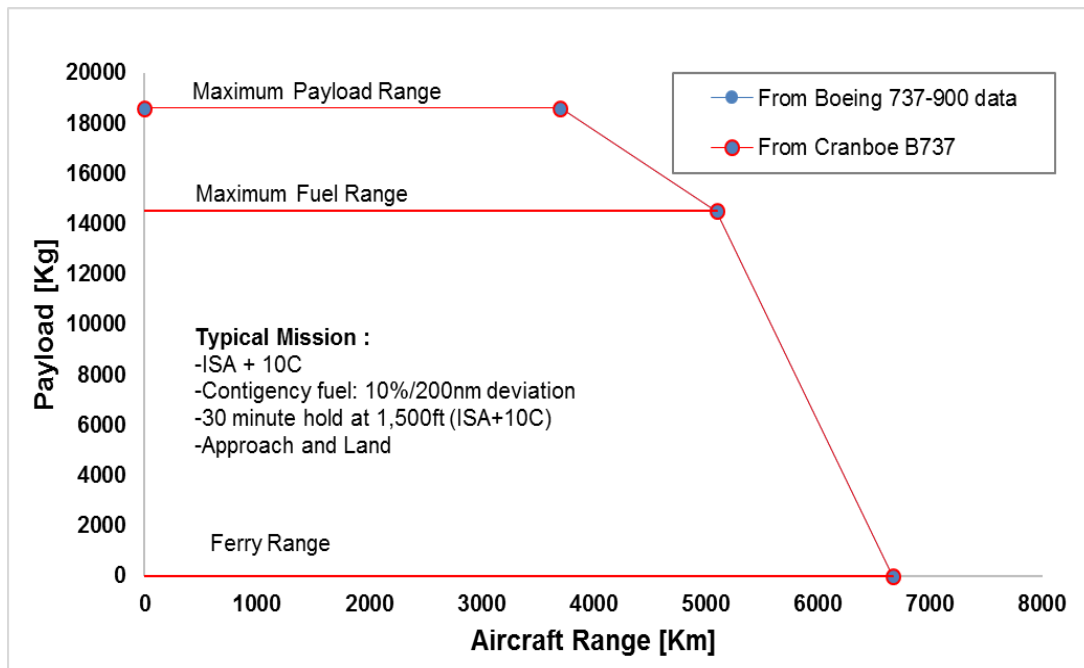


Figure 5-12: Payload-Range Diagram

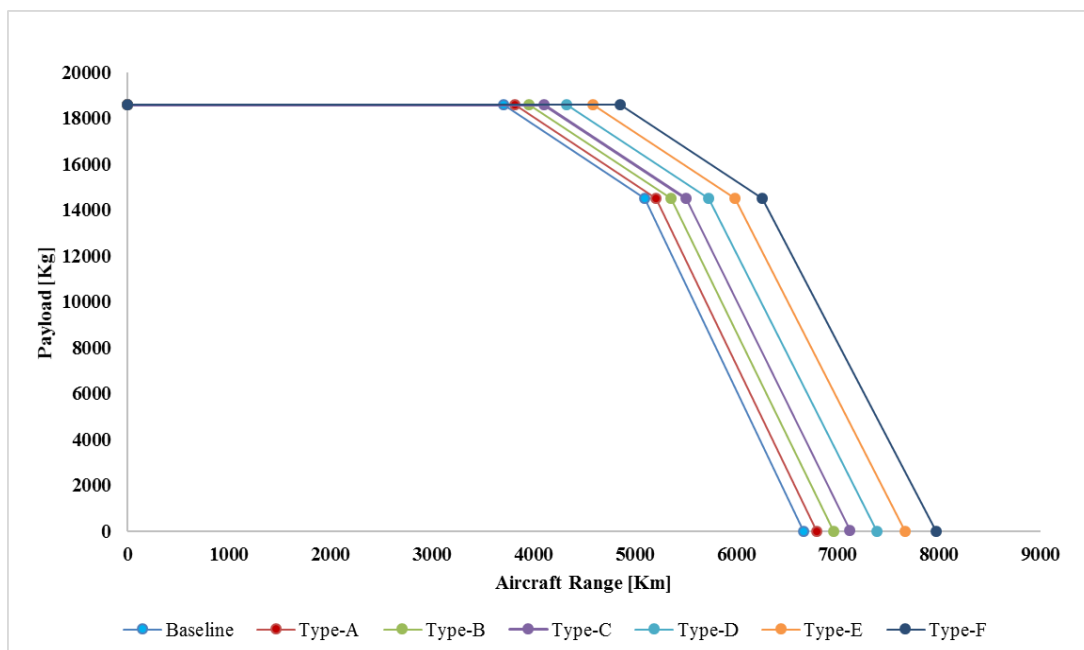


Figure 5-13: Range Extension

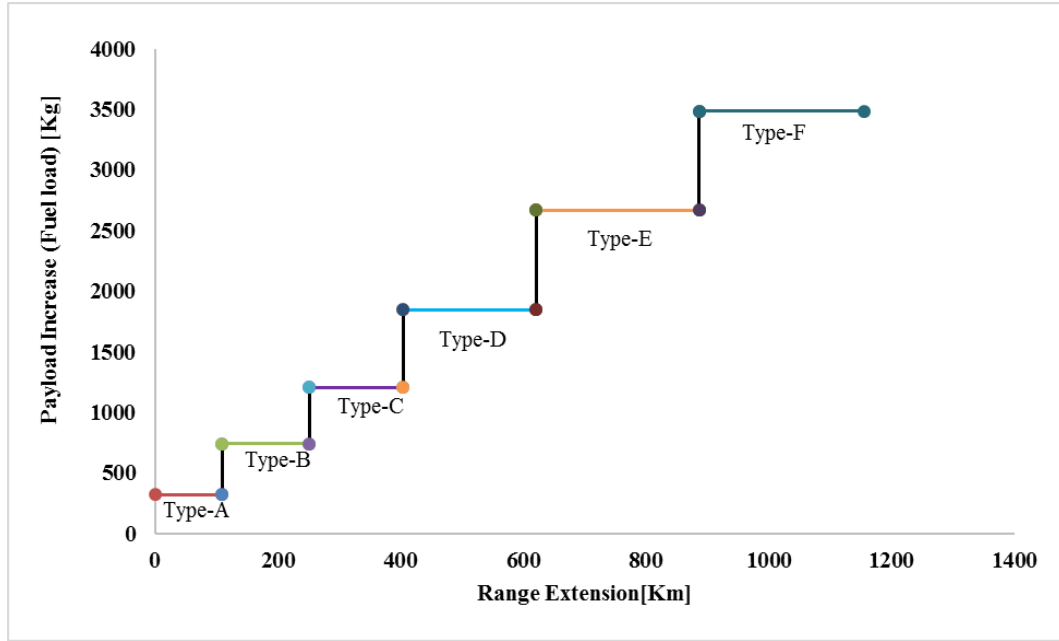


Figure 5-14: Effect of TBC and Range Extension on Payload

5.3.6 Performance Results Summary

This paper evaluates the impact of TBC upgrade on performance outcomes of aircraft engine, in terms of engine-life extension, take-off thrust improvement, and increase payload capability as well as shorter runway requirement and aircraft range extension. Six hypothetical TBC upgrades with effectiveness represented by their thermal conductivities ($\Delta T_{tbc} = 1.62, 1.44, 1.26, 1.08, 0.90$, and 0.72), the highest value indicating the most mature technology already commercially available in advanced systems with reasonable benefits and the lowest value suggesting advanced technologies with the promise of radically disruptive benefits, but only existing as prototypes in laboratories and test centres. Implementation of this study is deployed within the technoeconomic environmental and risk assessment (TERA) framework. The approach is particularly suitable as it carries out a comprehensive evaluation of the systems from a multidisciplinary perspective. The results demonstrated in this thesis focus on the realization of the technical aspect of the evaluation, therefore setting the basis for economic optimization and risk analysis of the systems.

The overreaching conclusion is that the investment in TBC upgrade on aircraft engine yields relative performance benefits compared to baseline engine, for both cases of improvement at constant cooling flow and improvement due to cooling flow reduction. The utilization of TBC upgrade extends engine life, with the maximum improvement limited to 36.5% increase relative to baseline, and corresponds to Type-F upgrade technology. This offers operators the opportunity to lower ownership costs through maintenance costs reduction per flight, therefore generating significant cost savings over time. The extra life attainable because of the TBC upgrade can be traded-off for increase in engine thrust, which in turn enables increase payload and shorten take-off length capability of the engine. A business case could be created with focus on the additional revenue generated from the extra passenger carried per flight and the increased utilization due to route-network expansion.

Finally, the investigation identifies, quantifies and establishes the performance outcomes associated with TBC upgrade and demonstrates opportunity for operational flexibility.

5.4 Economic Results

The decision of an operator to invest on TBC upgrade would normally be based on an effective cost-benefit analysis that satisfactorily meets their economic expectations. In this section, the economic benefit associated with the deployment of each of the TBC upgrade technology within the three-case scenarios considered have been quantified and analysed. This implies capturing the cost penalties and savings advantages associate with the investment. The major costs involve the upgrade capital costs, which are the TBC upgrade acquisition costs previously computed and present in Table 5-7 below. The application of these upgrades on the engine has been assumed through retrofitting during a schedule maintenance shop visit, hence the cost of installation is not considered in this study. The impact of the TBC upgrade technologies on the aircraft engine with regards to the engine life extension, range extension and payload improvement capability are discussed in the following subsections.

5.4.1 TBC Acquisition Costs

In order to estimate the economics of TBC upgrade investment on aircraft engine, the cost components of the upgrade must be determined. TBC acquisition cost is a function of the total development and testing costs, manufacturing costs and price dynamic factors. This study utilizes the EB-PVD TBC coatings commonly used in aircraft engine applications and currently cost around \$120 - \$200 per engine part according to Feuerstein et al [27]. However, it is worth highlighting that the scope of this work did not cover the complete costs estimate of TBC programme from development phase to manufacture and supplies, but only assumes price base on available data on public literature. The acquisition cost of baseline TBC within the considered engine with 80 HPT blades for example, is approximately \$16,000 or €14,240 (based on €/€ exchange rate of 18/03/2016). Furthermore, for estimating the acquisition cost of TBC upgrade options a performance-based cost incremental method is proposed. The model computes the upgrade acquisition cost as a function of increase in temperature drop across TBC relative to baseline TBC performance, as presented in Equation 5-1.

$$TBC\ cost = price\ rate * \left(\frac{\delta T_{tbc}}{\Delta T_{tbc}} + 1 \right) * Original\ price \quad \text{Equation 5-1}$$

Where

$$\delta T_{tbc} = (\Delta T_{tbc} - \Delta T_{baseline})$$

The price rate deployed in this model has been assumed as a cost variable purely due to speculation of TBC market dynamic forces. Table 5-7 presents the performance and acquisition cost of the TBC upgrade options. The trend observes TBC performance increase (i.e., increase in temperature drop across TBC) corresponding to the rise in TBC upgrade acquisition costs.

Furthermore, to implement the new TBC upgrade acquisition cost within the economic model of the TERA framework, the cost needs to be incorporated into the HESTIA code to enable the corresponding new maintenance costs and direct operating cost (DOC) is determined. This was done by adding the new TBC

upgrade acquisition cost to the aircraft single engine cost; collectively described as capital cost.

Table 5-7: TBC Upgrade Acquisition Costs

TBC-Type	K-value [W/Km]	ΔT_{tbc} [K]	δT_{tbc} [K]	TBC Upgrade Acquisition Cost [€]
Baseline	1.80	145.88	0.00	14240.00
Type-A	1.62	151.28	5.40	14767.45
Type-B	1.44	158.07	12.19	15430.03
Type-C	1.28	166.85	20.97	16287.15
Type-D	1.08	178.65	32.77	17438.93
Type-E	0.90	195.34	49.46	19068.06
Type-F	0.72	220.73	74.85	21546.58

5.4.2 TBC Upgrade Net Present Value (NPV)

The economic evaluation of the potential benefits of TBC upgrade to an aircraft operator determines the attractiveness and viability of the investment. This is implemented through the discounted cash flow analysis, which uses the concept of Net Present Value (NPV) and Internal Rate of Return (IRR). NPV generally indicates the future values of the investment discounted throughout the investment period.

$$NPV = \sum_{1}^n \frac{\text{Annual benefit}}{(1 + i)^n} - \text{Investment Cost} \quad \text{Equation 5-2}$$

Where

i = discounted cash flow rate

n = period of investment (in years)

For this study, the attractiveness and benefit of the TBC upgrade was evaluated based on reduction of engine maintenance costs and payload improvement (extra passenger) potential of the upgrade. The cost savings derived from engine

maintenance cost reduction is computed and used as the annual benefit due to this upgrade [8].

$$Annual\ benefit = (EMC_{baseline} - EMC_{upgrade}) \times N_{fpy} \quad \text{Equation 5-3}$$

Where

EMC = Engine maintenance cost per flight hour

N_{fpy} = the number of flight hours per year

Increase in payload (extra passenger) potential is another benefit of TBC upgrade and can be computed as:

$$Annual\ benefit = (N_{ep} \times N_{fpy} \times P_{ticket}) - (DOC_{upgrade} - DOC_{baseline})$$

Equation 5-4

Where

N_{ep} = Number of extra passengers

P_{ticket} = Average cost of a single flight

$DOC_{upgrade}$ = Direct operating cost with TBC upgrade

$DOC_{baseline}$ = Direct operating cost without upgrade

5.4.3 Engine Life

Engine life extension due to the deployment of TBC upgrades can generate attractive economic benefits as it promises significant cost savings per aircraft flight. This are savings derived from the relative decrease in engine maintenance cost (EMC) as TBC upgrade effectiveness increases. The higher life indicates longer engine removal time (that is, fewer maintenance shop visit over the engine life cycle) which translates to reduction in engine maintenance cost (EMC). Figure 5-15 shows the relationship between the increase in engine life and engine maintenance cost (EMC) reduction, associated with each upgrade technology in the CEUP67 engine – Cranboe A330 aircraft systems combination.

The engine life (i.e. time between overhaul, TBO) is evaluated base on the life estimate of the engine dominant failure mode, which for this short range mission flight is the low cycle fatigue (LCF) because of the frequent variation in thermal cyclic loading due to the high take off–cruise-landing cycles experienced. The engine TBO (-life) estimated for the baseline TBC was 25,864 operating hours for the 990Km mission range of 1.53 flight hours and 2,887.99 hours of annual utilization (or 1884 flight cycle). However, as TBC effectiveness increases from baseline through Type-F TBC upgrade, the engine TBO (-life) increases by up to 14,855 hours relative to the baseline life, and corresponds to the Type-F TBC upgrade technology for the same flight mission and operating conditions.

The engine maintenance cost (EMC) decreases to the lowest value of €251 per flight, over 19% decrease from benchmark. This directly influences the flight operational expenses (OPEX) providing noticeable reduction in flight direct operating cost (DOC). The DOC is such an important cost category as it represents a common figure-of-merit frequently used in aircraft economics and trade-off studies. For the average mission and flight conditions previously discussed, the simulated baseline engine DOC is approximately €9,002 per flight. The DOC computed is an approximate result based on the approach described by Jenkinson al et.[54], and is within the range in publicly available literature such as aircraft commerce [93]. Figure 5-16 represents the components of baseline DOC with each percentage composition.

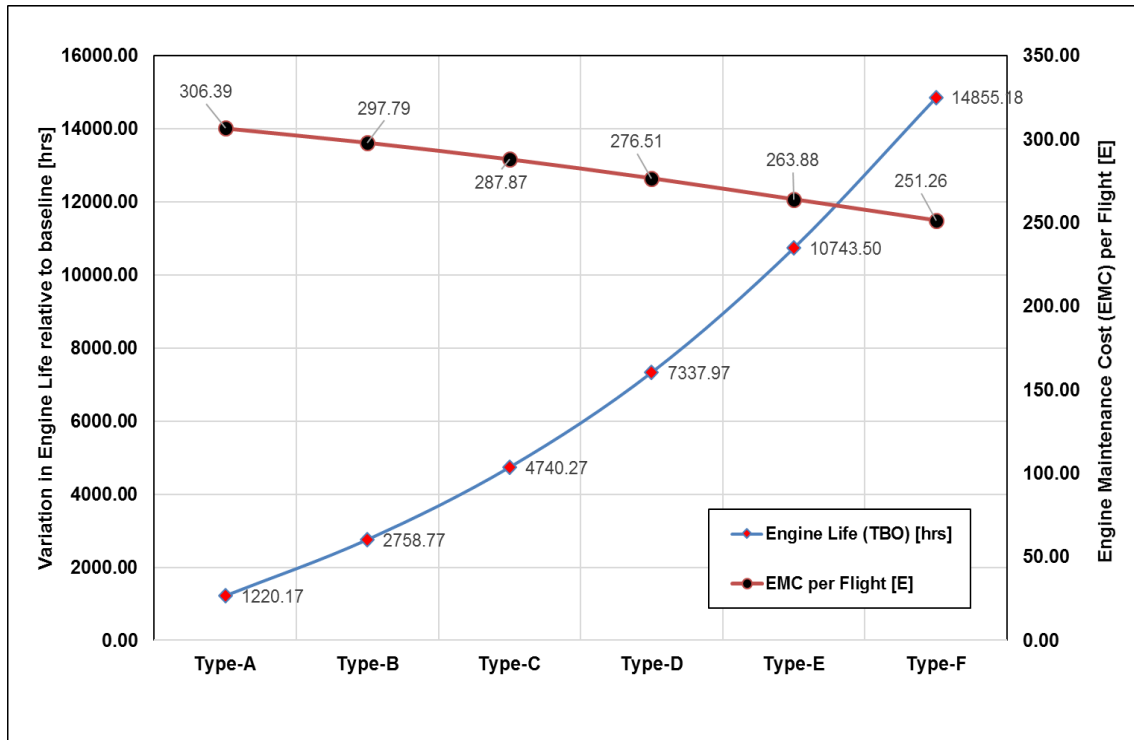


Figure 5-15: Effect of TBC Upgrade on Engine life and Engine maintenance cost per flight

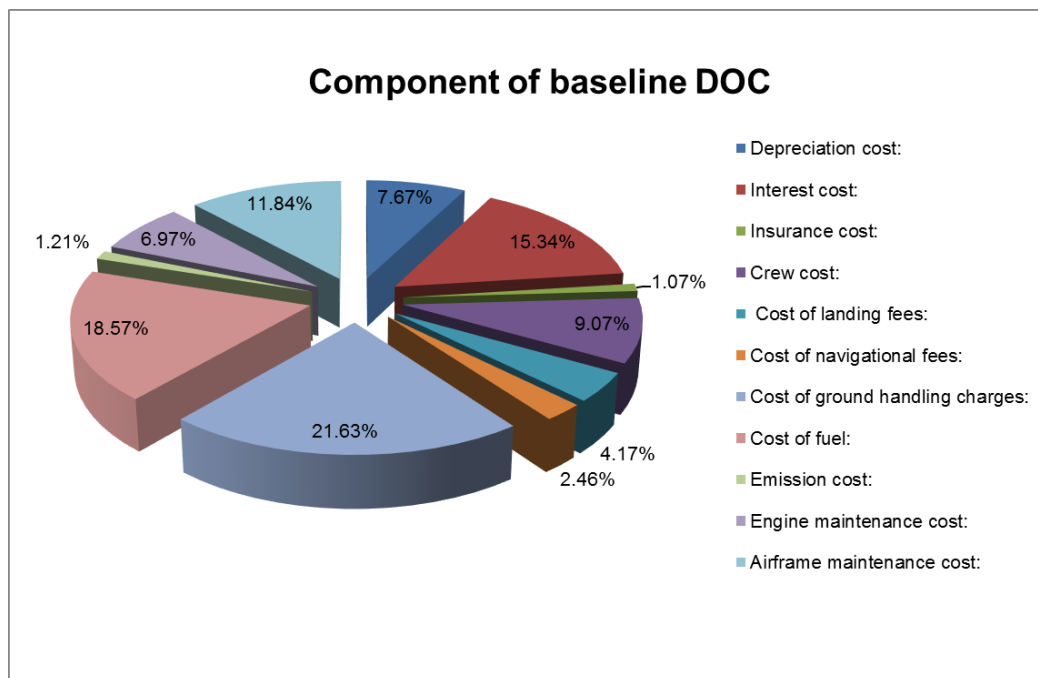


Figure 5-16: Component of Aircraft Direct operating costs for baseline engine

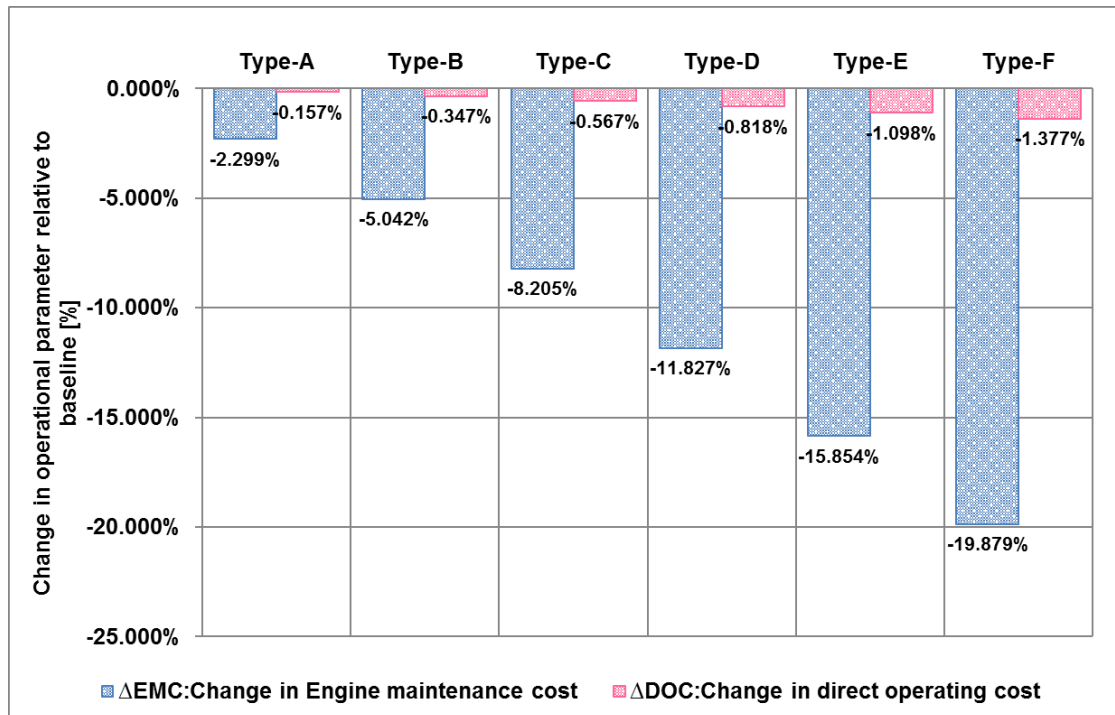


Figure 5-17: Percentage change in engine maintenance costs and DOC relative to baseline

The propulsion system efficiency strongly influences the fuel cost, emission and engine maintenance cost of the flight, therefore any variation in this parameter directly affects the DOC. From the figure, the engine maintenance cost (EMC) accounts for 3.48% of DOC, and represents the only component that varies as TBC upgrade effectiveness increases therefore affecting DOC directly. Figure 5-17 presents the reduction in engine maintenance cost (EMC) and DOC per flight with increase in TBC upgrade effectiveness. The maximum reduction in EMC and DOC of over 19.8% and 1.3% respectively is achieved with the TBC Type-F upgrade.

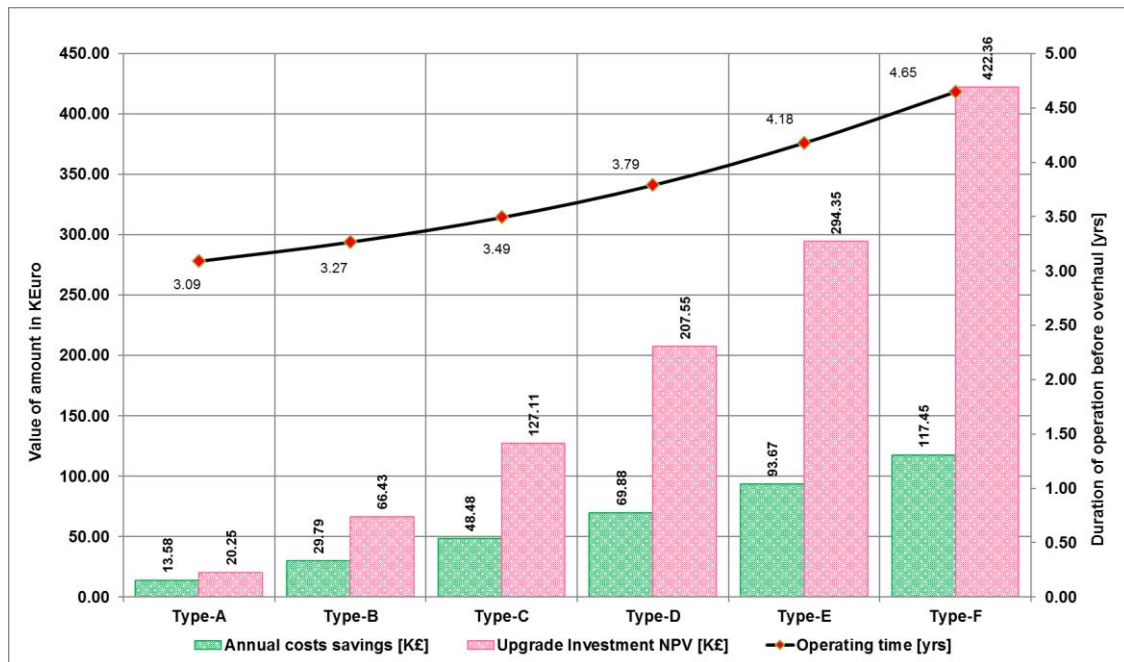


Figure 5-18: Annual costs savings, NPV and Operating period before overhaul associated with TBC upgrade

The economic attractiveness of TBC upgrade for engine life extension is an effective cost-benefit analysis of the system. Figure 5-18 shows the annual cost savings derived from the reduction in EMC and the Net Present Value (NPV) over the operating life of the TBC. The TBC operating life has been assumed equal to the engine TBO in years since TBC is replaced during engine maintenance overhaul, and rises proportionately with engine life as TBC upgrade improves. The annual savings is the product of the cost savings per flight and the average number of flight per year, with peak savings realised at K€117.45 annually.

The model presented in Equation 5-2 above is used for computing the Net Present Value (NPV), which is one of the decision-making criteria for any investment. The investment cost is the TBC acquisition cost reported previously and annual benefit is equal to the annual savings derived from the investment.

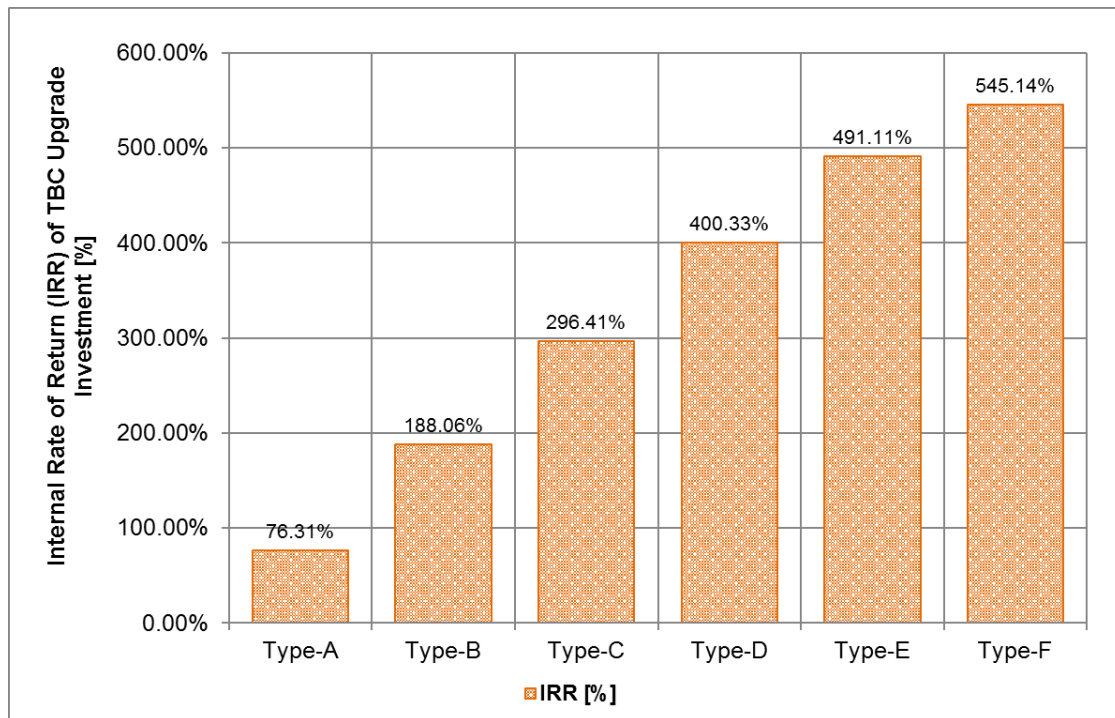


Figure 5-19: Internal Rate of Return (IRR) of the TBC Upgrade Investment

For this analysis, a 10% discounted rate is used to estimate the TBC upgrade investment NPV, although the typical value for airline is 7% [94] the 10% mark is used in this analysis to compensate for the simplified cost assumptions made during this work. The TBC upgrade investment NPV increases as the TBC effectiveness increases up to a maximum NPV of K€422.36 corresponding to the Type-F TBC upgrade technology. Therefore, the investment in TBC upgrade is considered economically viable with attractiveness increasing as TBC upgrade effectiveness increases since the NPV for all the upgrade options are higher than zero.

Although the benefits of engine life extension, in terms of cost savings and NPV suggest compelling attractiveness for this investment, further analysis of technology risk expanded in chapter 8 may reveal further useful insight for decision-makers.

5.4.4 Engine Payload Improvement

The additional engine life obtained through the deployment of TBC upgrade is sacrifice for increase thrust without compromising the original life of the engine. This is achieved by iteratively increasing the engine peak operating temperature (TET) while keeping original engine life constant. Figure 5-8 gave an illustration of the rise in take-off thrust as TET increases with improvement with TBC upgrade effectiveness. The engine capability to take-off with extra payload within “FAR take-off field length” requirements is greatly enhanced because of the excess thrust available at take-off. The additional payload capacity may be use to carry extra passengers, luggage, cargo or fuel, depending on the business strategy and priority of the airline. This work however, uses the extra passengers to evaluate the business case for this scenario. And is based on the simple condition that the benefits of extra revenue obtained from the additional passengers far outweighs the penalties of increase fuel cost, emission, EMC and other costs incurred.

Table 5-8 shows the DOC of the TBC upgrades relative to baseline. First sight observation reveals that, except the cost of flight-and-cabin crew and airframe maintenance cost, all other DOC elements vary as TBC effectiveness increase. The DOC elements can be categorized into time related costs, fuels related and emission related costs [54]. The time related costs refers to all applied cost during the active life of the asset, and comprise of the maintenance (airframe and engine) costs, flight-cabin crew costs and standing charges (depreciation, interest and insurance cost on capital investment). Fuels related cost represents the amount of fuel consumed, which is a function of fuel price, engine operations (TET) and efficiency. Finally, the emission costs indicate the total flight LTO emission (NO_x and CO_2) generated per flight mission.

In Table 5-8, the variation in the DOC elements at different TBC upgrade relative to baseline is proportional to the changes in TBC acquisition cost (capital cost) and engine peak operating temperature (TET) corresponding to the upgrade technology. The sensitivity of the TBC upgrade DOC elements to baseline follows

a steady increasing trend; with emission cost seemingly the most sensitive element of the DOC to improvement in TBC upgrade.

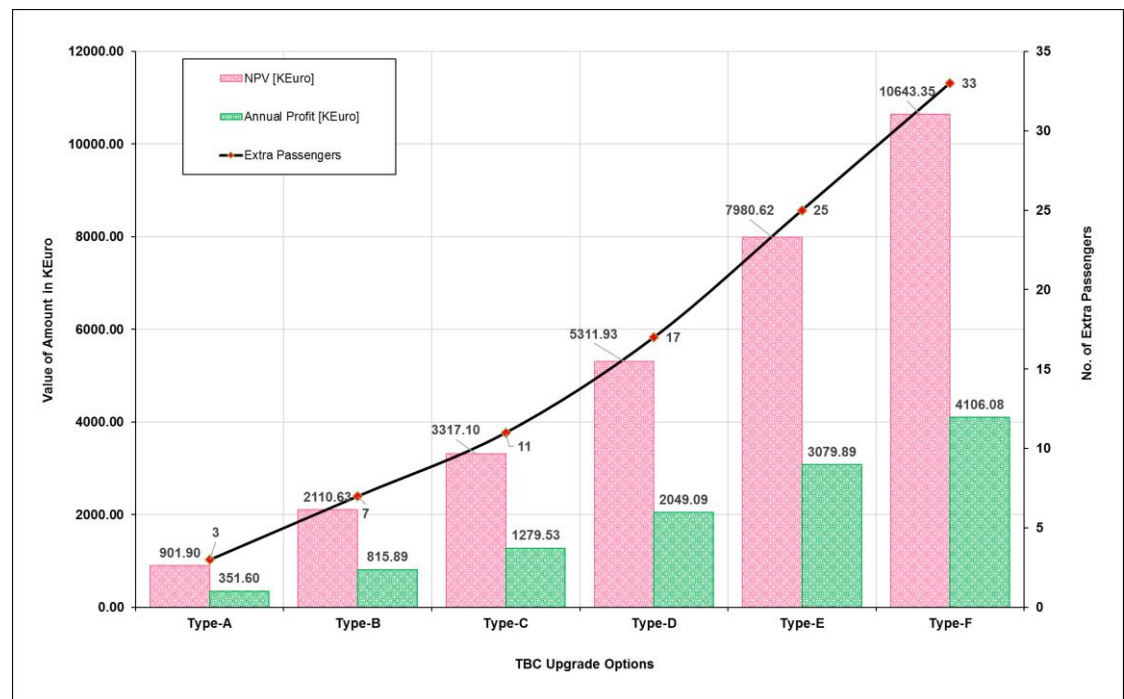


Figure 5-20: Annual revenue generated, NPV and No. of extra passengers due to TBC upgrade

Table 5-8: Effect of TBC Improvement on DOC per flight - Payload Improvement

Airline Cost Per Flight Cycle 177 Passengers-Short Range-Narrowbody Aircraft							
	Baseline DOC [€]	Type-A [%]	Type-B [%]	Type-C [%]	Type-D [%]	Type-E [%]	Type-F [%]
Depreciation cost	690.50172	+0.483	+1.103	+1.786	+1.838	+1.846	+1.847
Interest cost	1381.00344	+0.483	+1.103	+1.786	+1.838	+1.846	+1.847
Insurance cost	95.995724	+0.512	+1.187	+1.931	+1.986	+1.993	+1.991
Costs of Flight and Cabin crew	816.816085	0.000	0.000	0.000	0.000	0.000	0.000
Cost of landing fees	375.683026	+0.514	+1.188	+1.933	+1.991	+1.993	+1.992
Cost of navigational fees	221.588772	+0.251	+0.580	+0.941	+0.958	+0.947	+0.936
Cost of ground handling charges	1947	0.000	0.000	0.000	0.000	0.000	0.000
Cost of fuel	1671.63413	+0.033	+0.028	+0.065	+0.020	+0.067	+0.051
Emission cost	109.228813	+5.442	+16.185	+24.865	+27.204	+27.620	+28.063
Engine maintenance cost	313.603454	+0.151	+0.333	+0.552	+0.941	+1.469	+2.607
Airframe maintenance cost	1065.42966	0.000	0.000	0.000	0.000	0.000	0.000
Others	313.603454	+0.151	+0.333	+0.552	+0.941	+1.469	+2.607
Total Direct Operating Cost	9002.08828	+0.226	+0.555	+0.887	+0.949	+1.003	+1.084

This indicates that the benefit of increase payload as discussed previously is accompanied with an associated cost penalty (DOC) for each upgrade utilised.

The business case for the increase payload scenario as mention previously is evaluated via an effective cost-benefit analysis of the upgrade. The benefit is the additional revenue generated from ticket-fare of extra passengers carried due to TBC upgrade. The cost penalties however, are associated with the TBC acquisition cost and the increase in DOC. Figure 5-20 presents the annual profit generated, Net present value (NPV) and number of extra passengers carried. The annual investment profit is calculated from Equation 5-4 above. A simple difference between the additional revenue generated (which is the product of ticket fare, number of extra passengers and annual flight utilization) and the extra operating expenses associated with the upgrade. For the typical London Heathrow (LH) to Malpensa Italy (MI) flight mission, an average ticket fare of €69 base on EasyJet website [95], 1884 annual flight cycle utilization and about 2.95 years (25864 hours) of TBO are deployed for this analysis. Providing a maximum annual profit of K€4,106.08 and investment NPV of K€10,643.35 for extra 33 passengers carried, and enabled by the TBC Type-F upgrade technology.

5.4.5 Economic Result Summary

This chapter evaluates the potential economic benefits associated with aircraft engine hypothetical TBC upgrades, with respect to operational cost reduction or cost savings and revenue improvements occasioned by the variety of ways the TBC upgrade can be put to use. The obtained results have shown that investment in TBC upgrade delivered on its promise of enabling a reduction in operational expenses (OPEX) in terms of decrease in engine maintenance cost (EMC) and the overall direct operating cost (DOC) per flight. With over 19% decrease in engine maintenance cost (EMC) from benchmark and strongly influencing a noticeable decrease in flight DOC of up to 1.3%, for the maximum TBC improvement corresponding to Type-F upgrade technology. The economic attractiveness of TBC upgrade for engine life-extension purpose, evaluated as

the cost-benefit analysis for the TBC operating years has been presented as the NPV and IRR for the investment. K€509.17 and 547.14% were realised as the NPV and IRR respectively for the TBC investment corresponding to Type-F upgrade technology.

For the purpose of achieving payload improvement, result shows that increasing the TET by 290K above baseline can increase the engine payload capacity by additional 33 passengers, therefore providing a maximum annual profit of K€4106.08 on the investment, an NPV of K€10643.35 for 2.95 years of operation with an interesting IRR of 16152.18% corresponding to Type-F upgrade under the defined mission and assumptions utilized in this investigation.

Finally, the investigation provides a comprehensive economic analysis of the TBC upgrade potential benefits and attractiveness to guide decision-makers on the appropriate investment for their target improvements. Although the cost-benefit analysis has been investigated in this study, the technology risk analysis (see chapter 8) should be performed prior to final investment decision.

5.5 SENSITIVITY ANALYSIS

A mission specific sensitivity analysis is conducted to investigate the effect of fuel price and TBC upgrade costs uncertainties on the TBC upgrade project benefits in annual DOC gains and NPV estimations. Figure 5-21 shows a mission specific method for creating a map used by operators (users) to assess prior to making any decision for investing on TBC upgrade, the attractiveness of the upgrade investment within several operational and costs variations. The mission ranges considered for this study varies between 800Km to 6000Km length (representing the short, medium and long-range missions). The upper limit was chosen based on the Cranboe B737 payload-range capability represented in Figure 4-11. This assumption according to the author is fairly reasonable as it represents typical operational missions the Boeing 737 aircraft is utilized for.

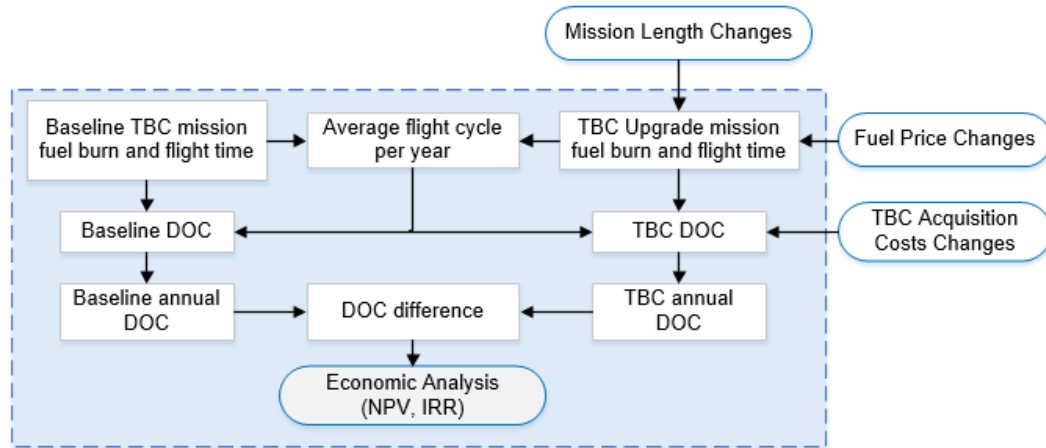


Figure 5-21: Sensitivity analysis

The economic impact of the fuel price uncertainties on the TBC upgrade investment is estimated base on the 150 to 200c\$/USgallon fuel price range taken from IATA's fuel monitor [96]. The baseline DOC is calculated base on the 179c\$/USgallon fuel price for March 2017 [96].

The TBC upgrade acquisition costs is estimated as discussed previously in subsection 5.4.1. The acquisition costs estimated attempts to quantify the costs of TBC improvements, which may not accurately represent the costs of this potential advanced future hypothetical TBC upgrade not yet in service. However, to approximately account for this cost uncertainty a price rate factor of 0%, 25% and 50% increase in TBC acquisition costs scenarios have been assumed for this analysis as shown in Table 5-9.

Table 5-9: Price rate variations in TBC upgrade acquisition costs

TBC-Type	K-value [W/Km]	TBC Upgrade Cost [€]-0% price rate	TBC Upgrade Cost [€]-25% price rate	TBC Upgrade Cost [€]-50% price rate
Baseline	1.80	14,240.00	17,800.00	21,360.00
Type-A	1.62	14,767.45	18,459.31	22,151.18
Type-B	1.44	15,430.03	19,287.54	23,151.18
Type-C	1.28	16,287.15	20,358.94	24,430.73
Type-D	1.08	17,438.93	21,798.66	26,158.39
Type-E	0.90	19,068.06	23,835.08	28,602.09
Type-F	0.72	21,546.58	26,933.22	32,319.87

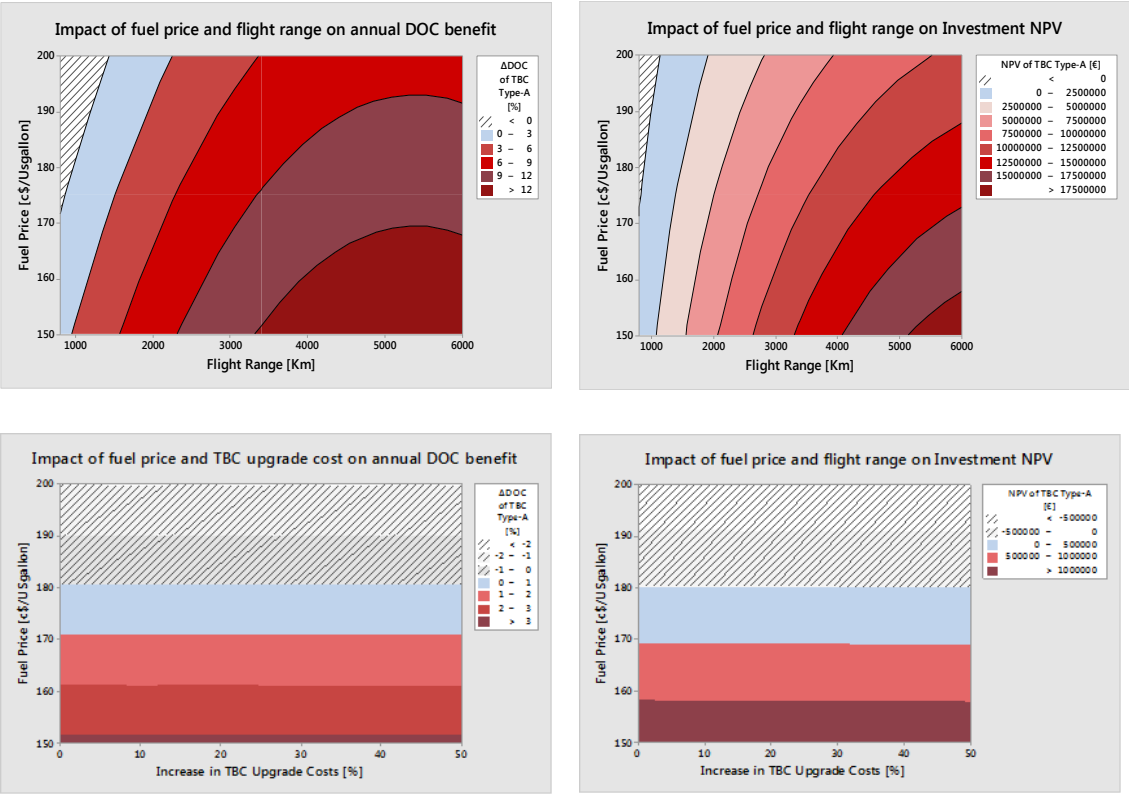
Figure 5-22 and Figure 5-23 shows the contour for the impact of fuel price, TBC upgrade costs and mission range variation on the annual DOC benefit and NPV of TBC upgrade Type-A and Type-F, representing the TBC improvement (with $K_{tbc} = 1.62$) and the most advanced TBC ($K_{tbc} = 0.72$), respectively.

The economic estimation is made base on the following operating cost assumptions: 6% depreciation, 2% interest rate, 0.5% insurance rate, 90 €/man-hour maintenance labour rate and 50 €/hr crew member cost as well as 140 €/hr flight crew member cost at an exchange rate of 0.89 \$/€.

The annual DOC benefit is estimated as the difference between the product of DOC per trip and average flight cycle per year for baseline and TBC upgrade engines. These parameters are self-compensating with one another, as mission range increases the DOC increases and flight cycles per year decreases, and vice-versa. As the mission range increases, the annual DOC benefit increases partly due to the reduction in engine maintenance costs (EMC) which is influenced by the engine life (TBO) increase as range increases but decreases as the fuel price increase. The engine life increase as mission changes from short to long range, however its worth noting that the dominating failure mode was fatigue and did not change to creep as mission changed from short to long range. This is because the maximum operating temperature necessary to meet the aircraft thrust requirement is not high enough to make creep the dominating failure mode for the engine life.

For the lowest range simulated mission of 800Km, annual DOC benefit is approximately 3% for the lowest fuel price of 150 c\$/USgallon and decrease to less than zero as the fuel price increases up to 200 c\$/USgallon. As fuel price increases, the percentage contribution of fuel to the DOC increases, thus decreasing the annual DOC benefits. However, the annual DOC benefit at 150 c\$/USgallon fuel price increases up to 12% as mission range increases to 6000Km. This clearly shows that operations within lower mission range are not seeing as much attractive benefits as the long-range mission at both low and high fuel price scenarios. This occurs as engine maintenance costs (EMC), which is a component of aircraft DOC decreases with mission length because the engine

life increase due to lower average take-off – landing cycle per year as mission length increases. Figure 5-22(b) shows the TBC upgrade project NPV estimated from Equation 5-2 based on the annual DOC benefits in Figure 5-22(a). The NPV contour follows a similar trend as the annual DOC benefits mapping the merits for TBC upgrade investment.

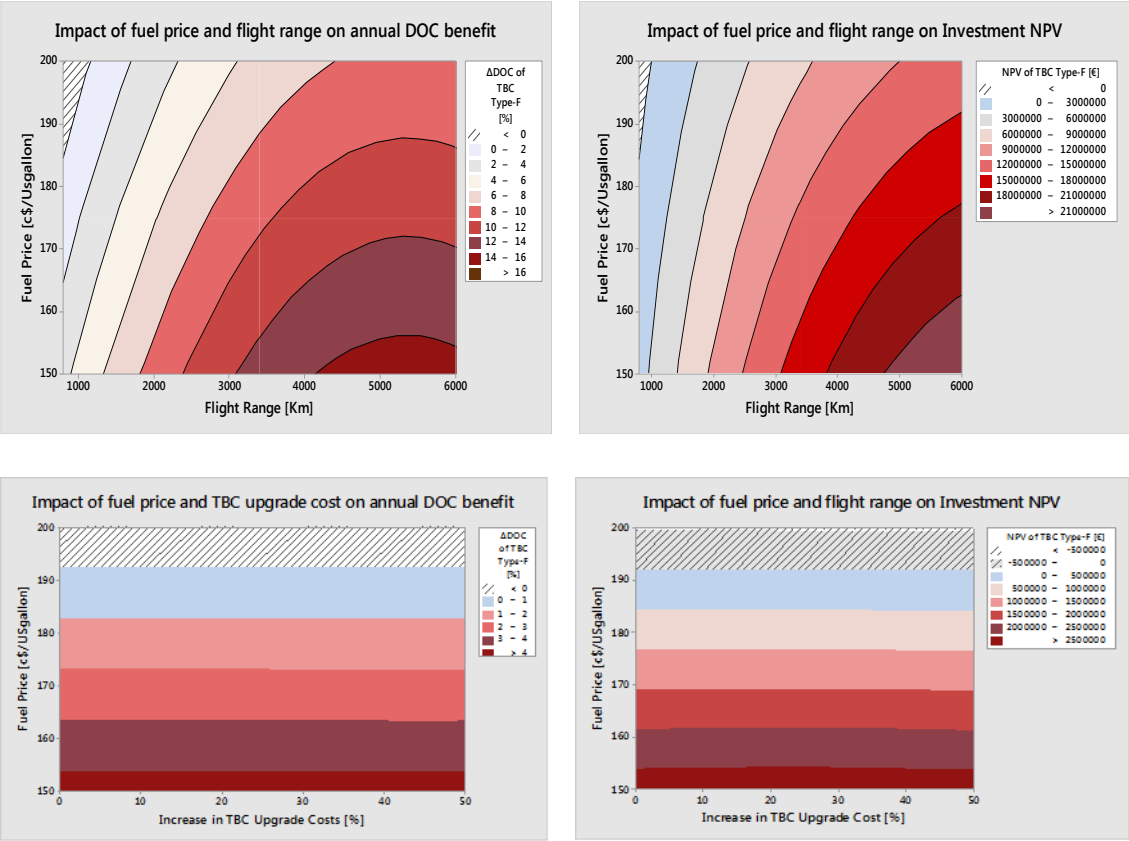


(a) Annual DOC benefit

(b) NPV

Figure 5-22: TBC Upgrade Type-A

Figure 5-23(a) and (b) shows the annual DOC benefit and NPV for the TBC upgrade Type-F, which is the most advanced upgrade option with the highest engine life (TBO) estimated. Because of this advantage of increased engine life, and hence engine maintenance costs (EMC), the annual DOC benefit and NPV shows more attractiveness compared to the TBC upgrade Type-A. At lower fuel price (150 c\$/USgallon) and mission (800Km), the annual DOC benefit is approximately 4% and increases up to 16% as the mission length increases to 6000Km. However, this benefit decreases as fuel price increases. The NPV also increases despite the increase in TBC acquisition costs.



(a) Annual DOC benefit

(b) NPV

Figure 5-23: TBC Upgrade Type-F

Chapter Six

TERA of Aircraft Engine Upgrade from Engine Manufacturer's Perspective

6. Introduction

The quest for aero engine solution with enhanced performance, increased fuel efficiency, cost-effectiveness and environmental friendliness are the major drivers of new aero engine technology development. The aviation industry is highly competitive, as engine manufacturers are constantly innovating new technology to meet customer's requirement of fuel burn improvement for direct operating cost (DOC) reduction and airline profitability, policy and regulatory legislation on noise and emission constraints. The development of new engine and concept cycle technology, although promises very high savings in fuel consumption their production time is usually lengthy and very capital intensive. The trend however, by OEMs is the continuous technology improvement throughout its engine lifecycle via the infusion of new technology into existing assets as upgrade, retrofit or modification.

With the steady growth in air traffic passengers globally, airline operators are concerned with maintaining engine operations at peak performance throughout the entire engine lifecycle for profit maximization. However, considering the growing fleets of mid-life and ageing engines in active commercial service, efficient maintenance programme to match their investment and operational goals must be opted for; which may involve upgrades, modifications or retrofits for maximum engine performance. As engines mature, the cost of maintenance increases while performance deteriorates over time, one way of maintaining success is by incorporating advanced new technology into existing engine to enhance performance. Which are primarily targeted at decrease direct operating costs (DOC), improve performance and residual value of the engine/aircraft

systems. Like previously stated, they are two ways of improving engine SFC: Increasing cycle efficiency through higher operating TET and OPR, and increasing engine propulsive efficiency via higher engine BPR. The development towards the latter direction has led to the design and development of high- and ultra-high BPR engines in service today. However, this research examines the feasibility of performance improvement through small modification of existing engines.

Several engine upgrade studies have been conducted over the years, In 1979 Fasching W.A [97] conducted a feasibility analysis of performance improvement and retention concepts for the CF6-6 and CF6-50 engines. The studies identified seven viable concepts for engine improvement, which were further developed. The U.S. Air Force in 2006 funded the research for “improving the efficiency of engines for large nonfighter aircraft” [98]. The study examined several potential engine modifications/upgrade and re-engine of current aircraft. According to the studies recommendation for engine modification/upgrade on the basis of fuel savings was difficult for the 2006 fuel price regime, although there was significant improvement in both operational and maintenance benefits.

This chapter focuses on an engine upgrade variant for performance and specific fuel consumption (SFC) improvement achieved by slightly increasing the fan diameter of the engine. This increases the fan airflow rate and the propulsive efficiency of the engine. The objective of this investigation is to evaluate the feasibility of engine performance improvement and the potential economic impact via increased engine fan diameter variant. The engine variant is implemented through fan and bypass nozzle components flow path modification without altering the engine core configuration. The corrected mass flow of the booster inlet is keep constant corresponding to the new FPR. The increased fan diameter engine variant design is intended as retrofit upgrade to enhance engine off-design performance through increasing the fan flow capacity proportional to the slight increase in diameter.

6.1 Method Description – Increased Fan Diameter

The bypass ratio (BPR) and fuel efficiency of an engine is largely influenced by the engine fan size, through the engine propulsive efficiency. The gains of increase diameter are usually constrain by the penalties of increased engine weight and pod drag due to larger pylon.

The upgrade presented in this chapter proposes a small increase in engine fan diameter for increasing inlet mass flow rate and consequently improving engine performance, without significantly altering the engine nacelle geometry. The upgrade engine variant implementation is deployed through fan and bypass nozzle component flow path modification, while maintaining the same baseline engine running line. A change in fan casing is required to accommodate the slight increase in engine fan diameter, with an assumption that the engine inlet internal geometry is aerodynamically optimized to suit the fan upgrade. To the author, this is consider realistic since the maximum fan diameter increase is less than an inch length as shown in Table 6-1 and Figure 6-1.

Table 6-1: Engine Fan Diameter Increase

Fan Diameter	Value [m]	Δ [cm]	Δ [inch]
D _{BL}	2.443	-	-
D _{UG1}	2.449	0.6	0.236
D _{UG2}	2.455	1.2	0.472
D _{UG3}	2.461	1.8	0.709

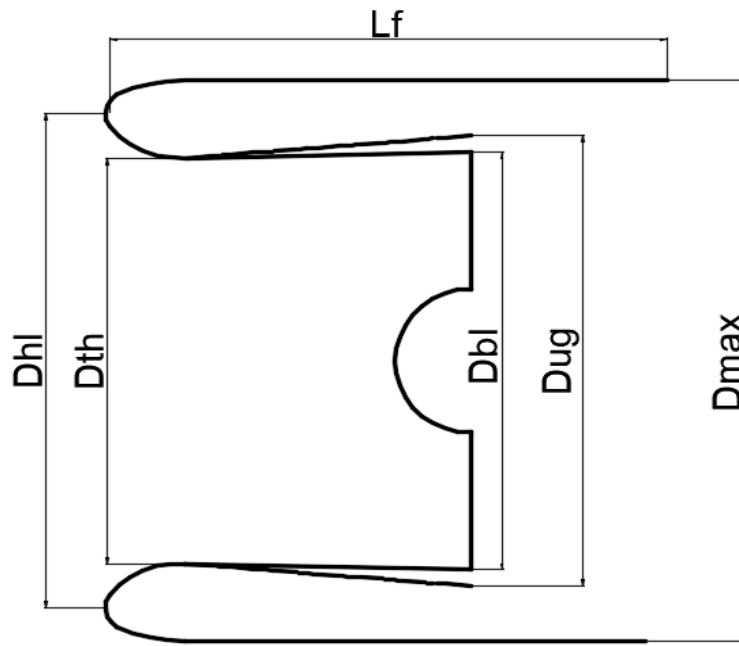


Figure 6-1: Increased fan diameter in engine nacelle forebody

Figure 6-2 shows the flow chart for the increased engine fan diameter upgrade implementation. The baseline design point (DP) calculation of CEUPCF6-80 engine is simulated in TURBOMATCH followed by the off-design (OD) point simulation to obtain the engine and fan compressor performance characteristics. TURBOMATCH creates the fan compressor map of the developed engine model by scaling the fan compressor corrected mass flow, pressure ratio, efficiency, and speed parameters of the reference map at different speed lines computed by the Equation 6-1, 6-2, 6-3, and 6-4.

The scaling factor for the corrected mass flow, pressure ratio, corrected speed and efficiency are given as follow:

$$WASF = \frac{(WAC_{Baseline})_{DP}}{(WAC_{Refmap})_{DP}} \quad \text{Equation 6-1}$$

$$PRSF = \frac{(PR_{DP} - 1)}{(PR_{DPrefmap} - 1)} \quad \text{Equation 6-2}$$

$$CSSF = \frac{(CS_{Baseline})_{DP}}{(CS_{Refmap})_{DP}} \quad \text{Equation 6-3}$$

$$\eta_{cSF} = \frac{(\eta_c)_{DP}}{(\eta_c)_{DPmap}} \quad \text{Equation 6-4}$$

A thermodynamic model of the engine that calculates the effect of increased fan blade diameter on engine inlet mass flow, bypass ratio, fan work requirement and other performance parameters. The thermodynamic model and TURBOMATCH calculation are matched to ensure the models output are the same. The change in inlet airflow with increase fan diameter is used to calculate the airflow-scaling factor relative to the baseline engine. The airflow-scaling factor is now use to scale the baseline CEUPCF6-80 TURBOMATCH engine model to create the increase fan diameter upgrade engine. The mass flow and thermodynamic parameters of the increased fan diameter compressor engine was calculated and the airflow scaling factor corresponding to the small increase in fan diameter evaluated by Equation 6-9. The increased fan upgrade variant was implemented in TURBOMATCH applying the fan compressor airflow capacity-scaling factor proportional to the small increase in fan diameter, and the new upgrade variant mass flow calculated by Equation 6-6.

$$UGWASF = \frac{(WAC_{Upgrade})_{DP}}{(WAC_{Baseline})_{DP}} \quad \text{Equation 6-5}$$

$$WAC_{Upgrade} = UGWASF * (WAC_{Baseline})_{DP} \quad \text{Equation 6-6}$$

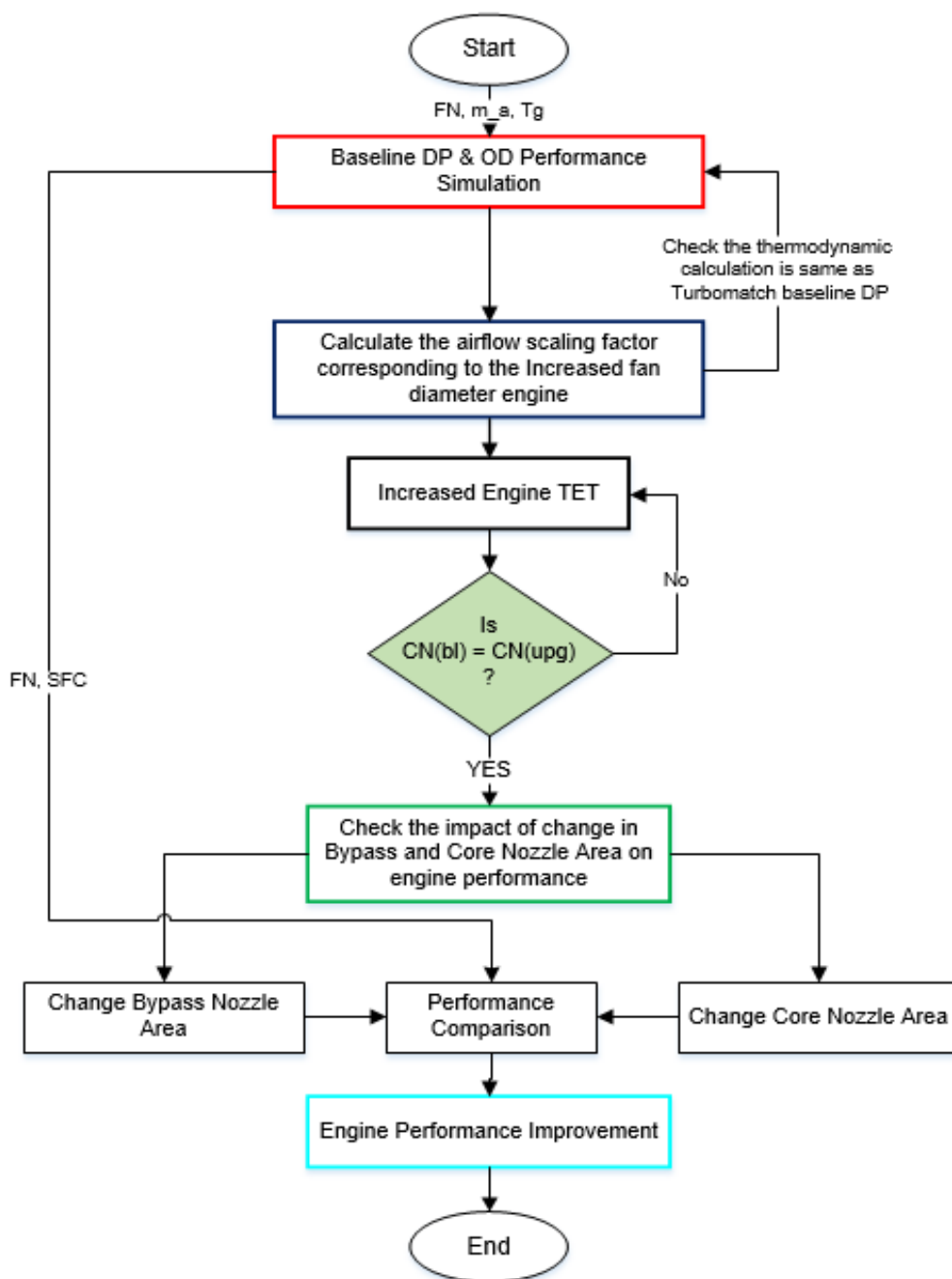


Figure 6-2: Increased engine fan diameter variant Implementation Procedure

The increase in fan diameter alters the component characteristics (i.e. Pressure ratio, corrected mass flow, corrected speed and isentropic efficiency) which in turn affects downstream component in the engine. The increase fan diameter reduces the component corrected speed, pressure ratio and efficiency. Power requirement to drive the fan is higher to accommodate the extra airflow passing through the fan, which in turn decreases the overall engine net thrust. To avoid unnecessary modification of engine downstream components, the engine TET is increase to ensure that the corrected speed of the variant is same as the baseline engine. The higher TET is base on the assumption that better component materials are used for the engine variant. The impact of changes in fan and core nozzle area on engine performance (thrust and SFC) is investigated by keeping the core nozzle area constant while varying the fan nozzle area and vice versa. A comparison between baseline and the upgrade variant engines is presented below in Table 6-2, showing notable changes and performance improvement.

Table 6-2: Changes and Performance Improvement

	Baseline engine	Upgrade variant 3	
Fan diameter	2.443	2.461	+ 0.737%
Airflow scaling factor	1.000	1.016	+ 1.628%
Pressure Ratio	1.700	1.716	+ 0.941%
Efficiency	0.910	0.904	- 0.651%
Corrected speed, CN	1.000	1.000	0.000%
Surge Margin, Z	0.850	0.869	+ 2.199%
Work consumed	4.844E+07	5.011E+07	+ 3.456%
Bypass nozzle area	2.071	2.071	0.000%
Core nozzle area	0.522	0.522	0.000%
Bypass nozzle velocity	314.200	318.630	+ 1.410%
Core nozzle velocity	541.900	546.410	+ 0.832%
Turbine entry temp	1,667.00	1,722.500	+ 3.329%
Airflow capacity	873.600	881.616	+ 0.918%
Fuel flow	3.018	3.172	+ 5.093%
SFC	9.715	9.860	+ 1.495%
Take-off thrust	310.656	317.687	+ 2.263%

6.2 Increased Fan Diameter Calculation Equations

6.2.1 Fan Input Parameters

Table 6-3 below shows the baseline input parameters required for the computation of the engine inlet mass flow and thrust. The fan tip diameter was obtained from the public literature for engine similar to CF6-80E1A3 with thrust rating of 310KN. The other parameters were read from TURBOMATCH simulation of the engine.

Table 6-3: Fan Input Parameters

Parameters	Value
Fan tip diameter	2.443m
Fan hub-to-tip ratio	0.380
Fan Isentropic efficiency	0.910
Fan pressure ratio	1.700
Fan face Mach number	0.475
Fan RPM	3,835

6.2.2 Ambient and Inlet Conditions

The following equations expressed below were used for the calculation of the changes in engine performance with variations in engine fan diameter.

Ambient pressure and temperature is a function of altitude (h) and ISA day temperature ΔT_{ISA} .

$$P_0 = f_p(h) \quad \text{Equation 6-7}$$

$$T_0 = f_T(h) + \Delta T_{ISA} \quad \text{Equation 6-8}$$

The stagnation conditions at the engine inlet depends on the flight Mach number, M_{ft}

$$T^0_1 = T_0 \left(1 + \frac{\gamma_c - 1}{2} M_{ft}^2 \right) \quad \text{Equation 6-9}$$

$$P^0_1 = P_0 \left(\frac{T^0_1}{T_0} \right)^{\frac{\gamma_c}{\gamma_c - 1}} \quad \text{Equation 6-10}$$

A pressure loss factor π_d is introduced to account for engine inlet losses and the exit conditions can be expressed as;

$$T^0_2 = T^0_1 \quad \text{Equation 6-11}$$

$$P^0_2 = \pi_d P^0_1 \quad \text{Equation 6-12}$$

6.2.2.1 Engine Fan

Given fan pressure ratio π_{fan} and fan efficiency, η_{fan} , the fan inlet and exit properties can be calculated.

Fan intake static pressure, $P_{1,2}$

$$P_{1,2} = \left[(\pi_d P^0_1) / \left(1 + \frac{\gamma_c - 1}{2} M_{fan}^2 \right) \right]^{\left(\frac{\gamma_c}{\gamma_c - 1} \right)} \quad \text{Equation 6-13}$$

Fan intake static temperature, $T_{1,2}$

$$T_{1,2} = \frac{T^0_1}{1 + \frac{\gamma_c - 1}{2} M_{fan}^2} \quad \text{Equation 6-14}$$

Flow rate, Q

$$Q = M_{fan} \sqrt{r} \left(\frac{y_c}{R} \right) \left(1 + \frac{(y_c - 1)}{2} M_{fan}^2 \right)^{K_1} \quad \text{Equation 6-15}$$

Where

$$K_1 = 0.5 \left[\frac{y_c + 1}{y_c - 1} \right]$$

Fan annular area, A_{annfan}

$$A_{annfan} = \frac{[D_{tipfan}^2 (1 - hubTipRatio^2) \pi]}{4} \quad \text{Equation 6-16}$$

Air mass flow rate, m_a

$$m_a = \frac{A_{annfan} (1000 Q \pi_d P_{1,2})}{\sqrt{T_{1,2}}} \quad \text{Equation 6-17}$$

Fan blade tip speed, U_{tipfan}

$$U_{tipfan} = \frac{\pi D_{tipfan} RPM_{fan}}{60} \quad \text{Equation 6-18}$$

The air mass flow through the cold $m_{1,3}$ and hot m_{25} section of the engine is expressed by:

$$m_{1,3} = m_a \frac{BPR}{BPR + 1} \quad \text{Equation 6-19}$$

$$m_{25} = m_a \frac{1}{BPR + 1} \quad \text{Equation 6-20}$$

Where BPR is called bypass ratio. This is the ratio of the cold and hot section air mass flow of the engine.

Fan outlet total temperature, $T_{1,3}$

$$T_{1,3} = T_2^0 + \frac{T_2^0}{\eta_{fan}} \left(FPR^{\left(\frac{y_c - 1}{y_c} \right)} - 1 \right) \quad \text{Equation 6-21}$$

The power required to drive the fan is given as:

$$W_{fan} = m_a c_p (T_{1,3} - T_{1,2}) \quad \text{Equation 6-22}$$

Table 6-4 shows the effect a slight increased fan diameter has on the hub-to-tip ratio, fan annular area and the fan blade tip speed. It is obvious that the inlet mass flow rate and the fan blade tip speed increased with the increase in fan diameter, but the percentage increase in mass flow is higher than the blade tip speed. However, since the mass flow is more sensitive to increase in fan diameter the benefit of additional thrust is higher than the blade life penalty associated with increase blade stress due to higher blade tip speed.

Table 6-4: Calculation Results

D_{tipfan} [m]	HTR	m_a [Kg/s]	A_{annfan} [m ²]	U_{tipfan} [m/s]	Engine Weight [Kg]	Scaling Factor
2.443	0.3800	874.5192	4.0106	490.5543	4865.232	1.0
2.446	0.3795	877.0311	4.0221	491.1567	4870.075	1.0029
2.449	0.3791	879.5460	4.0336	491.7591	4877.839	1.0057
2.452	0.3786	882.0640	4.0452	492.3615	4885.615	1.0086
2.461	0.3772	889.6365	4.0799	494.1687	4909.019	1.0173

6.3 Results and Discussion

Engine performance improvement through the increased engine fan diameter upgrade variant was investigated in this chapter. The proposed approach to enhance engine performance through slight fan diameter increase without altering the engine core configuration is originally intended as retrofit offerings. As previously mentioned, the Cranfield in-house simulation software (TURBOMATCH) was used to simulate the design point and off-design point performances of the CEUP6-80 baseline engine investigated to establish a reference for comparison with the upgrade variants. The effect of the increased

fan diameter for the variant model was based on off design compressor map airflow scaling proportional to the change in fan diameter. The upgrade engine variant (new increased fan diameter) off-design conditions calculated required the imposition of changes to the component corrected mass flow, corrected speed, isentropic efficiency and pressure ratio, as presented in Equation 6-23 [99].

$$W_{new} = (1 - \Delta W\%) * UGWASF * WASF \times W_{map} \quad \text{Equation 6-23}$$

$$\eta_{f(new)} = (1 - \Delta \eta\%) * UGETASF * ETASF \times \eta_{map} \quad \text{Equation 6-24}$$

Where $WASF$ and $ETASF$ are scaling factors associated with the changes ($\Delta W\%$ and $\Delta \eta\%$, respectively) of derived CEUP6-80 model map with reference to the compressor map within TURBOMATCH. Also, $UGWASF$ and $UGETASF$ represent scaling factors that account for the change in fan diameter (for upgrade engine variant).

Implementing the fan diameter scaling affects the component corrected for rotor speed $N_{corr} = N/\sqrt{T_1}$, pressure ratio (P_2/P_1), isentropic efficiency and consequently the inlet air mass flow as shown in Table 6-5. As the fan diameter increase causes a reduction in speed, the swallowing capacity ($W\sqrt{T}/P$) of the engine first core compressor decreases faster than the bypass propelling nozzle, therefore increasing the engine bypass ratio [7]. This changes the operating line of the component. Generally the increase in bypass ratio improves specific fuel consumption (SFC) and deteriorates specific thrust, with accompanying increase weight and drag penalties. The rise in bypass ratio increases fan tip speed and reduces shaft rotational speed. Increasing fan-turbine loading (ratio of fan flow to fan-turbine flow) and decrease in efficiency.

Table 6-5: Parameters of scaled engines before TET increase

	Baseline engine	Upgrade variant 1	Upgrade variant 2	Upgrade variant 3
Fan diameter [m]	2.443	2.449	2.455	2.461
Airflow scaling factor [-]	1.000	1.0054	1.0108	1.0163
Pressure ratio [-]	1.700	1.699	1.699	1.698
Efficiency [-]	0.910	0.9097	0.9094	0.9091
Airflow rate [Kg/s]	873.600	872.910	872.088	871.214
Corrected speed, CN [-]	1.000	0.996	0.993	0.989
PCN [-]	1.000	0.997	0.993	0.989
Bypass ratio [-]	5.300			5.353
Surge Margin, Z	0.850	0.854	0.859	0.864
TET [K]	1,667	1,667	1,667	1667
WC1 [J]	4.844E+07	4.838E+07	4.832E+07	4.8245E+07
Bypass nozzle area [m2]	2.071	2.071	2.071	2.071
Core nozzle area [m2]	0.522	0.522	0.522	0.522
Bypass nozzle velocity [m/s2]	314.200	314.200	314.200	314.06
Core nozzle velocity [m/s2]	541.860	541.890	541.910	541.93
SFC [g/s.KN]	9.715	9.709	9.705	9.702
Sp. Thrust [KN/Kg/s]	355.604	355.185	354.767	354.336
Net Thrust, FN [N]	310,655.88	310,655.88	309,388.12	308,703.04

To avoid unnecessary effect of fan diameter increase on downstream components, the upgrade variant corrected speed is adjusted to the same speed as the baseline ($N_{corr} = 100\%$) by increasing the engine TET on the basis that better component materials/cooling systems are used in the hot gas path components to maintain a significantly constant engine life and the fan blade tip stresses (due to increase speed) are within certification limits. This results in a corresponding rise in fan pressure ratio and inlet air mass flow, as well as a decrease in fan efficiency. Although the upgrade variants have some drawbacks in terms of efficiency and increased take-off SFC of up to 1.4952% for the 2.461m

fan diameter upgrade variant, it also promises a net thrust improvement of up to 2.263% as shown in Table 6-6.

Table 6-6: Parameters of scaled engines with TET increase

	Baseline engine	Upgrade variant 1	Upgrade variant 2	Upgrade variant 3
Fan diameter [m]	2.443	2.449	2.455	2.461
Airflow scaling factor [-]	1.000	1.0054	1.0108	1.0163
Pressure ratio [-]	1.700	1.705	1.710	1.716
Efficiency [-]	0.910	0.908	0.906	0.904
Airflow rate [Kg/s]	873.600	876.323	878.969	881.616
Corrected speed, CN [-]	1.000	1.000	1.000	1.000
PCN [-]	1.000	1.000	1.000	1.000
Surge Margin, Z [-]	0.850	0.856	0.862	0.869
TET [K]	1,667.000	1,705.300	1,713.700	1,722.500
WC1 [J]	4.844E+07	4.899E+07	4.954E+07	5.011E+07
Bypass nozzle area [m ²]	2.071	2.071	2.071	2.071
Core nozzle area [m ²]	0.5222	0.5222	0.5222	0.5222
Bypass nozzle velocity [m/s ²]	314.200	315.480	316.540	317.630
Core nozzle velocity [m/s ²]	541.860	543.350	544.840	546.410
SFC [g/s.KN]	9.715	9.762	9.810	9.860
Sp. Thrust [KN/Kg/s]	355.604	357.163	358.740	360.346
Net Thrust, FN [N]	310,655.88	312,989.77	315,320.82	317,687.32

Figure 6-3 shows the effect of fan diameter scaling and TET increase on the engine inlet mass flow rate of the upgrade variant engines. The linearly scaled fan diameter and the +55.5K TET increased produced an airflow rate increase of +8.016Kg/s and a consequent engine net thrust improvement as previously mentioned. However, the fan component efficiency reduction of up to 0.65% is experienced despite the pressure ratio rise (+0.94%) due to TET increase as

shown in Figure 6-4. The efficiency deterioration increased the fuel consumption up to about 1.4952%. The performance in terms of net thrust and SFC of the different engine upgrade variant corresponding to the increase in fan diameter and the baseline engine is presented in Figure 6-5. The graph shows increase in both thrust and fuel consumption at take-off condition, with the thrust gain higher than the fuel consumption rise.

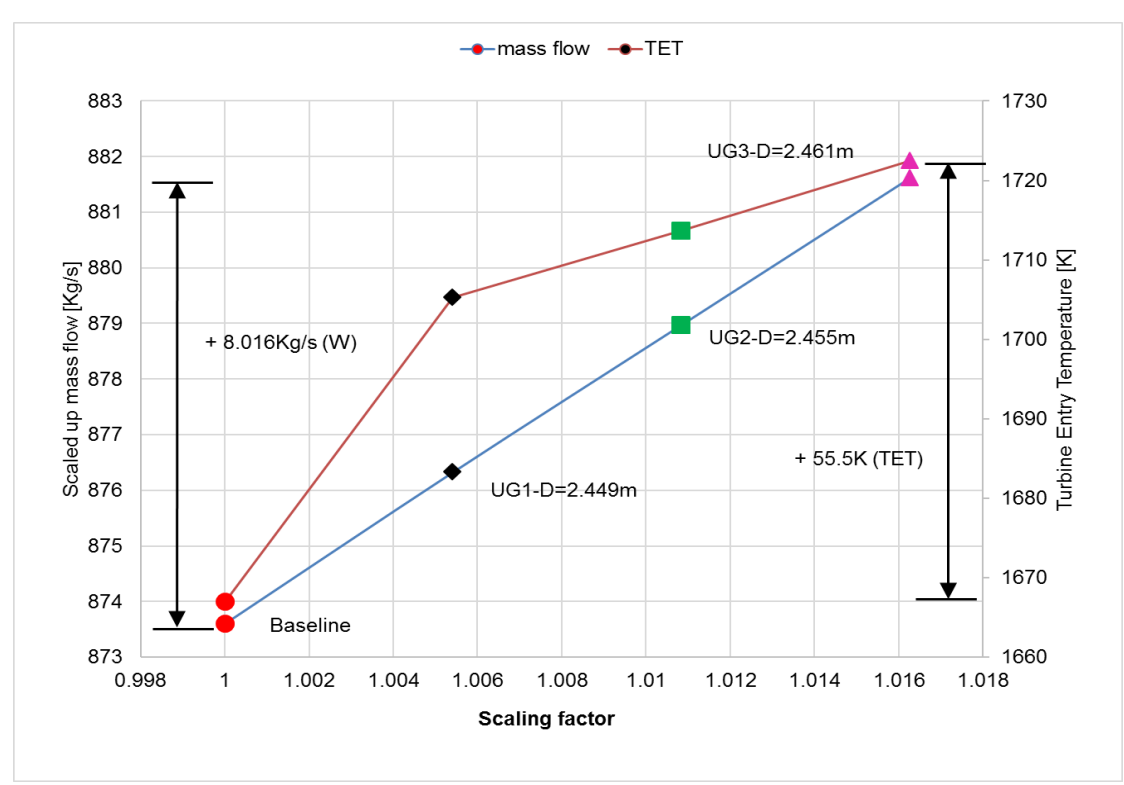


Figure 6-3: Effect of fan scaling factor and TET increase on mass flow

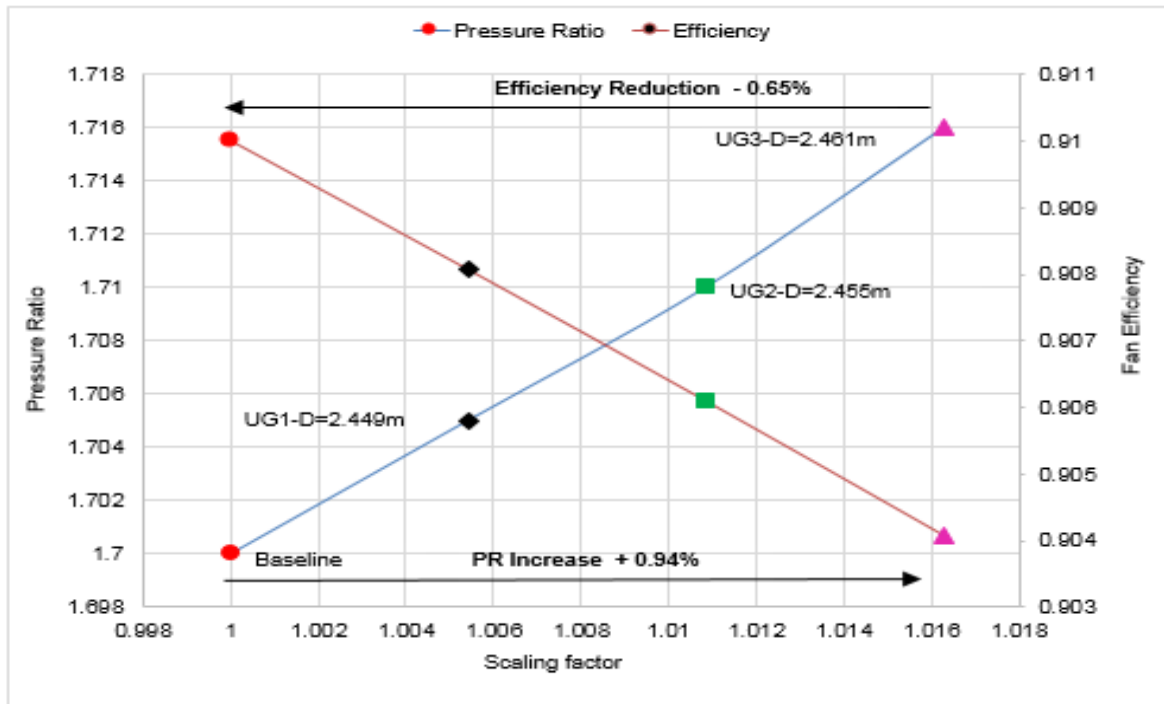


Figure 6-4: Effect of Upgrade on Fan pressure ratio and efficiency

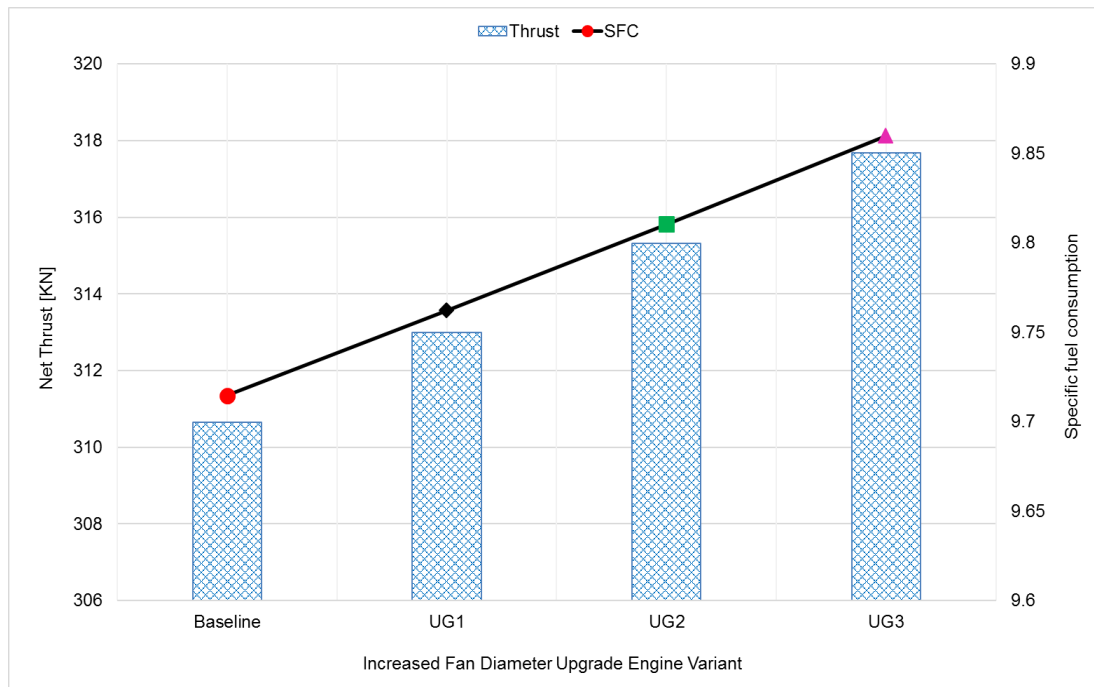


Figure 6-5: Effect of Upgrade on Net thrust and Specific fuel consumption

6.3.1 Compressor Characteristic Maps

The fan compressor maps shown in Figure 6-6 and Figure 6-7, illustrates the impact of upgrade on the corrected mass flow, pressure ratio and efficiency at any given speed line. For each speed line there is a maximum flow, which cannot be exceeded no matter how much the pressure ratio is reduced (towards choke condition). The baseline engine map is represented by the blue lines while the upgrade engine variant (UG3, D=2.461m) represented in red. Figure 6-6 uniquely shows that both engines have the same operating line allowing both engine core to be unaltered, therefore no need for any modification of downstream components. However, the slight increase in mass flow and pressure ratio for the upgrade variant at any given speed line, shows the effect of the increased fan diameter upgrade. In Figure 6-7, the efficiency decreases with increasing mass flow. As would be expected with compressor performance characteristics.

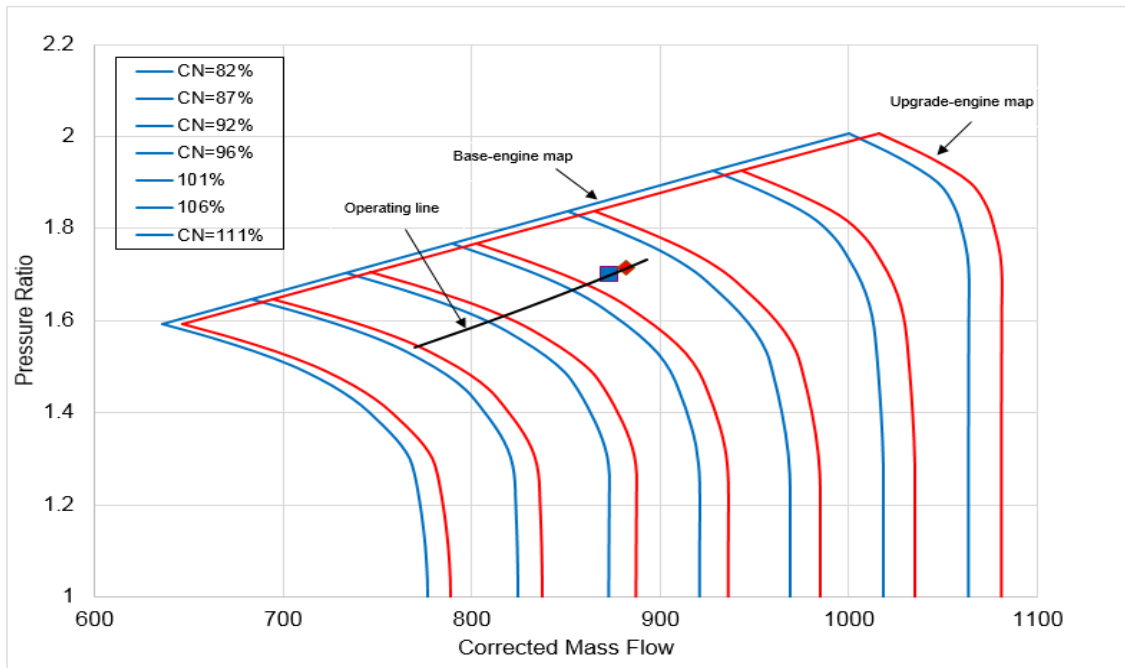


Figure 6-6: Fan compressor map - corrected mass flow vs pressure ratio

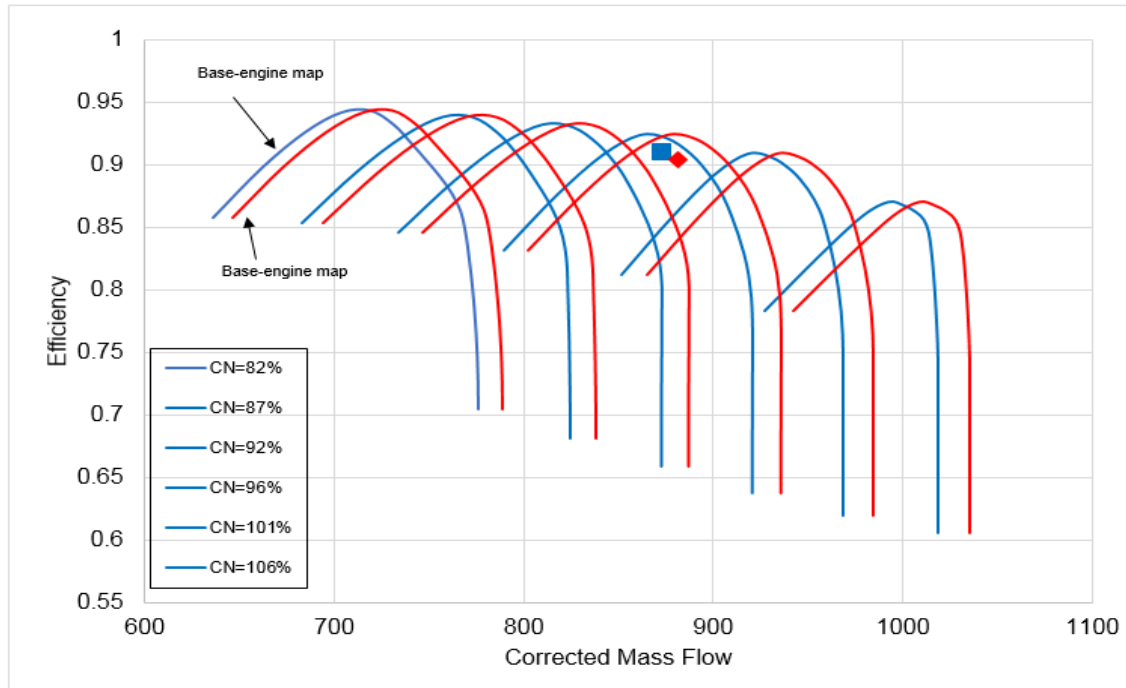


Figure 6-7: Fan compressor map - corrected mass flow vs efficiency

6.3.2 Check Potential for further Modification

Change in engine core and fan bypass nozzle areas affect the engine airflow capacity, pressure ratio and thrust, by adjusting the compressor running line towards or away from the surge line. Increasing the nozzle area at any given compressor speed reduces the pressure ratio, hence lowering the running line (i.e., move away from the surge line) [2]. This accelerates airflow thus affecting engine thrust and specific fuel consumption (SFC). Reducing the nozzle area, however increases pressure ratio, decreases flow and raise the running line towards the surge line. Since the upgrade variant is operated at higher TET with increased mass flow and pressure ratio, there is a need to explore further opportunities for increased thrust and improved SFC. Although such additional benefits must be considered in relation to the potential weight penalty of variable nozzle geometry.

6.3.2.1 Bypass Nozzle Area Change

Impact of further modification on the engine performance was investigated by varying the bypass nozzle area while core area is held constant. Figure 6-8 and Figure 6-9 shows the effect variable fan nozzle area on net thrust and SFC respectively, for three different upgrade variants (UG1, UG2 and UG3). For all cases, the potential gain was less than 0.2% considering the huge weight penalty associated with incorporating variable geometry device. Thus, the modification was not feasible and the fan nozzle areas of the upgrade engine variant untouched.

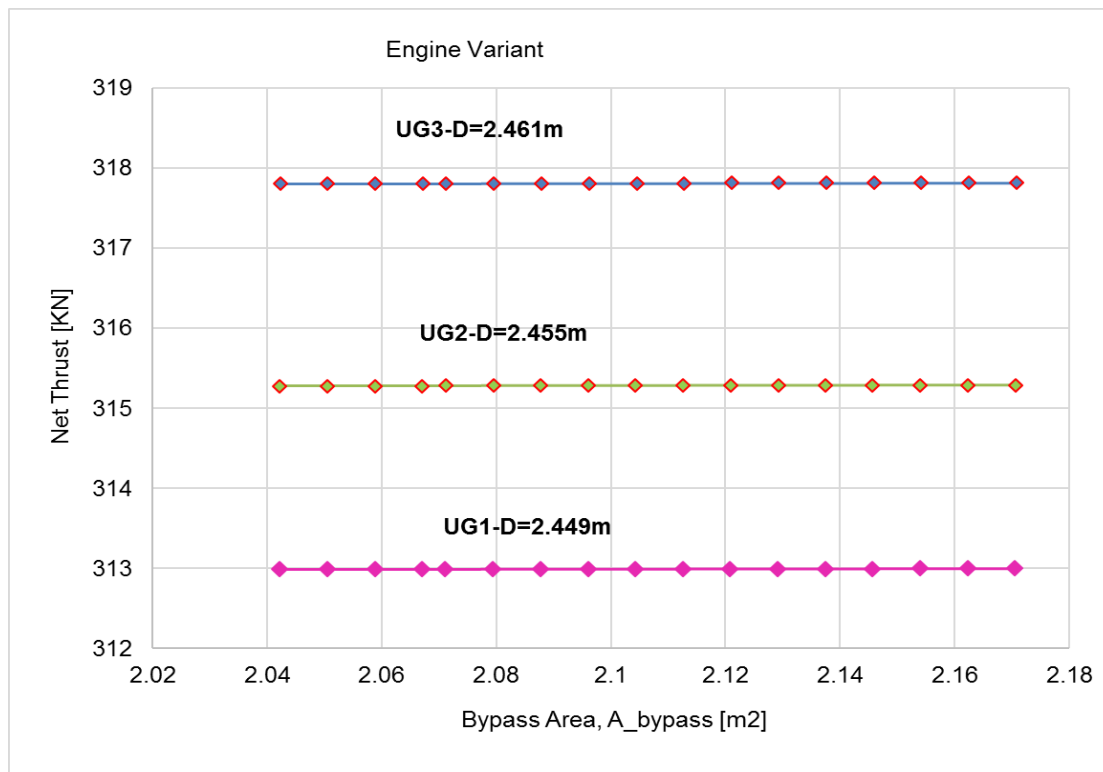


Figure 6-8: Effect of change in Bypass nozzle area on engine net thrust

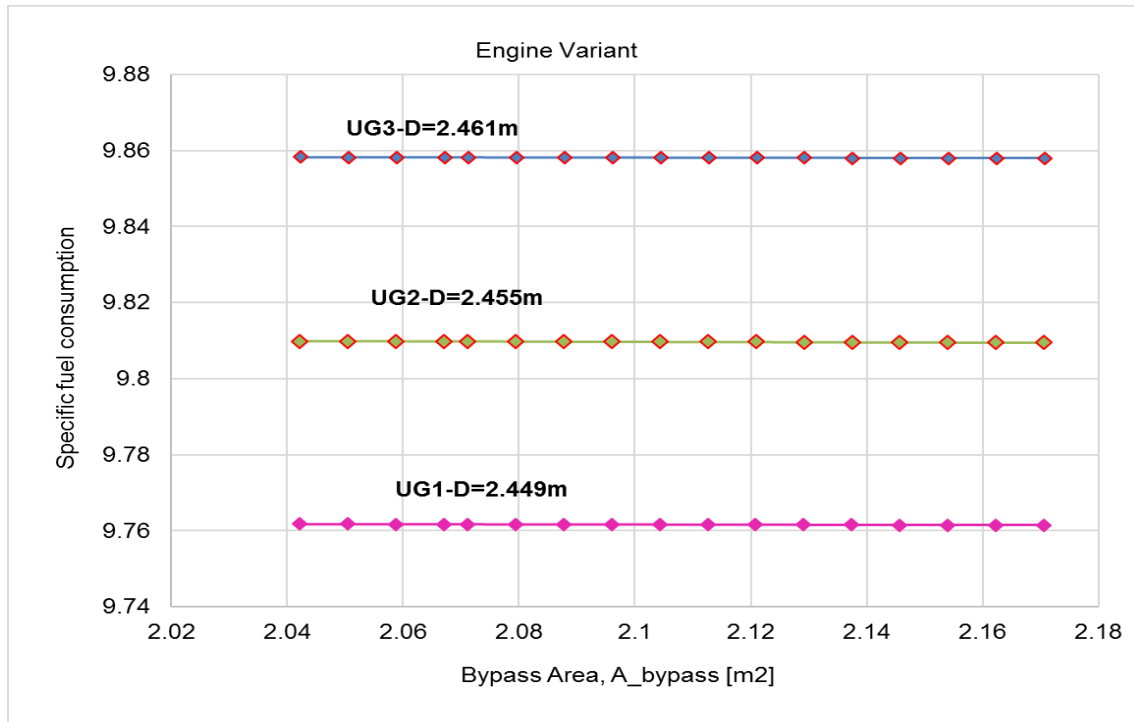


Figure 6-9: Effect of change in Bypass nozzle area on engine SFC

6.3.2.2 Core Nozzle Area Change

Similarly, the fan nozzle area was kept constant and the core nozzle area varied to investigate potential gains. Figure 6-10 and Figure 6-11 shows the impact on engine net thrust and SFC, respectively. As illustrated in the graph both parameters show slight improvement as would be expected. However, the gains were less than 0.5% which is not sufficient to offset the associated penalties in weight, complexity etc. Therefore, the modification is not feasible. Thus, the upgrade engine variants presented in Table 6-6 are utilised for aircraft mission and performance benefit analysis.

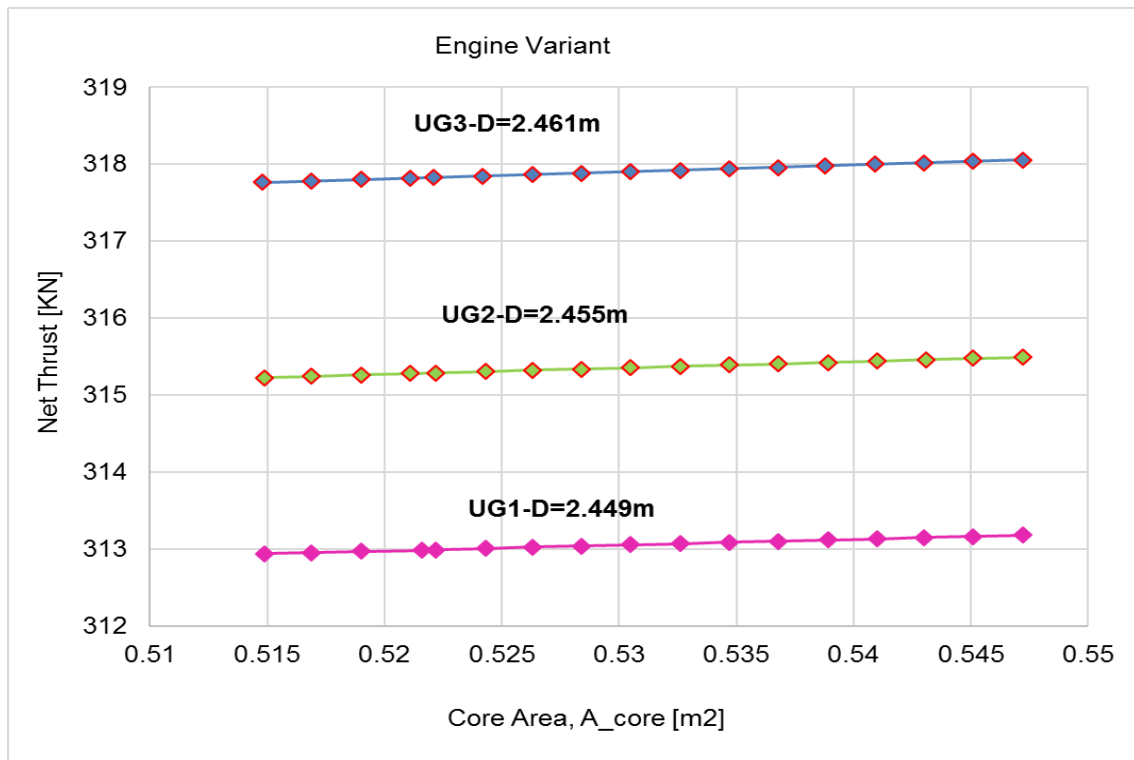


Figure 6-10: Effect of change in core nozzle area on engine net thrust

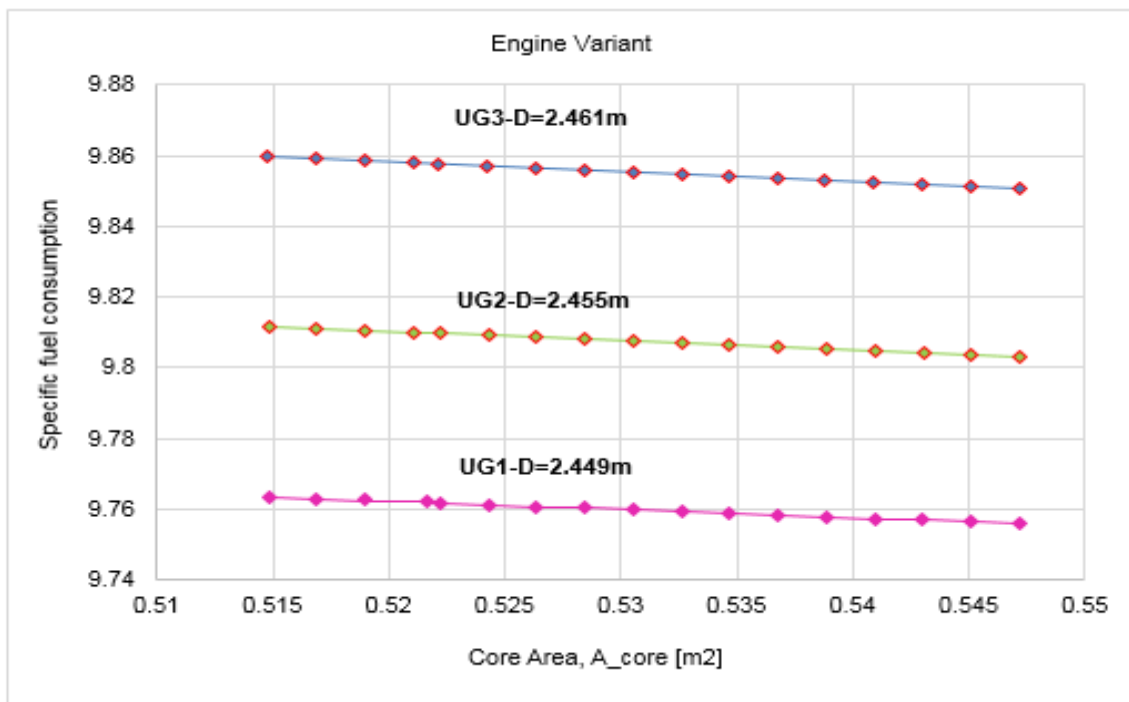


Figure 6-11: Effect of change in core nozzle area on engine SFC

6.3.3 Effect of Upgrade on Engine Weight

The potential weight increase of the upgrade variants is estimated using the weight models discussed previously in chapter 3 is shown in Figure 6-12. As the engine, fan diameter increases the weight penalty rises. An additional weight of up to 48.37Kg relative to CEUP6-80 engine weight was gained after implementing the upgrade (UG3, D=2.461m). Other upgrade variants produces engine weight increase of +10.73Kg (UG1, D=2.449m) and +29.52Kg (UG2, D=2.455m). The effect of this engine weight increase is experienced in aircraft performance analysis, since it increase the aircraft total weight and consequently the aircraft fuel burn as indicated by the Brequet equation [6].

$$\text{Fuel mileage} = V \cdot (L/D) / SFC \cdot W$$

Equation 6-25

This weight increase is implemented in the HEMES code to predict the aircraft performance.

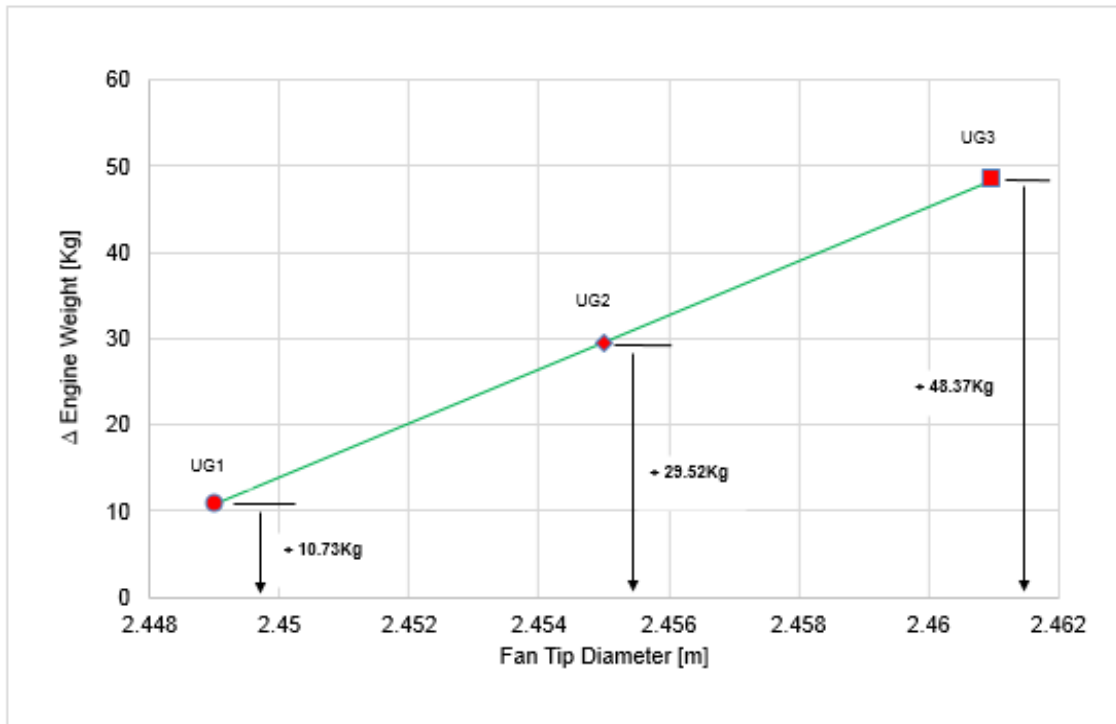


Figure 6-12: Effect of Upgrade on engine Weight

6.3.4 Effect of Component Efficiency

As observed previously there is deterioration in fan efficiency of the upgrade variant engines. To effectively maximise the benefit of this upgrade a fan blade of improved aerodynamic design to yield high efficiency is assumed. Figure 6-13 shows the impact of increased fan efficiency on the upgrade variant performance in terms of SFC and net thrust. The UG line shows approximately where the UG1 ($\eta_{fan}=0.90807$), UG2 ($\eta_{fan}=0.90807$), and UG3 ($\eta_{fan}=0.90807$) variant fan efficiency falls, and their corresponding SFC and net thrust. With an increased fan efficiency of $\eta_{fan}=0.91$ (same as baseline engine), the UG-E line shows the corresponding improvement in SFC and net thrust of the different upgrade variants.

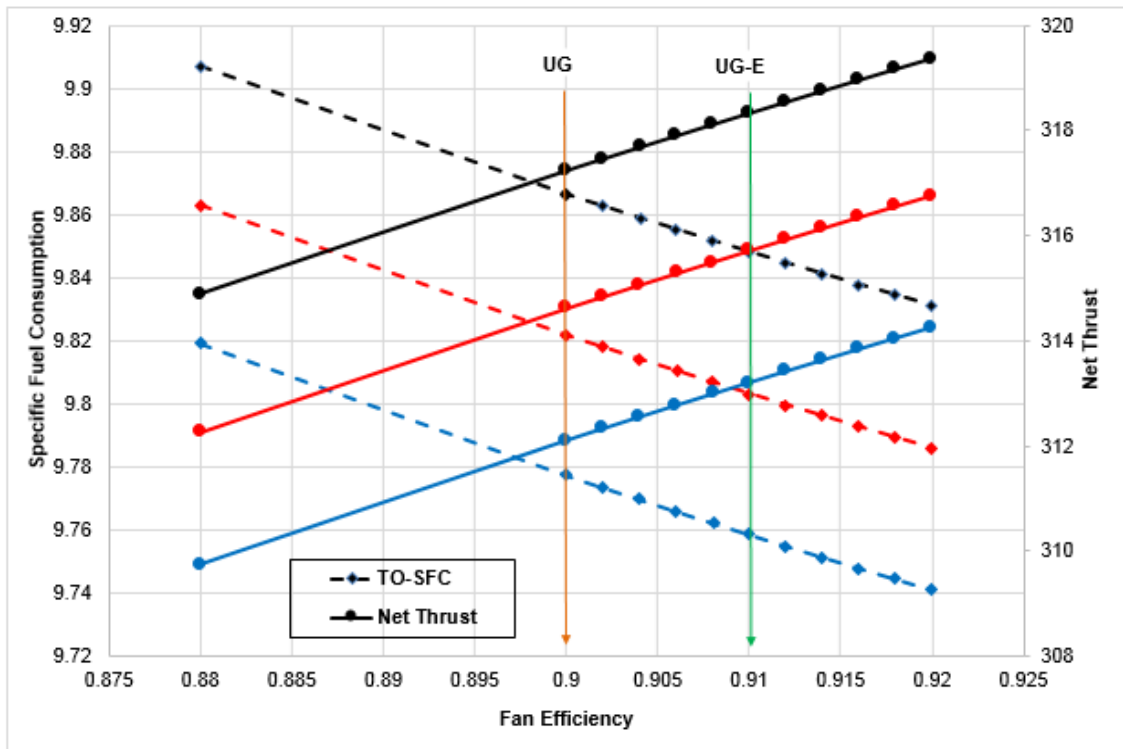


Figure 6-13: Effect of Increased fan efficiency on SFC and net thrust

6.3.5 Impact on Aircraft Performance Systems

This subsection investigates the impact of the different upgrade engine variants on aircraft performance and the potential benefits in terms of aircraft fuel burn reduction, payload improvement, take-off length or balance of field length (BFL) reduction, and aircraft direct operating cost (DOC) improvement. To quantify and analyse the potential benefits of these upgrade variants on the aircraft performance, two case studies are discussed. The fuel burn improvement (Case-1) and the payloads benefit (Case-2).

6.3.5.1 Reference Aircraft and Mission Profile

A long-range aircraft is used as a reference vehicle to access the upgrade variant technology. The long-range aircraft configuration is a 230,000 Kg MTOW Cranbus-A330 model based on Airbus A330-like resemblance, carrying 283 passengers, maximum range of 17,000Km (9179nm), cruising speed of Ma 0.82 and take off field length of 2531m. The choice of airplane selection and range is to allow aircraft operation sufficient time on cruise phase where fuel burn is most important (long-range aircraft, therefore providing the opportunity to reap the most benefits of improved specific fuel consumption (SFC) the increased fan diameter engine upgrade offers. Figure 6-14 shows the reference aircraft cabin layout.

A trans-Atlantic flight route from Murtala Muhammed International Airport (Lagos, Nigeria) to John F Kennedy International Airport (New York, USA) was selected as reference mission in this analysis. The total flight range is approximately 8453Km (4565nm) apart, and flying at a cruise altitude of 35000ft (10668m).

The aircraft performance simulation performed in HERMES was repeated for all the upgrade engine variants to predict the block fuel consumed for the given aircraft payload-range and flight mission specified, as well as the total flight duration and total range covered.

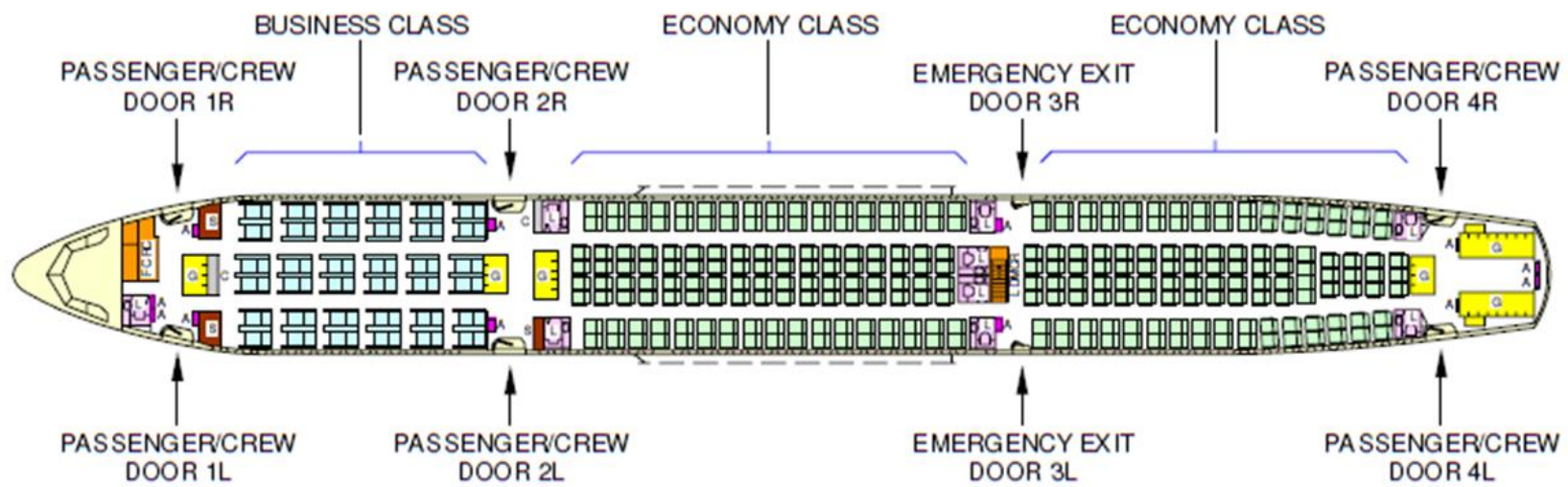


Figure 6-14: The long-range Cranbus-A330 (Airbus A330) reference seat/cabine layout or configuration

Table 6-7: Aircraft fuel burn performance of the engine upgrade variants

	Baseline	Change in Efficiency			Constant Efficiency		
		UG1	UG2	UG3	UG1-E	UG2-E	UG3-E
Engine Weight [Kg]	5091	5101.73	5120.52	5139.37	5101.73	5120.52	5139.37
TET [K]	1697	1705.3	1713.7	1722.5	1705.3	1713.7	1722.5
Payload [Kg] *	29735	29735	29735	29735	29735	29735	29735
Seats	283	283	283	283	283	283	283
MTOW [Kg]	230000.00	230000.00	230000.00	230000.00	230000.00	230000.00	230000.00
Actual TOW [Kg]	201384.69	201368.29	201375.83	201378.99	201323.71	201296.82	201258.97
Block fuel [Kg]	51570.68	51532.83	51502.94	51468.697	51487.38	51422.10	51345.93
Block Time [mins]	603.71	603.73	603.76	603.77	603.81	603.92	604.02
Block Range [Km]	8509.08	8509.02	8508.99	8508.95	8509.02	8508.98	8508.94
Fuel burn per seat-Km	0.02142	0.02140	0.02139	0.02137	0.02181	0.02135	0.02132

*One of the key benefits of this upgrade for payload improvement is discussed in section 6.3.8.

Table 6-7 presents the different engine upgrade variant performances when installed on the aircraft. Even with the increased aircraft weight due to engine weight increase and higher TET, there is slight improvement in fuel burn as upgrade fan diameter increases, and more gains experienced with engine variants with improved fan efficiency.

6.3.6 Economic Evaluation of Upgrade Benefits

This section discusses the economy the economic model of the TERA framework utilised in this study. Once the performance models of the engines and aircraft are established as discussed in previous subsections, the aircraft-engine systems are then simulated to investigate the economic perspective of the system upgrade. The economic framework enables the economic-investment costs analysis (also known as the cost-benefit analysis) of the upgrade variant technologies which may determine the economic viability of the upgrade investment. The evaluation aims to present the performance benefit of the upgrade variant technologies from an economic perspective for decision makers and financiers of upgrade technologies.

Predicting the economic performance of these upgrade variants requires the estimation of the aircraft operating costs. These costs are usually of two components, the direct and indirect operating costs. The indirect operating costs for a project are typically more demanding to attribute as they include items like administrative costs, and other miscellaneous costs difficult to fully capture as it varies from project to project. Therefore, for the purpose of this simulation only the direct operating cost (DOC) of the aircraft is used.

6.3.6.1 Aircraft Operating Costs

Direct operating costs (DOC) consist of three-cost constituents: time, fuel and emission related costs [66][54]. The fuel and emission costs are a function of the engine fuel efficiency and the mission flown. They are inter-related, the more fuel burnt the higher the emission produced. The time related costs are basically

associated with the purchase and ownership cost of the aircraft, and includes crew salary, depreciation, interest, insurance costs, and maintenance costs.

Figure 6-15 shows the aircraft direct operating cost (DOC) breakdown for baseline engine at reference flight mission. The highest cost component 39.49% is the total standing charges, which are made up of costs of depreciation, interest and insurance of aircraft. It is followed by the cost of fuel 27.53%, indicating the importance of engine fuel efficiency and fuel price to airline profitability.

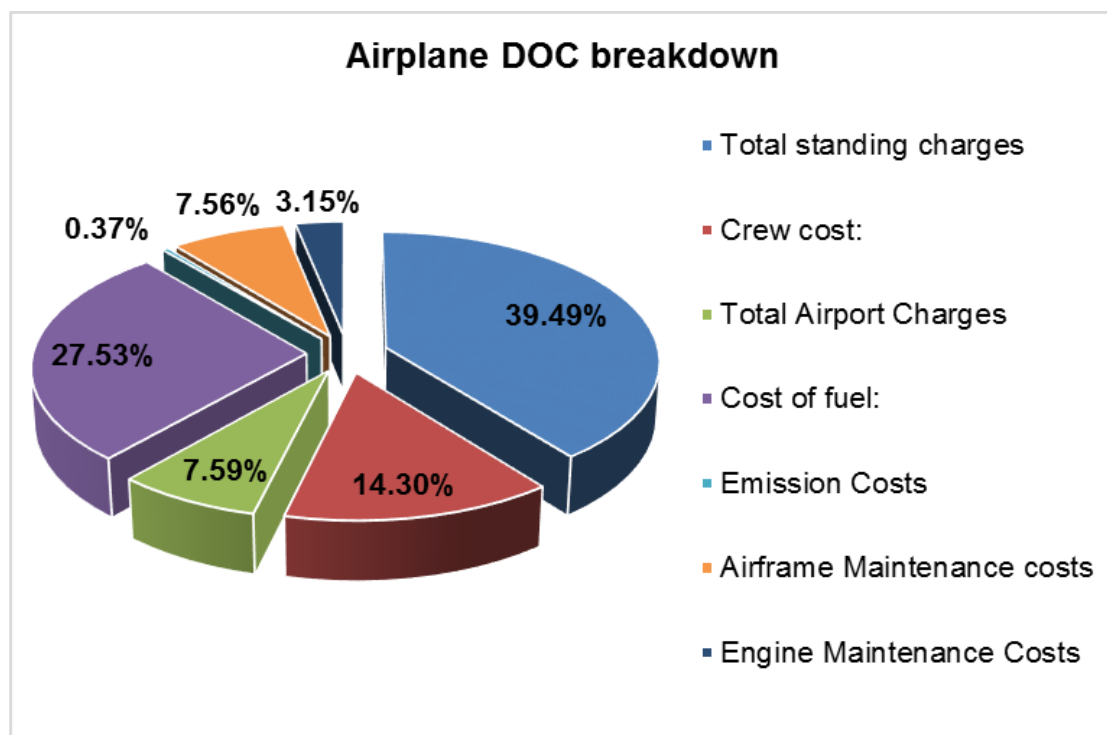


Figure 6-15: Aircraft Direct Operating Cost (DOC) of baseline engine at reference mission

6.3.6.2 Upgrade/Modification Costs Estimation

The economic viability of upgrade investment depends significantly on the costs of the upgrade project. To estimate the cost of these upgrade engine variants, assumptions are made based on Fasching modification costs [97]. Table 6-8 shows the estimated costs to carry out Fasching's engine modification of

increasing fan diameter from 2.195m to 2.311m at 1977 USA dollar. Based on this data and the level of fan diameter increase implemented, the cost of the engine variants (UG1, UG2, and UG3) modifications were calculated and converted to 2017 value of USA dollar. To incorporate the cost of the modification in the investment economic analysis, the new engine price given by Equation 6-26 is then used

New Engine Cost

Equation 6-26

$$= \text{Old Engine Cost} + \text{Cost of Modification}$$

In the author's view the assumptions made here are rather over-exaggerated as the modification proposed in this work is little compared to Fasching's proposed modifications [97].

Table 6-8: Modification cost estimation based on Fasching's modification data

	Original Dia. [m]	Mod. Dia. [m]	Δ- Change [m]	Δ- Change [%]	Mod. cost@1977 dollar	Mod. cost@2017 dollar
Fasching mod. [97]	2.195	2.311	0.116	5.285	200,000	
UG1	2.443	2.449	0.006	0.246	9,294.68	38,190.65
UG2	2.443	2.455	0.012	0.491	18,589.35	78,381.30
UG3	2.443	2.461	0.018	0.737	27,884.03	117,571.94

6.3.6.3 Net Present Value (NPV) and Internal Rate of Return (IRR) Analysis

One of the most popular concepts for assessing project viability and investment decision making is the Net Present Value (NPV). The NPV estimates the future values of present investments taking into account that the cash flow value of the future holds less weight to the same present value. This is accomplished by using the discounted cash flow analysis. The discount factor applied is the interest rate, a value that represents the costs a company attributes annually to debt and equity. The NPV is calculated by Equation 6-27

$$NPV = \sum_{n=1}^{life} \frac{Profit}{(1+r)^n} - X \quad \text{Equation 6-27}$$

Where X is the investment cost of upgrade technologies

The Internal Rate of Return (IRR) is also a suitable way of assessing investment viability. It is that rate value for which the investment/project just breaks even. The point where the NPV is zero – the expenditure exactly cancels out revenue. In the aviation industry, the value typically lies between 6 – 8% [66][94]. However, the higher the IRR value, the better the return on investment of that project. The IRR is calculated by Equation 6-28.

$$0 = \sum_{n=1}^{life} \frac{Profit}{(1+IRR)^n} - X \quad \text{Equation 6-28}$$

6.3.7 CASE 1: FUEL BURN IMPROVEMENT

The first case considers the effect of increased Fan Diameter Engine Upgrade on aircraft fuel burn improvement, operating cost benefits and the overall viability of the upgrade project investment via NPV analysis. Six Engine upgrade variants (UG1, UG2, UG3, UG1-E, UG2-E, and UG3-E) with engine performance characteristics discussed previously are considered and simulated individually with the Cranbus A330 aircraft model in HERMES at a reference mission range of 8454.38Km, as illustrated in Table 6-7.

Aircraft engine rate of fuel consumption is usually expressed in terms of specific fuel consumption (SFC). Engine SFC is defined as the engine fuel mass flow rate divided by the engine net thrust. For a given aircraft speed, range and fuel type, the SFC of an engine is proportional to both thermal efficiency and propulsive efficiency. This means increasing these efficiencies results in SFC reduction. Increasing simultaneously both OPR and TET increase the thermal efficiency, which is one way of improving SFC. The other method of decreasing SFC is through engine BPR and FPR. For a given BPR there is an optimum FPR which

minimises SFC. Also for a given OPR, the SFC decreases with increase in engine BPR. This is achieved because increasing BPR, decreases FPR and gas jet velocity, which in turn produces propulsive efficiency improvement and consequent reduction in SFC. In the increased fan diameter engine upgrade variants used in this study, the upgrade modification was associated with increase mass flow and TET, which in turn increases engine thrust and thermal efficiency, and consequent mid-cruise SFC. The upgrade engine TET (and OPR) increase was based on the assumption of the use better materials to cope with the increased compressor delivery temperature and TET.

The potential impact/benefits of the upgrade engine installed on aircraft quantitatively summarised below. Figure 6-16 shows the potential fuel burn reduction, engine take-off (TO) SFC, and flight mid-cruise SFC corresponding to the different engine upgrades variant and baseline. A steady trend of fuel burn improvement and mid-cruise SFC with increasing fan diameter upgrade is observed, even though the engine TO SFC increases due to the increased TET associated with the upgrade. An approximately 0.436% fuel burn savings reference to baseline is gain when operating the UG3-E engine variant.

Figure 6-17 shows the impact of the engine upgrade variant relative to baseline on parameter such as TET, net thrust, engine weight, and Balance of field length (BFL). As illustrated in Figure 6-17, increasing fan diameter upgrade engine comes with associated increase in TET, net thrust, and engine weight reference to baseline. The higher net thrust as a result of increase TET have improved the aircraft capability for shorten take-off field length for any given payload and airport local air conditions. With around 2.41% reductions in BFL when operating with UG3-E upgrade variant.

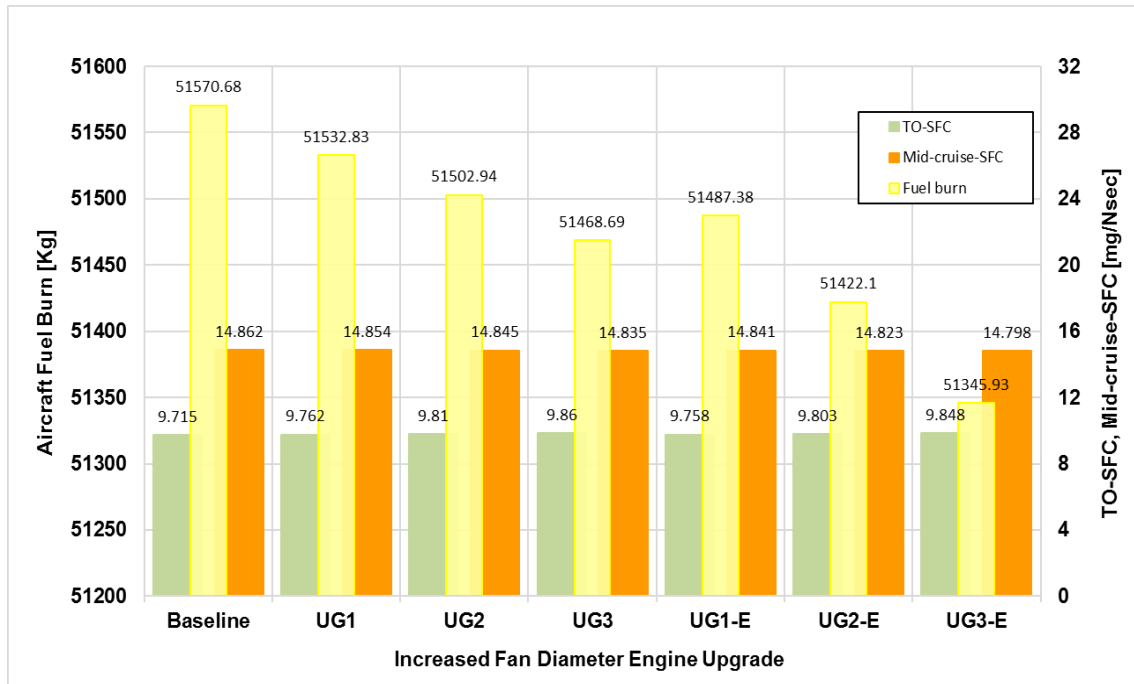


Figure 6-16: Effect of Increased fan diameter engine upgrade on fuel burn, TO-SFC, and mid-cruise SFC

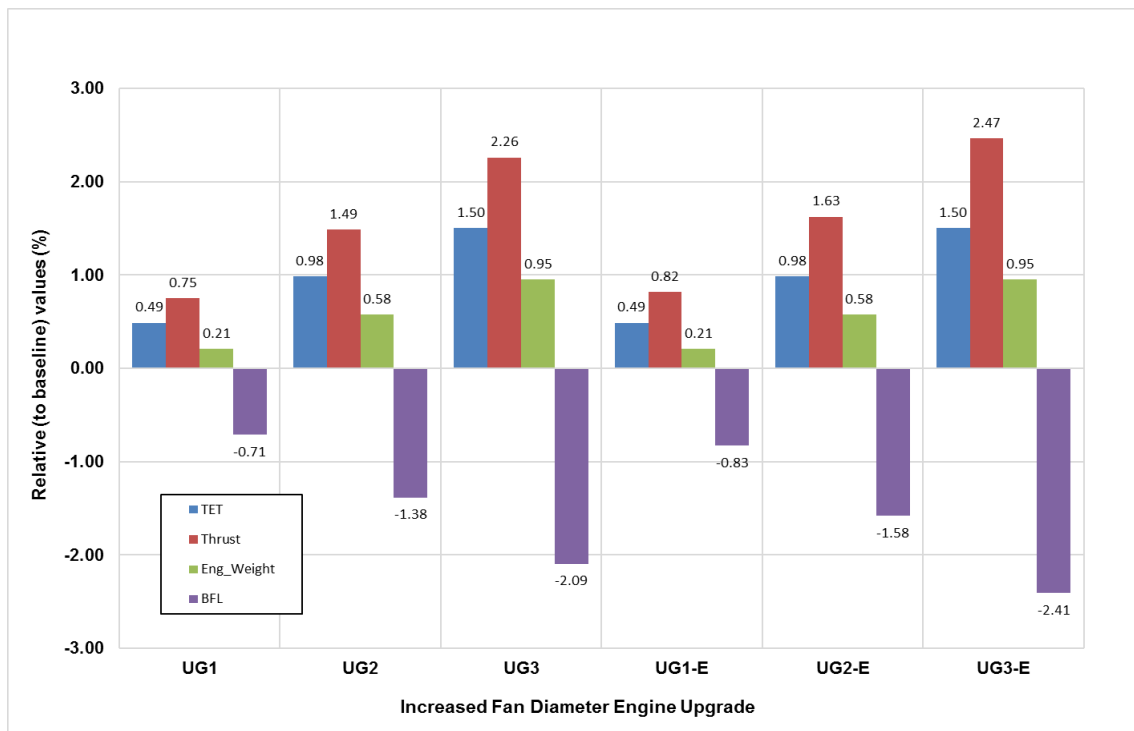


Figure 6-17: Effect of Increased fan diameter engine upgrade on TET, Thrust, Engine weight and BFL (balance of field length)

The economic performance for the aircraft/engine combination of the different increased fan diameter engine upgrade variants is illustrated in both Figure 6-18 and Figure 6-19. The results are based on a set of reference mission parameters such as payload (29,735Kg), and fuel price (179c\$/US gallon) at 0.92\$/€ money conversion value. Figure 6-18 shows the effect of the upgrade engine variants on any possible gain in direct operating costs per flight (Δ DOC), annual profit/savings and the upgrade investment cost. The direct operating cost is made up of constituent cost components as illustrated in Figure 6-15. The total standing charges are calculated annually based on the assumed average utilisation of the aircraft which is then computed per flight hour basis. For the reference mission specified, the computed maximum annual utilisation 313 flight cycles or 3158 flight hours and 10 hours per flight for baseline engine technology was reported. Other important input costs variables used for DOC calculation is shown in Table 6-9.

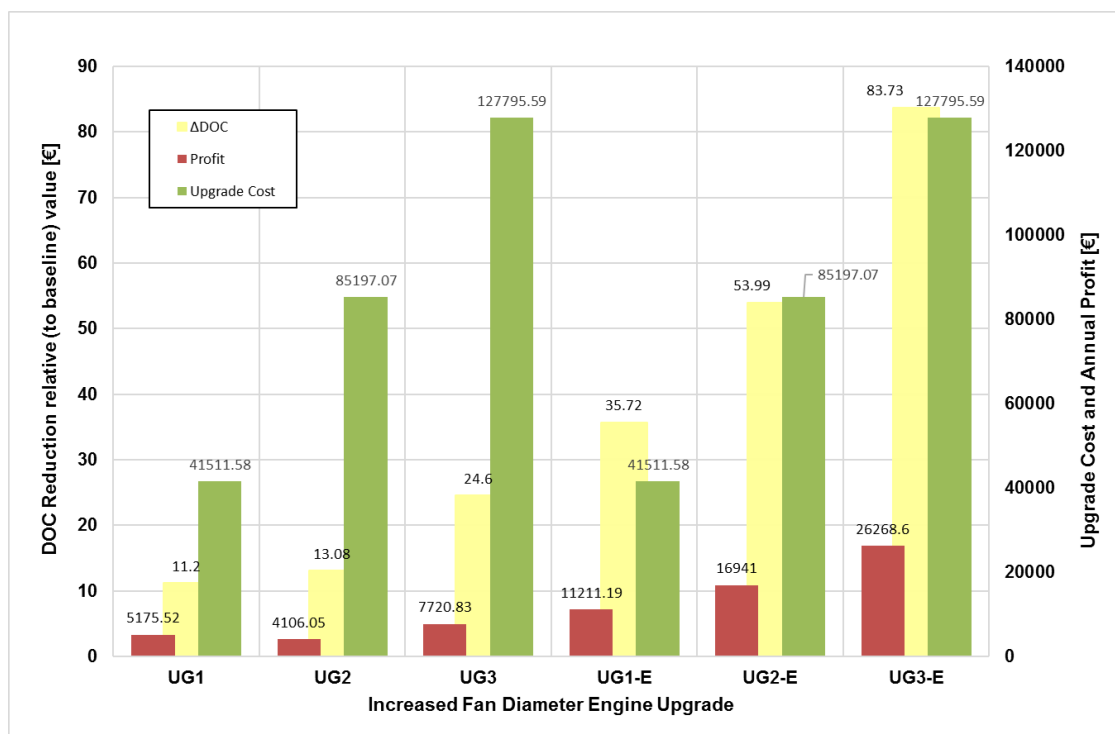


Figure 6-18: Effect of Increased fan diameter engine upgrade on DOC, annual savings/profit, and upgrade Investment costs

Table 6-9: DOC costs variables

DOC Costs Variables	Values
Depreciation	6.0%
Interest rate	2.0%
Insurance rate	0.5%
Maintenance labour rate [€/man-hour]	70
Cost of crew member per block hour	90
Cost of flight crew member per block hour	360

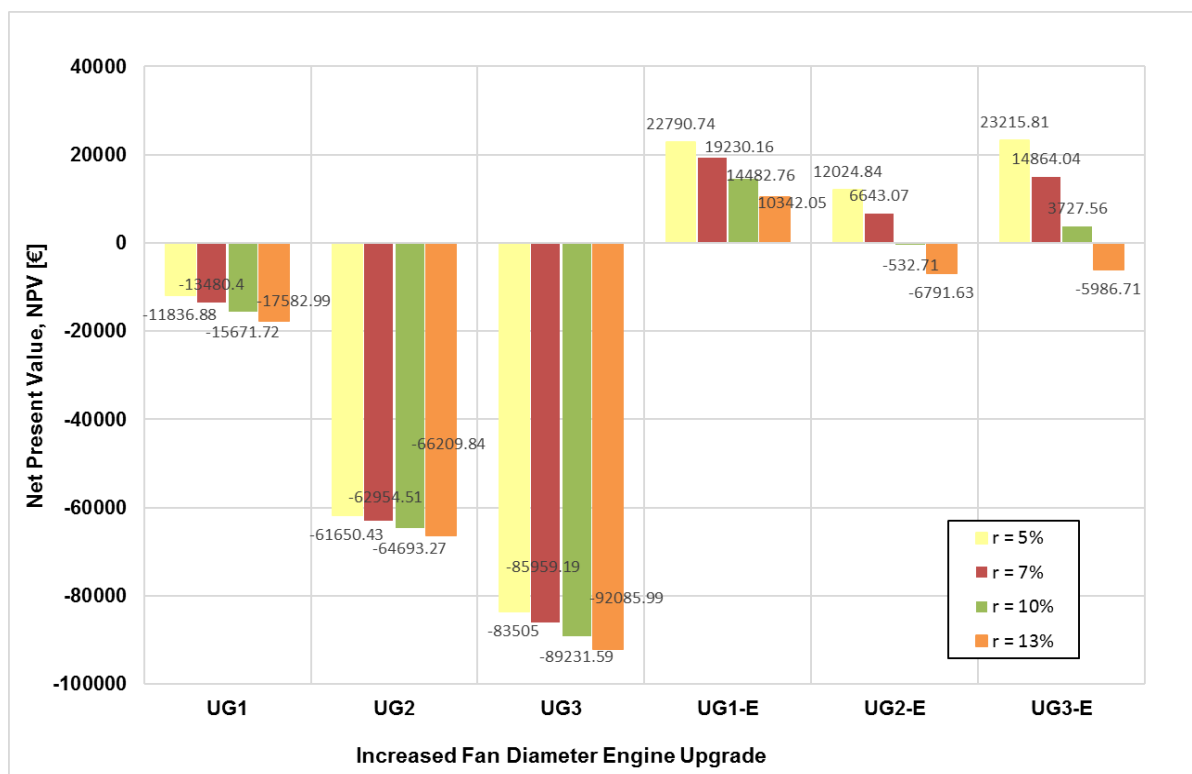


Figure 6-19: Increased fan diameter engine upgrade Investment NPV at different discounted rates

The gains from the upgrade technology are evaluated in terms of annual savings in direct operating costs (called profit) reference to baseline engine DOC. The profit/savings accrual DOC reduction for the upgrade variant is calculated by Equation 6-29.

$$Profit = [(DOC * N_{flight})_{baseline} - (DOC * N_{flight})_{upgrade}] \quad \text{Equation 6-29}$$

Where N_{flight} is the number of flight cycles per year.

This parameter captures the effect of change in mission range on the potential saving accrual.

The upgrade investment cost is very crucial to whether the investment would be economically viable or commercially acceptable or not. The upgrade investment cost is incorporated in the calculation by summing the old engine price and the upgrade/modification investment cost to get the new engine price, as shown in Equation 6-26.

Figure 6-19 shows the NPV for the different upgrade variant investment at 5%, 7%, 105%, and 13% discounted rate. The NPV is calculated based on annual savings in DOC using Equation 6-27 above. As illustrated in Figure 6-19, the NPV values for UG1, UG2, and UG3 for all four different discounted rates are negative and positive for UG1-E, UG2-E, and UG3-E except for the 13% discounted rate for the UG2-E and UG3-E engines. As it's commonly known, any investment with negative NPV value is non-viable.

Considering the investments with negative NPV, although they all produced annual savings in DOC for the operational period (i.e., engine TBO in years), their gains were not sufficient to offset the upgrade investment cost. This however, provides useful insights for decision makers, policy makers and financiers of upgrade technologies.

6.3.8 CASE 2: PAYLOAD IMPROVEMENT

Having established and quantified the potential performance and economic benefits, and identify limitations associated with the increased fan diameter engine upgrade variants when applied for the purpose of obtaining cost savings due to fuel burn reduction, the next case examines the application for increased payload carrying capacity of the aircraft for a given take-off field length. Figure 6-20 shows the payload increase capability and the consequent fuel burn of an aircraft due to the increased fan diameter upgrade technology. A payload increase benefit of up to 7.36% (2189.15Kg) was achieved when UG3-E engine variant is used in the aircraft, with the accompanying consequence of fuel burn increase of 0.3657% (188.6Kg).

However, despite the accrued penalty in fuel burn, the business opportunity in this application is accessed from the perspective that the additional revenue obtainable from the increased payload to carry extra passengers or cargo would be sufficient to offset the increased cost, with surplus accounting for the investment gains.

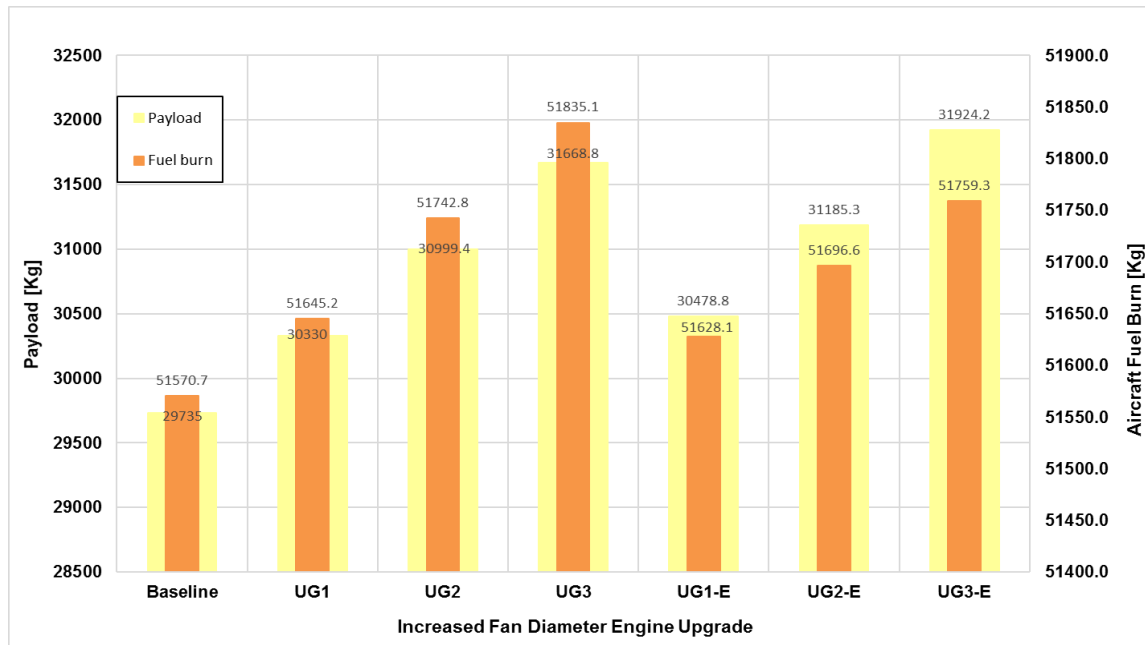


Figure 6-20: Effect of Increased fan diameter engine upgrade on Payload, and Fuel burn of aircraft

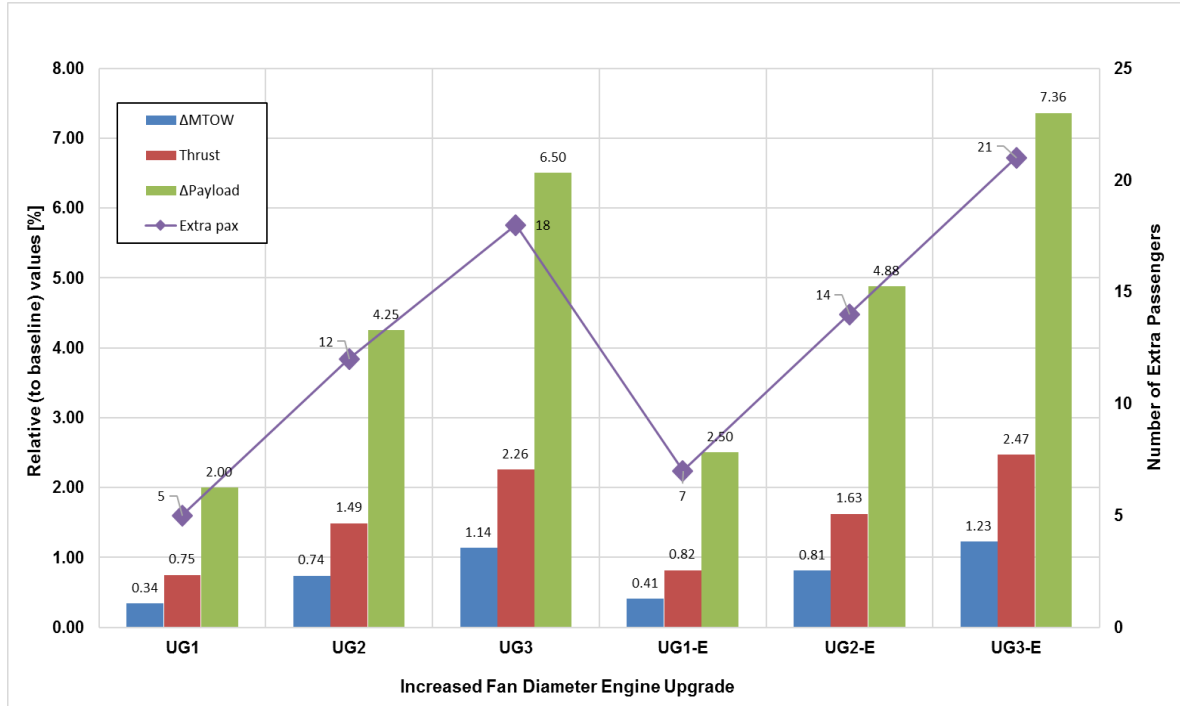


Figure 6-21: Effect of Increased fan diameter engine upgrade on MTOW, Thrust, Payload and Extra pax

Figure 6-21 shows the effect of the upgrade engine variant on parameters such as aircraft maximum take-off weight (MTOW), TO-thrust, and extra payload reference to baseline engine, as well as additional passenger that can be carried. For example, the UG3-E engine delivering a net thrust increase of 2.47% is able to carry 21 (7.36% increase) additional passenger with a given take-off field length (baseline engine BFL=2531m).

To evaluate the economics of this application the annual profit is calculated by Equation 6-30.

$$Profit = \left[(N_p \times T_p \times N_{flight}) + \left[(DOC \times N_{flight})_{bl} - (DOC \times N_{flight})_{upgrade} \right] \right]$$

**Equation
6-30**

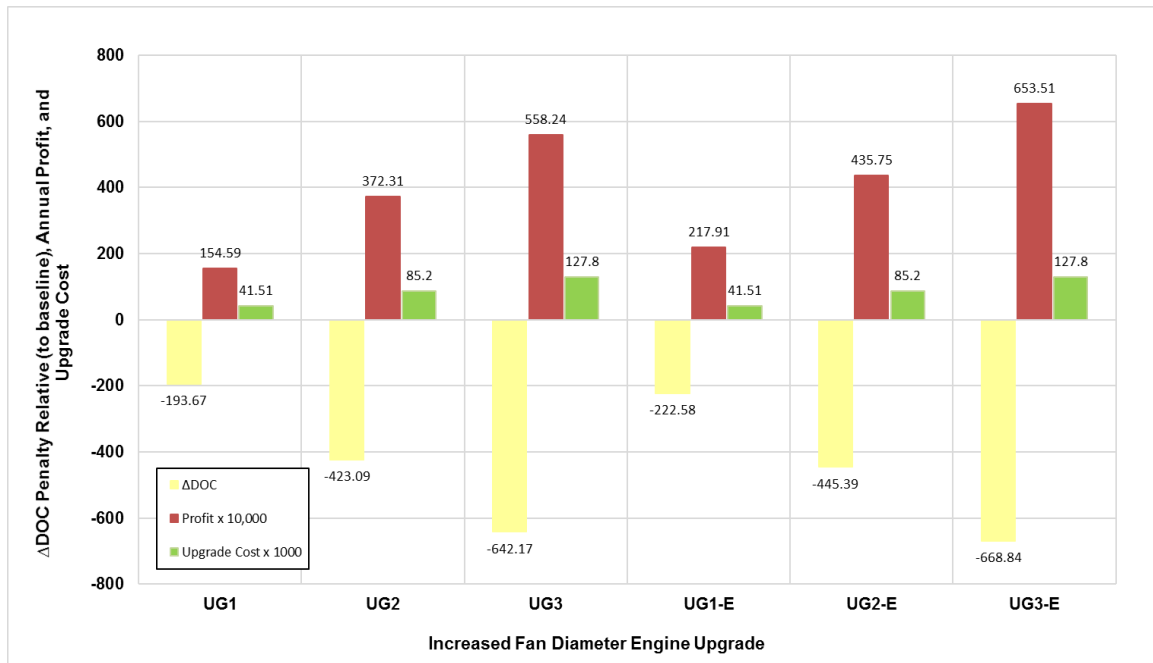


Figure 6-22: Effect of Increased fan diameter engine upgrade on DOC, annual profit/savings, and upgrade investment costs

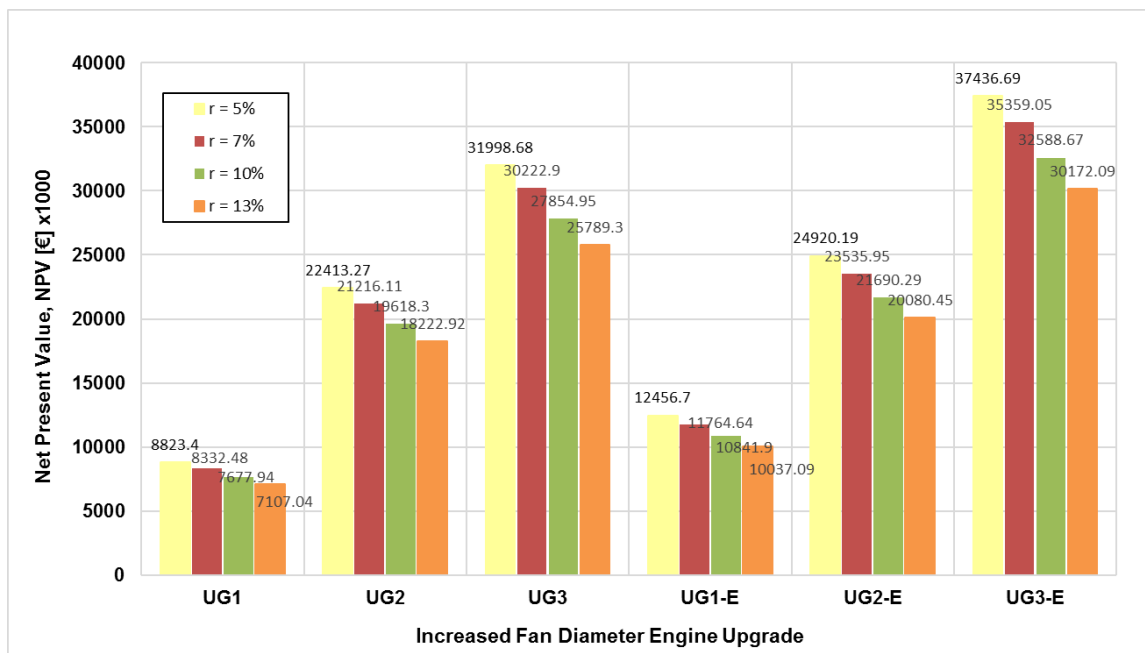


Figure 6-23: Increased fan diameter engine upgrade investment NPV at different discounted rates

The benefit accrued is from the revenue generated from the extra passenger and any potential gains in fuel burn savings. In this case, there was no savings rather costs penalties due to increased fuel burn. Therefore, for the investment to produce any reasonable gains the revenue obtained from the extra passenger must be significantly greater than the costs increase.

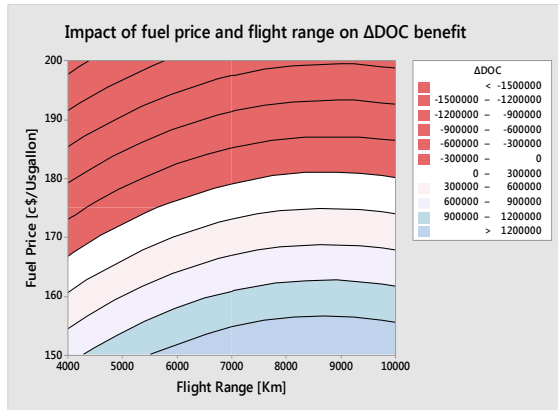
Figure 6-22 shows the direct operating cost, profit and upgrade investment cost associated with the different engine upgrade variant. As illustrated the Δ DOC penalty and profit gains both increase as the fan diameter increases. The NPV of the object with different discounted rates is presented in Figure 6-23. All the NPV values are positive indicating that the revenue from the extra passengers is greater than the costs penalties from both the increase fuel burn and investment cost.

6.3.9 SENSITIVITY ANALYSIS

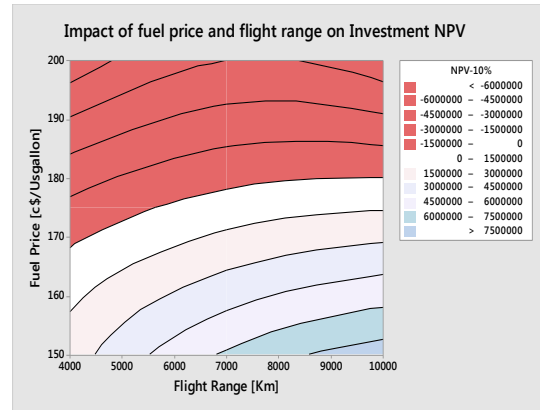
The economic profitability associated with the upgrade investment is influenced by both performance and operational parameter/strategy the engine-aircraft system uses. Sensitivity analysis is usually performed to explore the influence of small deviations or perturbation on the main performance/economic parameter reference to baseline values. The outcomes of this analysis provide insight on the feasible operational range for which investment in the technology proves economically viable.

Sensitivity Analysis on Fuel Burn Improvement

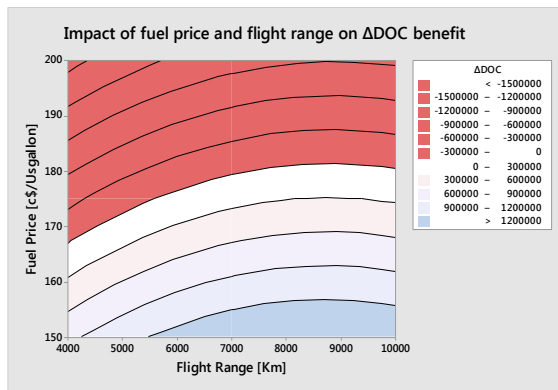
The sensitivity analysis conducted focused on the effect of two key parameters: the fuel price and flight range on the project gains in DOC and NPV values, as shown in Figure 6-24. The analysis considered only the UG1-E, UG2-E and UG3-E engine upgrade variants because of their better performance over the other pairs.



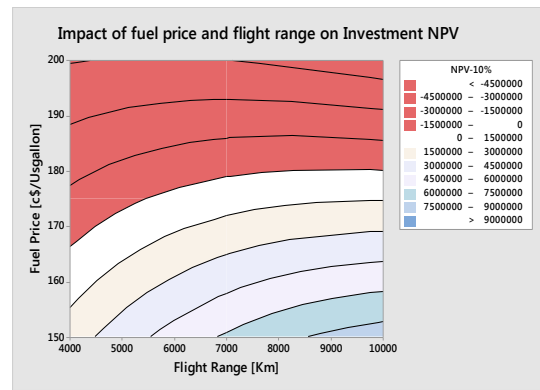
(a) Δ DOC of UG1-E



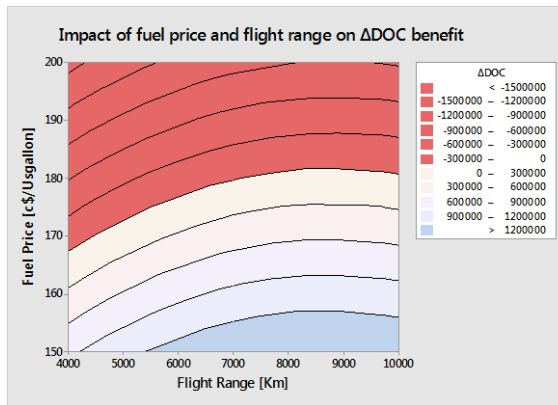
(b) NPV of UG1-E



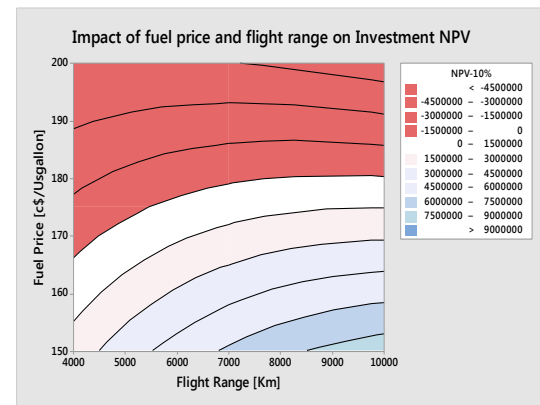
(c) Δ DOC of UG2-E



(d) NPV of UG2-E



(e) Δ DOC of UG3-E



(f) NPV of UG3-E

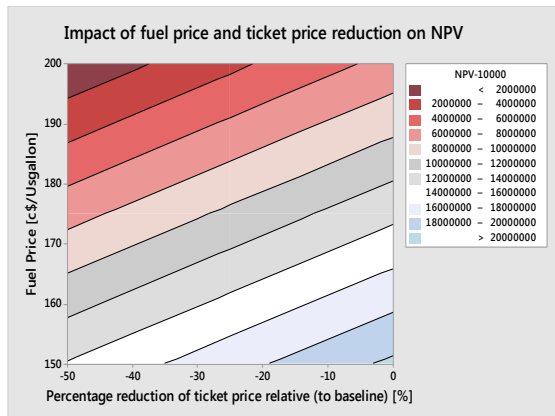
Figure 6-24: Sensitivity analysis for flight range and fuel price variation on DOC and NPV parameters of the Fuel burn Improvement Case study

The mission flight range of 4,000Km – 10,000Km (which is -52.687% decrease and +18.28% increase relative to the reference mission) and a fuel price range of 150 – 200 [c\$/US gallon] (i.e., -16.20% and +11.73% variation) was chosen for this analysis. The influence of these two parameters can be considered as partially compensating one another (at the same investment and load factor). Figure 6-24(a) and (b) shows the impact of these changes on Δ DOC benefits and project NPV, respectively for the UG1-E variant. Any operation within the fuel price and flight ranges that lies inside the deep coloured regions are considered economically non-feasible because the potential Δ DOC gains are less than zero (i.e., incurring costs penalties) and negative project NPV. Figure 6-24 (c) and (d) and Figure 6-24 (e) and (f) present the analysis for the UG2-E and UG3-E engine variants, respectively. However, it can be observed that the Δ DOC benefit and NPV have better values for UG3-E compared to the others at any price-range combination, therefore indicating a more promising investment for stake-holders consideration.

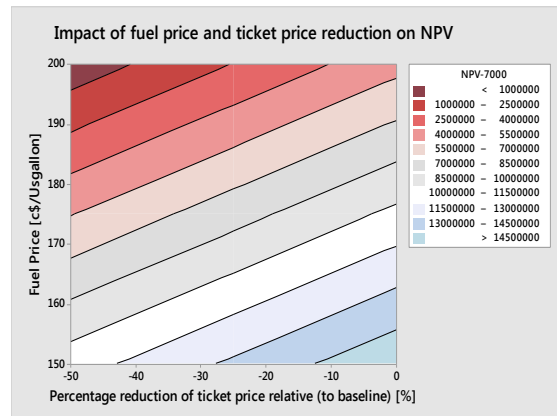
Sensitivity Analysis on Increased Payload Improvement

The sensitivity analysis accesses the effect of flight ticket price and fuel price on the project NPV for three missions with corresponding ranges of 10,000Km, 7,000Km and 4,000Km as shown in Figure 6-25 through Figure 6-27. Like the previous evaluation, the analysis was conducted on only UG1-E, UG2-E, and UG3-E engine variant with different payload (i.e. equivalent to extra passengers) capability mentioned earlier. The ticket price reduction of 50% (-50% - 0%) and fuel price range of 150 – 200 [c\$/US gallon] were selected to examine the investment viability with these operational region.

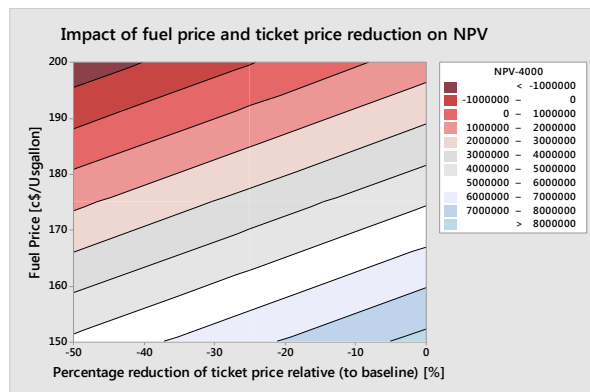
In order to capture the same effect of ticket price reduction on the different mission range, the ticket price corresponding to each range was extrapolated from the reference mission data as shown in Table 6-10.



(a) 10,000Km



(b) 7,000Km



(c) 4,000Km

Figure 6-25: Sensitivity analysis for Ticket price and fuel price variation on NPV parameters of the UG1-E Investment

Table 6-10: Flight range and corresponding ticket price

Reference Mission Data: Range=8454.38Km, Ticket Price= €1023.70			
Flight Range	Ticket Price Reduction		
	0%	-25%	-50%
10,000Km	€1210.85	€908.138	€605.425
7,000Km	€847.596	€635.697	€423.798
4,000Km	€484.34	€363.255	€242.17

Figure 6-25 shows the UG1-E upgrade investment NPV for the 10,000Km, 7,000km and 4,000km mission range within the specified parameter variations. The most regions have positive NPV indicating economically feasible investments except some high fuel price and low ticket price regions of the 4,000Km mission range operation.

As indicated in Equation 6-27 and Equation 6-30, the calculated NPV is a function of a number of parameters such as, number of extra passengers, ticket price, number of flights per year and change in DOC relative to baseline.

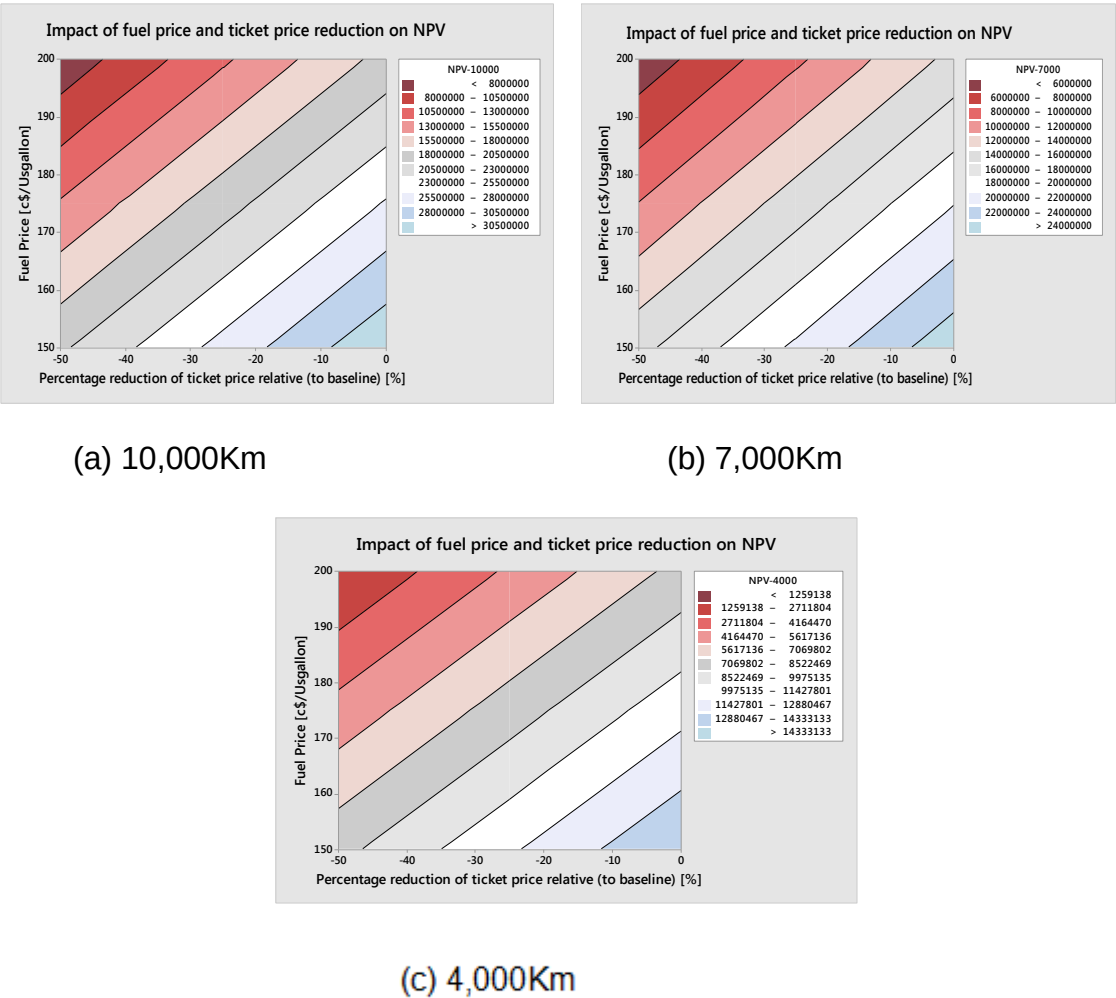


Figure 6-26: Sensitivity analysis for Ticket price and fuel price variation on NPV parameters of the UG2-E Investment

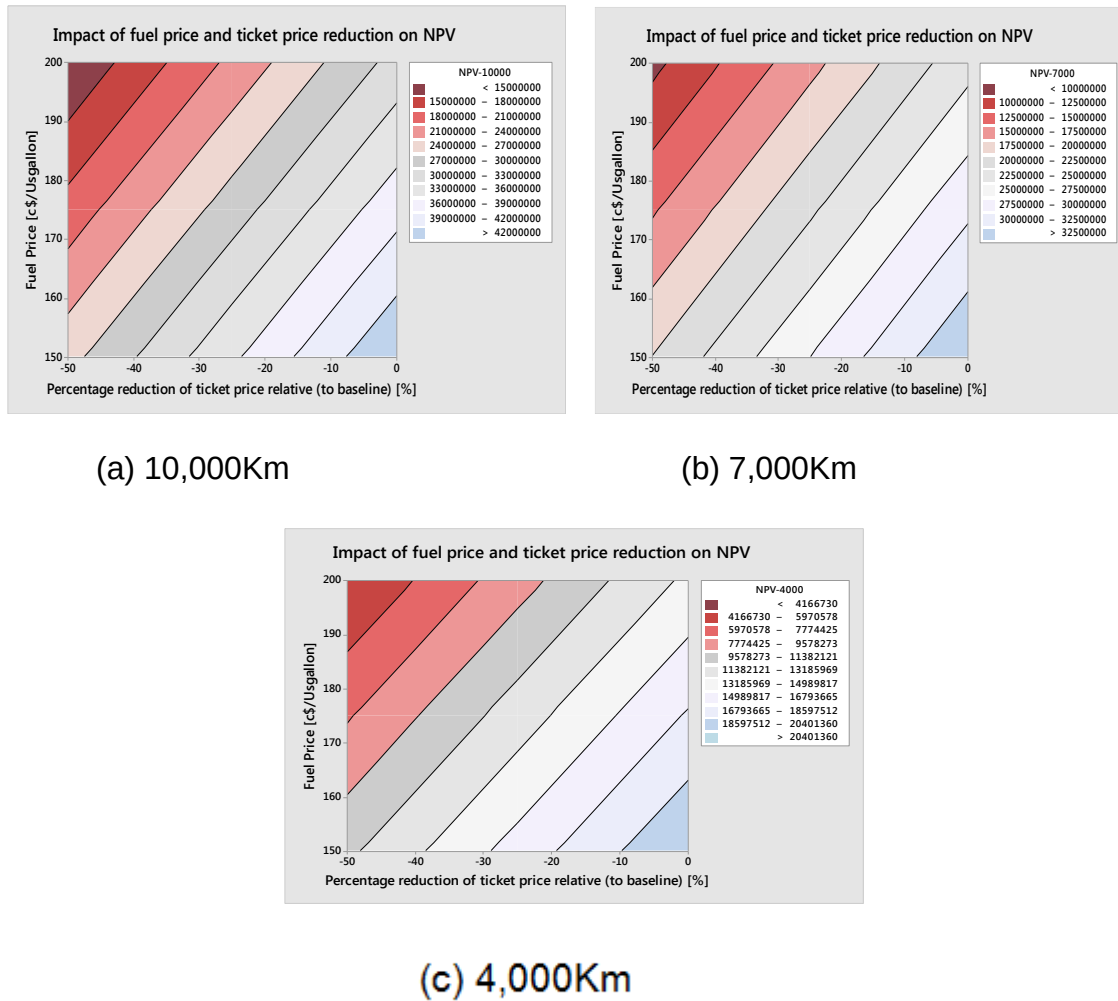


Figure 6-27: Sensitivity analysis for Ticket price and fuel price variation on NPV parameters of the UG3-E Investment

These parameters are partially compensating one another, as the mission range changes from long to short range. For example, the 10,000Km range have a block flight time of 11.82hours, annual utilisation of 3085.26 flight hours or 261.028 flight cycles at €1210.85 ticket price. The 4,000Km range mission have 5.0065 hours of flight time, and annual utilisation of 3295.08 flight hours or 658.168 flight cycles at €484.34 ticket price.

Even though the extra passengers ($N_p = 7$) and upgrade investment cost for the UG1-E are the same, the higher NPV values for the 10,000Km mission range can

be attributed to engine cruise-SFC which translate to better fuel burn performance over long flights compared to the short ones.

Similar trends are experienced in Figure 6-26 and Figure 6-27 corresponding to UG2-E and UG3-E upgrades respectively. The UG3-E upgrade (see Figure 6-27) is showing an overall better NPV values because of the higher payload carrying capability ($N_p = 14$) than others.

6.4 Chapter Conclusion

The chapter investigated the potential performance and economic benefits associated with the increased fan diameter upgrade engine variant, with respect to fuel burn improvement and increased payload improvement benefits. The upgrade was performed based on certain assumptions made and the engine flow path modification. Six variants base on fan diameter increase and fan component efficiency were produced and their mission performance and economic benefit evaluation on aircraft model simulated to quantify the gains attributed to the upgrade. A sensitivity analysis is performed to predict the operational condition where profitability/losses lies and presents a map of Δ DOC and NPV regions that can be achieved with the upgrade investment.

Before any upgrade concept is adopted for development by the manufacturer, it must be able to prove a viable investment from both the performance and economic perspective. This work however, provides detail methodology based on TERA framework to assess the combined techno-economic performance of the upgrade variant engine. The study methodology provides manufacturer the opportunity to evaluate potential performance and economic benefits obtainable from the upgrade technology prior to making any commitment on the upgrade development. It also provide useful guide for appropriate upgrade pricing. The assessment conducted suggests that the upgrade investment have greater potential for success when used for the increase payload application rather than the fuel burn improvement application.

Chapter Seven

Re-Engine Upgrade from Aircraft Manufacturer's Perspective

7. Introduction

This chapter describes the TERA evaluation of the re-engine upgrade, with an advanced engine to replace the Trent 700 engine powering Airbus A330 aircraft: the ultra-high bypass ratio conventional turbofan engine inspired by the future Rolls Royce's Trent 7000. This engine is an advanced future design developed to power the new Airbus A330NEO offer as replacement for existing Airbus A330 aircraft family. The engines are due to enter service during the latter part of 2017 and are currently undergoing testing and certifications.

The primary focus of the propose re-engine upgrade is to establish whether the technology upgrade will result in additional operating profit that justifies the investment. The analysis is expected to establish whether the potential benefits are sufficient to surpass the offerings of current technology and whether the high acquisition costs and other complexities can be offset by potential savings in fuel consumption, maintenance costs and emission costs.

7.1 Brief Background

Re-engining powerplants on existing aircraft are usually driven by a variety of factors, which include the following:

- To improve aircraft performance (such as better take-off characteristics or greater range)
- Improve economic efficiency (reduced operating costs due to lower SFC or decreased maintenance costs due to improved reliability)

- Environmental factors (noise and emission)

For airline operators to consider re-engine upgrades there must be sufficient economic and/or environmental benefits associated with the potential re-engine options. There are two categories of re-engining existing aircraft: installing new or different powerplants.

For the re-engining aircraft upgrade with a new powerplant case, considerations should be given to the high cost of the engine, the cost of modification and the potential revenue lost due to downtime for modifying the aircraft. The latter case of re-engining upgrade with a different powerplant, decision should be based on a cost-benefit evaluation on whether the option can deliver sufficient economic benefit compared to baseline.

Several significant re-engining programs have been carried out over the last six decades. In the early 1960s the American airline and Qantas re-engined the 707-100 aircraft to obtain better performance [100]. The JT3C Pratt & Whitney turbojet engine was replaced by JT3D turbofan engine, producing increased performance. There is also significant history of the DC-8 (McDonnell Douglas) aircraft conversion program. The aircraft re-engining from JT3D to CFM56-2 engines were driven by the advent of more stringent noise regulations in the 1970s. This motivated the replacement of Pratt & Whitney JT8Ds with Rolls Royce's Tay and CFM56 engines on 727-100 and 737-300 aircrafts respectively. The success of the re-engining DC-8-60 aircraft program from JT3D-3 to CFM56-2 engines was indicated by the relative accuracy of the program [98]. The program achieved all the financial and operational targets set, such that the re-engined DC-8-60 had the best trip costs except for the 767 which was the latest aircraft technology acquired by the airline during that period. The re-engining was only possible because the DC-8-60 airframe had the required structural capability to allow the larger engine (CFM56-2 turbofan engine) to provide improved efficiency, performance and noise reduction benefits.

Another similar re-engining program was the KC-135 re-engining (military re-engining program), which reported an expected performance improvement but the NPV calculation from the costs-benefits analysis could not justify the initial

program target because of the extent of modification required and the number of aircraft fleets involved. However, a increase mission utilization was experienced for the KC-135 tanker aircraft when re-engined with CFM56-2. Re-engining program is not simply the replacing of old engines with new engines on wings, but involves lots of complexities as it affects the entire aircraft system (structural, aerodynamics, avionics, electrical, hydraulics and pneumatics). Therefore, significant analysis and certifications are necessary for the re-engining upgrade program. Details on other re-engining programs conducted is provided by Wyman [101].

7.2 Method Description

Figure 7-1 shows the TERA approach used for the investigation of the merits of re-engine upgrade. It consists mainly of the engine and aircraft performance models, lifing and economic models. The engine performance for both the new engine used for re-engining and the baseline is modelled in TURBOMATCH. The aircraft and mission performance is evaluated in HERMES and the engine life estimated with HESTIA. The economic model evaluates the direct operating cost (DOC) and upgrade benefits in terms of fuel savings and payload improvement. The methodology enables quantitative evaluation of the cost-benefit analysis of the re-engine upgrade to justify any potential investment.

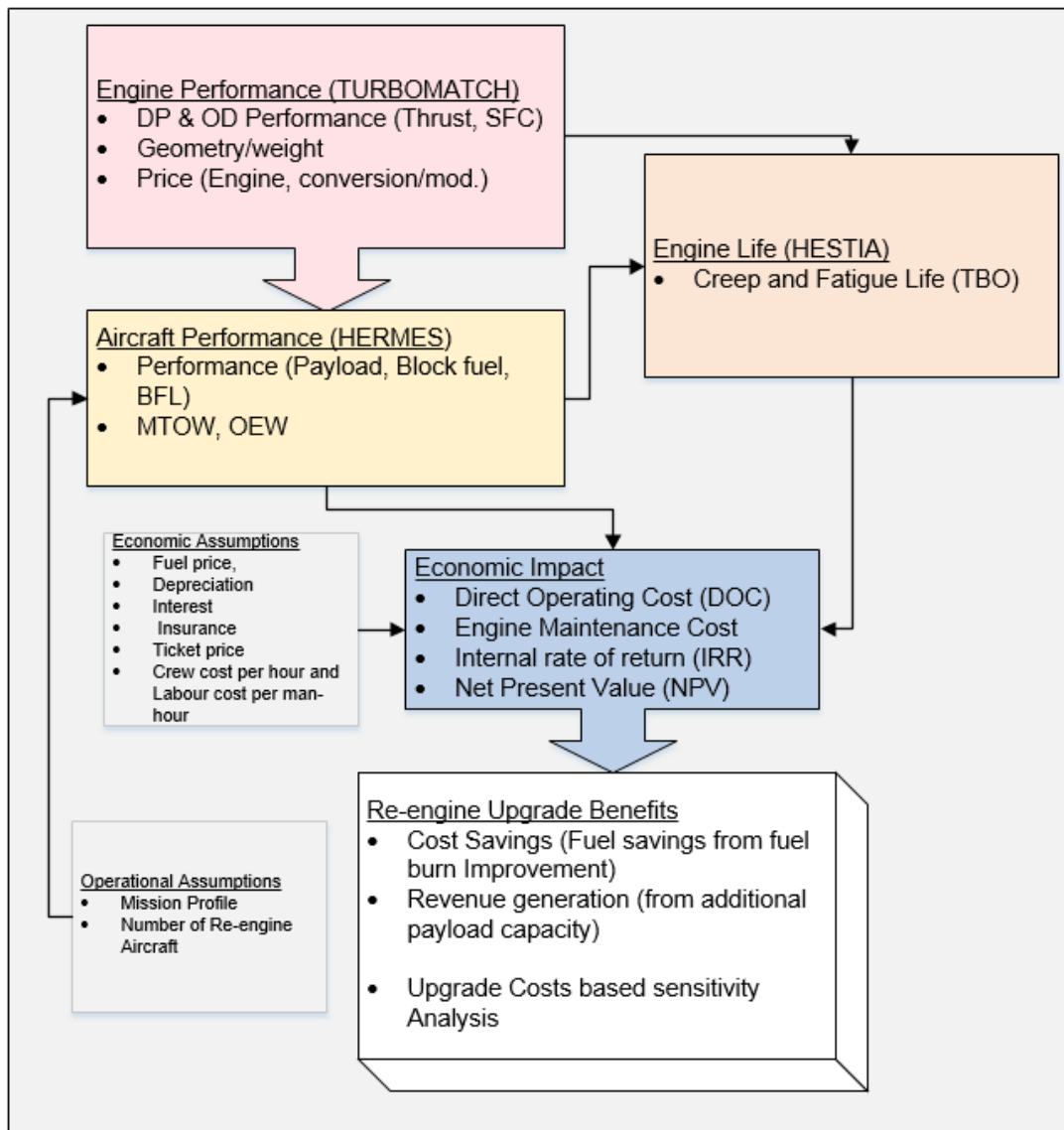


Figure 7-1: TERA framework for Re-engine Upgrade

7.2.1 CEUP-7000 Engine (Inspired by Rolls-Royce's Trent 7000 Specification)

The proposed new engine model (code-named CEUP-7000) for the re-engining aircraft upgrade analysis is inspired by the Rolls-Royce Trent 7000 engine originally developed for Airbus A330NEO aircraft. Trent 7000 engine is high-bypass ratio contra-rotating turbofan engines built for powering the new Airbus A330NEO due to enter service in 2017. The evolutionary efficient engine was developed by fusing the Trent 700 engine experience, Trent 1000 architecture and engine technology of Trent XWB [102].

The engine manufacturers are promising up to 10% improvement in specific fuel consumption and 14% fuel burn compared to the Trent 700 model, thanks to its small, high pressure-ratio engine core and its newest fully swept, wide-chord fan technology. It is also claimed to be 6dB quieter than the Trent 700 model. These improvements were achieved through the deployment of new component technology throughout the entire engine, such as blisk blade and disc design in the compressor or the advanced, modulated turbine clearance control system.

7.3 CEUP-7000 Engine Performance Modelling

The engine performance models for the engines under consideration were modelled and simulated in TURBOMATCH. The lack of available certified data on the CEUP-7000 engine model (i.e. Trent 7000 inspired engine), majorly because they are still under development, presented some challenges during modelling as it allowed the author plenty of freedom for assumptions.

At the time of modelling the CEUP-7000 engine, the literature available in public domain were mostly documents published by the engine manufacturers and containing limited and unverified information, such as percentage improvement in specific fuel consumption, fuel burn, emission pollutants, noise, etc. However, the author decided to use the engine cycle parameters available in public domain, such as take-off thrust, bypass ratio and overall pressure ratio and reasonable assumptions made for information not available. Table 7-1 presents the engine information that was available to the author at the time of modelling the engine.

Table 7-1: Trent 7000 Engine Available Data [103]

Parameters	Trent 7000
Take-off Thrust	72,000lbf (320KN)
Overall Pressure Ratio	50:1
Bypass ratio	10:1
Stage Count (F-IPC-HPC-HPT-IPT-LPT)	1-8-6-1-1-6

Table 7-2: Engine Models Design Parameters

<u>Design point data</u>	<u>Trent 700</u>	<u>CEUP-7000</u>
Design point: Cruise (10,668m, ISA)		
Mach Number	0.820	0.820
Cruise Mass flow rate [Kg/s]	333.9	480.00
Bypass Ratio	5.03	10.10
Overall Pressure Ratio	35.50	50.00
Fan Pressure Ratio	1.80	1.53
IPC Pressure Ratio	6.031	8.170
HPC Pressure Ratio	3.27	4.00
Cruise Temperature [K]	1365	1475
Fan Isentropic Efficiency	0.918	0.925
IPC Isentropic Efficiency	0.915	0.920
HPC Isentropic Efficiency	0.915	0.920
HPT Cooling Flow [%]	10	20
Combustion Efficiency [%]	99.99	99.99
Combustion Fractional Pressure Loss [%]	5	5
Turbine Entry Temperature [K]	1638	1700
HPT Efficiency	0.915	0.920
IPT Efficiency	0.920	0.930
LPT Efficiency	0.920	0.930
Flight Altitude [m]	10,668	10,668

Assumptions Made:

It was assumed that the component efficiencies would increase slightly since the new engines are expected to be built with better materials and advanced technology compare to Trent 700 model. Trent 700 engine is a counter-rotating engine with the IP turbine and compressor rotating in the same directions. A set of fixed stator vanes are incorporated behind the fan to straighten the flow and after each rotating turbine stage to eliminate swirl imparted on the flow inside the turbine. These induces drag which eventually leads to loss in efficiency. The CEUP-7000 engine is based on contra-rotating concept of rotating different shafts

in opposite direction, therefore allowing very small changes in nozzle area resulting in an increase in IP and HP compressor efficiencies. This compressor component efficiencies for the CEUP7000 engine model was difficult to quantify these assumptions since at the time of modelling this engine the author was not aware of any document that verifies this increase in component efficiencies, however, for this work a maximum of 2-point increase in efficiency was assumed as shown in Table 7-2.

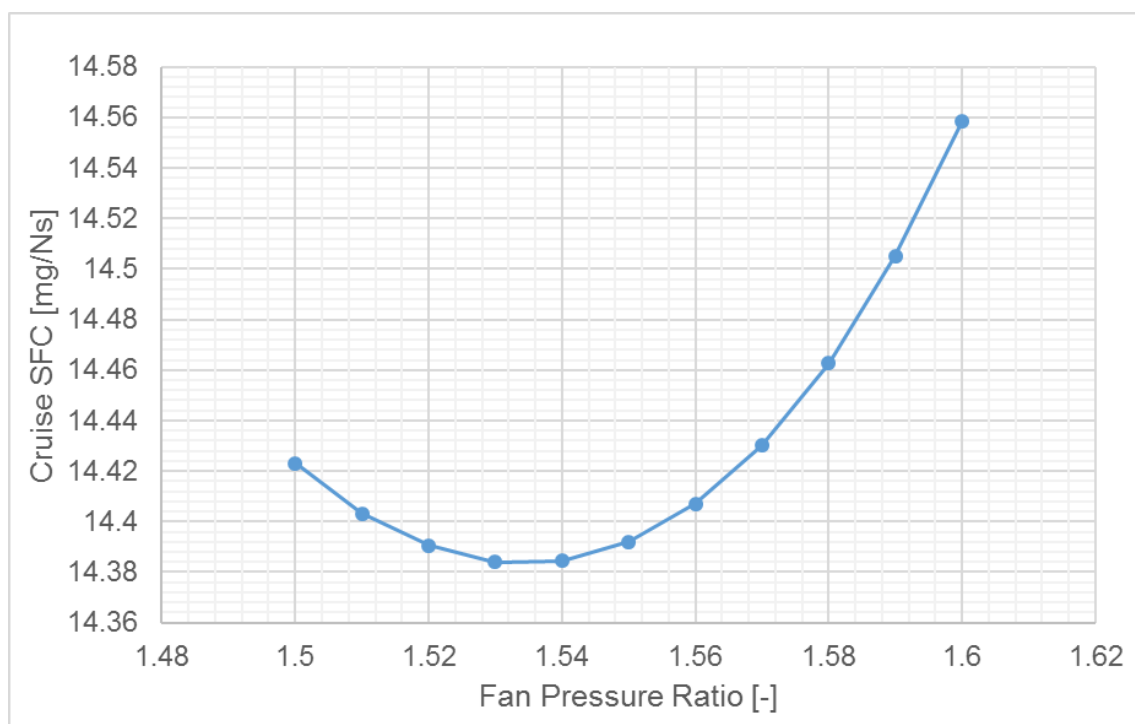


Figure 7-2: Optimisation of CEUP-7000 Engine Fan Pressure Ratio

Figure 7-2 shows the optimisation process to select the fan pressure ratio with the best engine cruise SFC. The design point calculation for CEUP-7000 engine was modelled at cruise conditions. A 9.514% reduction of cruise SFC relative to Trent 700 engine was achieved less than the 10% offerings claimed by Trent 7000 engine manufacturers. **Table 7-3** shows the performance characteristics of the Trent 700 and CEUP-7000 engine at take-off and cruise conditions. The take-off thrust for CEUP-7000 matches the available public data for Trent 7000 engine (see **Table 7-1**).

Table 7-3: Engine Performance Characteristics

<u>Design point data</u>	<u>Trent 700</u>	<u>CEUP-7000</u>
Cruise At 10,668m, ISA (DP)		
Cruise Thrust [KN]	53.513	58.640
Cruise SFC [mg/Ns]	15.900	14.380
Cruise TET [K]	1365.00	1475.00
Cruise Fuel Flow Rate [Kg/s]	0.850	0.840
Take-off At 0 Atl., M=0, ISA, SLS		
Take-off Thrust [KN]	316.560	320.870
Take-off SFC [mg/Ns]	9.550	7.360
Take-off TET [K]	1638.00	1700.00
Take-off Fuel Flow Rate [Kg/s]	3.020	2.360

7.3.1 Off-Design Point Performance

The off-design performance of CEUP-7000 engine was evaluated at different operating and environmental conditions during the different flight phase of the aircraft missions (such as different operating altitudes above sea level, varying flight Mach number and ISA temperature deviation). The effect of varying the flight altitude, Mach number and TET on engine net thrust and SFC are presented in appendix A.2.

7.4 Aircraft Mission Performance

This subsection assesses the engine performance when integrated within an aircraft model. The integrated engine-aircraft performance model, called HERMES, was used for this investigation to determine any potential improvement in fuel burn.

The aircraft model based on Airbus A330 resemblance, and powered with Trent 700 engine was used as baseline for this investigation. The CEUP-7000 engine

model is used as the re-engining upgrade options for the Airbus A330 aircraft investigation in this study. The differences between the baseline and the new engine geometry and weight are implemented during the integration of the engines onto the aircraft model. The aircraft model predicts the potential impact of the increase in nacelle drag due to the larger engine size and the effect of increased engine weight on the aircraft performance.

Table 7-4 presents a summary of the weights and dimensions of the upgrade engine options and the baseline engine.

Table 7-4: Trent 700 and CEUP-7000 engine Weight and Dimensions [103][104]

<u>Parameter</u>	<u>Unit</u>	<u>Trent 700</u>	<u>CEUP-7000</u>
Engine Dry Weight	[Kg]	6160	7277
Engine Length	[m]	5.639	5.812
Engine Diameter	[m]	2.744	4.002
Fan Diameter	[m]	-	3.000

To begin the assessment of re-engining upgrade on an aircraft, the payload-range diagram for both the baseline and re-engining upgrade option engines integrated on an airplane (i.e. the Cranbus A330 airplane model) is calculated as shown in Figure 7-3. The Figure shows significant increase in both range and payload capabilities of the CEUP-7000 engine compared to the baseline. There are three range-points that characterize an engine-aircraft payload-range diagram: the ferry range, fuel range and the maximum payload range.

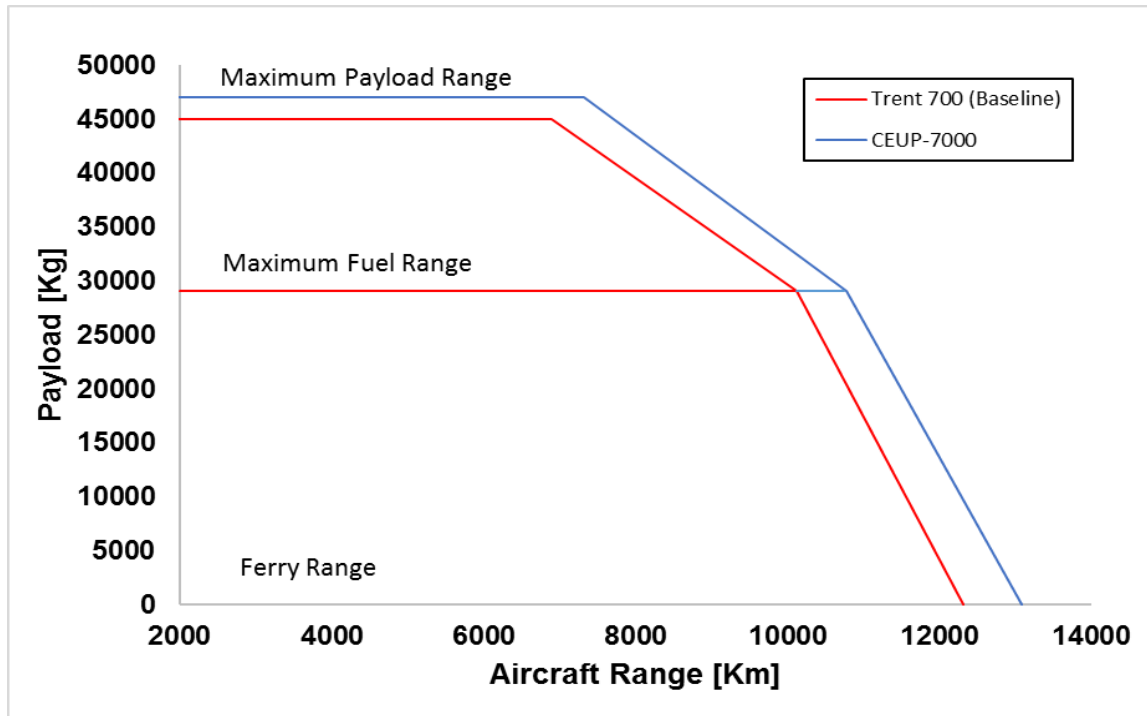


Figure 7-3: Payload-Range diagram for Trent 700 (baseline) and CEUP-7000 with Cranbus A330 aircraft model

The CEUP-7000 engine shows a 6.17% (759.93Km) increase in ferry range, 6.33% (641.03Km) increase in fuel range and 5.97% (411.94Km) increase in maximum payload range over the Trent 700 (baseline) engines.

To evaluate the potential improvement in fuel burn associated with the re-engine upgrade of Cranbus A330 with CEUP-7000 engine, three typical flight missions were investigated: short, medium and long-range missions for the Cranbus A330 aircraft. These missions analysed were based on flight distance from London Heathrow Airport (London, UK) to Leonardo Da Vinci International Airport (Rome, IT) – short range, Murtala Muhammed International Airport (Lagos, NG) – medium range and Beijing Capital International Airport (Shunyi Beijing, CN) – long range, respectively. The missions' fuel burn was predicted based on assumed payload of 29,085Kg, which is equivalent to 277 passengers with full baggage is presented in Table 7-5.

Table 7-5: Engine Mission Fuel Burn Performance Comparison

<u>Mission</u>	<u>Block Fuel Burn Improvement</u>	
	<u>Trent 700</u> <u>(baseline)</u>	<u>CEUP-7000</u>
Short Range (1446Km)	10491.11Kg	9526.26Kg [9.2%]
Medium Range (5011Km)	31057.48Kg	29039.48Kg [6.5%]
Long Range (8144Km)	50394.27Kg	47213.58Kg [6.31%]

The results shows significant fuel burn improvement for CEUP-7000 engine compared to the baseline engine. This improvement is attributed to the increase in propulsive efficiency due to the high bypass ratio (HBR), despite the associated weight and nacelle drag penalties. It also shows that as the mission length increases, fuel burn provement progressively reduces indicating that most of the performance gains were achieve during the climb phase.

7.5 Results Analysis

Performance and economic results of re-engining Cranbus A330 aircraft with CEUP-7000 engine model is presented in this subsection. Figure 7-4 shows a comparative performance between baseline (Trent-700) and CEUP-7000 engines deployed for the investigation. The differences in terms of engine TBO, aircraft nacelle-drag, takeoff BFL, engine-weight and aircraft blockfuel for the medium-range mission specified. The engine TBO (-life) estimated was 51,930 operating hours for the 5011km mission range of 6.15 flight hours and 3282 hours of annual utilization (or 533 flight cycle). Although indicating significant reliability improvement over baseline engine, as at the time of this work the author was not aware of any publicly available documentation of Trent-7000 engine life, except the maker's claims of the same reliability as that of Trent 1000 engine [105]. A nacelle-drag of 49.646% increase relative to baseline value is reported on the chart, an expected penalty because of CEUP-7000 large engine geometry as

shown in Table 7-5. The increased thrust capability of CEUP-7000 (4.4906%) relative to baseline despite the additional 1117Kg of engine weight have enabled 162m takeoff BFL reduction compare to baseline. On the medium-range mission, CEUP-7000 engine gives a fuel burn improvement estimate of 6.4976% fuel savings.

The attractiveness of this upgrade/conversion program is due to the fuel savings potential and performance improvement from the advanced CEUP-7000 engine. However, the chance of qualifying the upgrade for investment consideration is base on an effective cost-benefit analysis to determine whether the potential gains are sufficient to offset the high investment cost and still prove profitable.

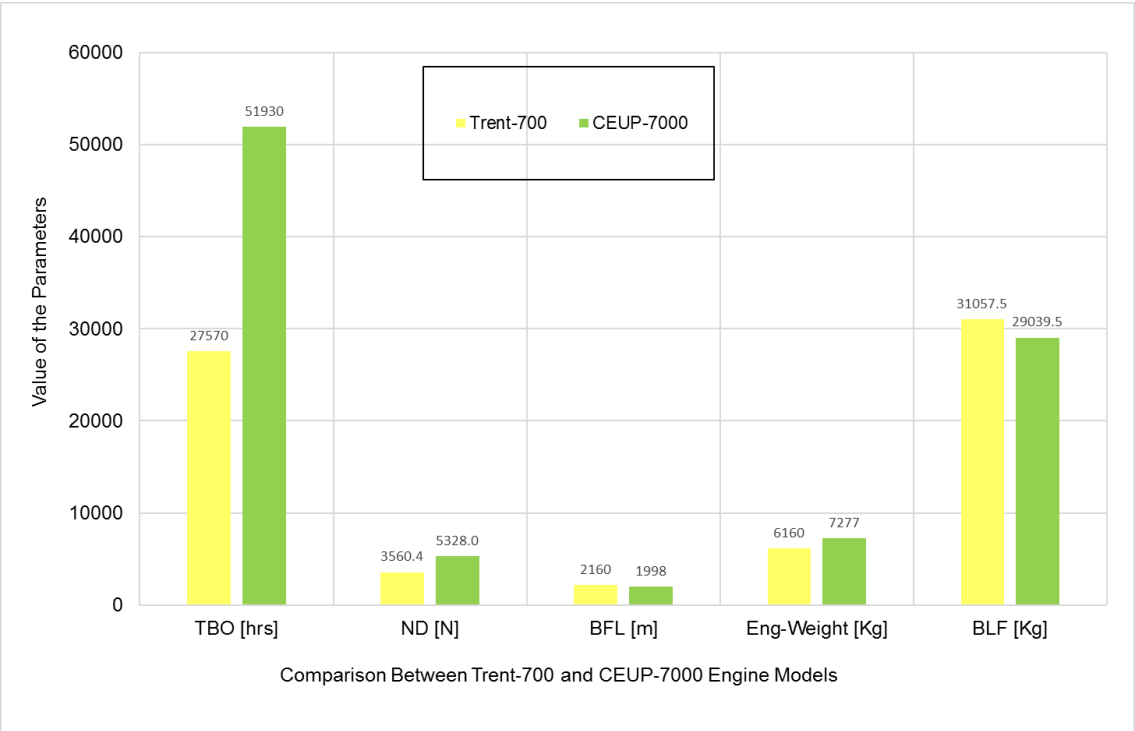


Figure 7-4: Performance Comparison between Trent-700 and CEUP-7000 engines

7.5.1 Re-engine Upgrade Cost-Benefit Analysis

This subsection evaluates the cost-benefit analysis of the re-engined upgrade from both the manufactures and operators perspectives. The assumption is that

for such an upgrade/conversion project to occur it must be sufficiently beneficial to both the OEMs and the operators. The benefits of the upgrade are examined further by identifying viable alternative scenarios for using this upgrade. The potential benefit achievable is evaluated and quantified to indicate whether the upgrade justifies the high project investment costs.

7.5.1.1 Cost-Benefit Analysis for the Manufacturer

It is assumed that the OEM will develop an engine with compatible interfaces for each aircraft to be retrofitted. This is part of the OEM non-recurring cost, which may contain other recurring costs such as costs of conversion, downtime and equipment used. However, the OEM sales price to the operators (users) must cover all the cost of development including a reasonable profit. The economic profitability of the project was assessed by calculating the break-even point (where the total income from upgrade sales equals the total investment costs per unit) of the project.

Engine Price of CEUP-7000 (Trent-7000)

The list price of the engine including nacelle is \$37.91 Million per unit [106]. The engine spares costs was calculated using Equation 3-55 as K\$172.6168. It is assumed that the OEMs would have considered the engine development costs before setting the engine sales price. To account for the impact the number of aircraft fleet conversion has on the economic assessment, a discount rate is assumed depending on the number of engines ordered. The discount rates of 5% for 50 engines, 10% for 333 and 15% for 857 engines. These assumptions are scaled down values presented in the RETROFIT analysis [107].

Re-engine Upgrade Conversion/Modification Costs

The SESAB project provides several re-engine conversion packages, with price ranging from K€300 to K€1500 per aircraft [108]. This price is a function of the performance requirements, age of aircraft upgraded and the number aircraft fleet being converted. For this study the modification cost assumed is between K€150 to K€350, and K€250 on the average. A little lower than those provided in the SESAB project [108]. The downtime during the conversion is assumed as the

cost of leasing A330 aircraft for two weeks, given as K€100 [109]. The total re-engine upgrade investment cost is calculated as shown in Table 7-6.

7.5.1.2 Cost-Benefit Analysis for the Operators (Users)

From the operator’s (user’s) perspective, the cost-benefit analysis is evaluated based on the benefit of cost savings due to potential fuel burn reduction and payload improvement. The direct operating cost (DOC) for the re-engined upgrade is calculated for the short (1446Km), medium (5011Km) and long-range (8144Km) flight missions.

7.5.1.3 Cost-Savings from Fuel Burn Reduction

The cost savings due to the fuel burn reduction is analysed to attempt a justification for investment in the re-engined upgrade programme.

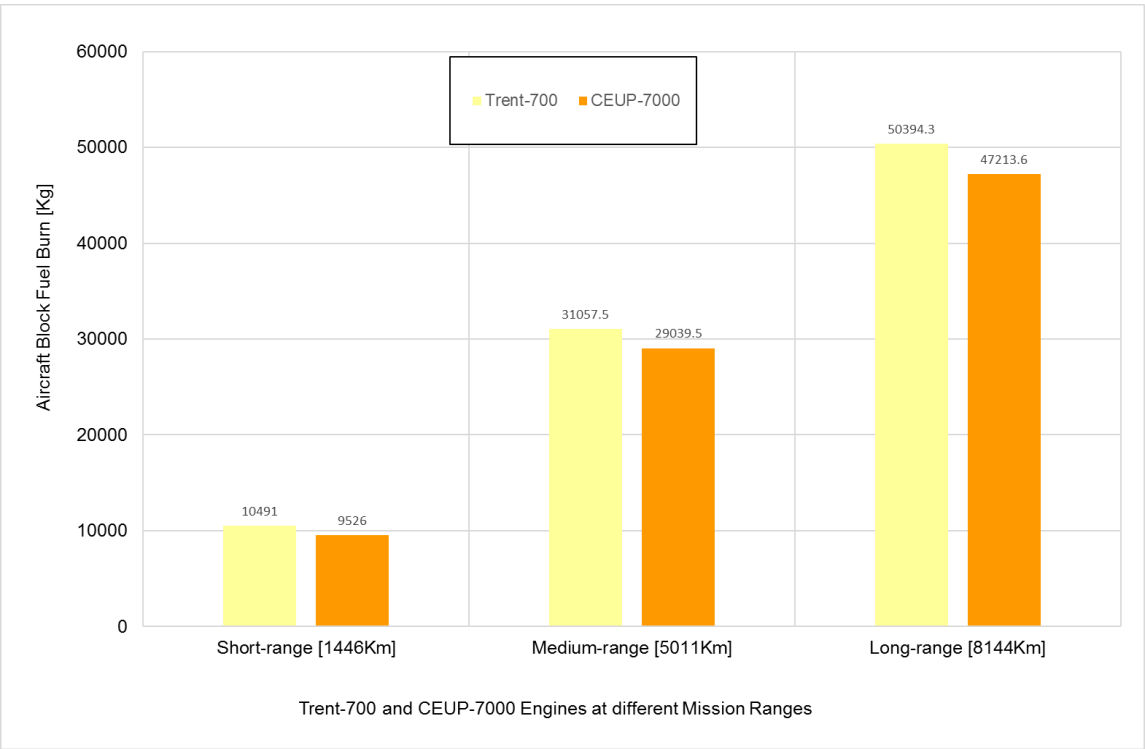


Figure 7-5: Comparison of Engines Flight Fuel Burn Improvement

Table 7-6: Total Re-engine Upgrade Investment Costs

No. of aircraft Re-engined	No discount	50 (at 5% discount)			333 (at 10% discount)			857 (at 15% discount)		
Engine Price: K€	35042.3	33290.21			31538.09			29785.98		
Modification Costs: K€ [107][108]	250	150	250	350	150	250	350	150	250	350
Downtime Cost (2 weeks lease): K€ [109]	100	100	100	100	100	100	100	100	100	100
Total Investment Cost: K€	35392.34	33540.21	33640.21	33740.21	31788.09	31888.09	31988.09	29985.98	30135.98	30235.98

Figure 7-5 shows the flight fuel burn comparison for three different mission profiles defined in Table 7-5. The CEUP-7000 engine show significant fuel burn improvement compared to the baseline. These cost savings are analysed further in terms of aircraft DOC per trip and NPV of the re-engine project over a 10 years is chosen since age is a critical factor for performance.

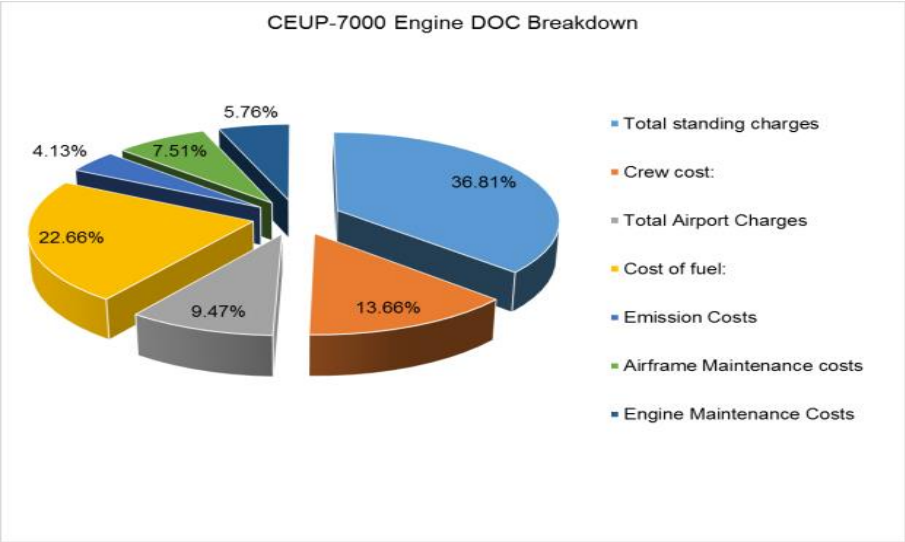


Figure 7-6: Aircraft Direct operating Cost (DOC) for CEUP-7000 Engine

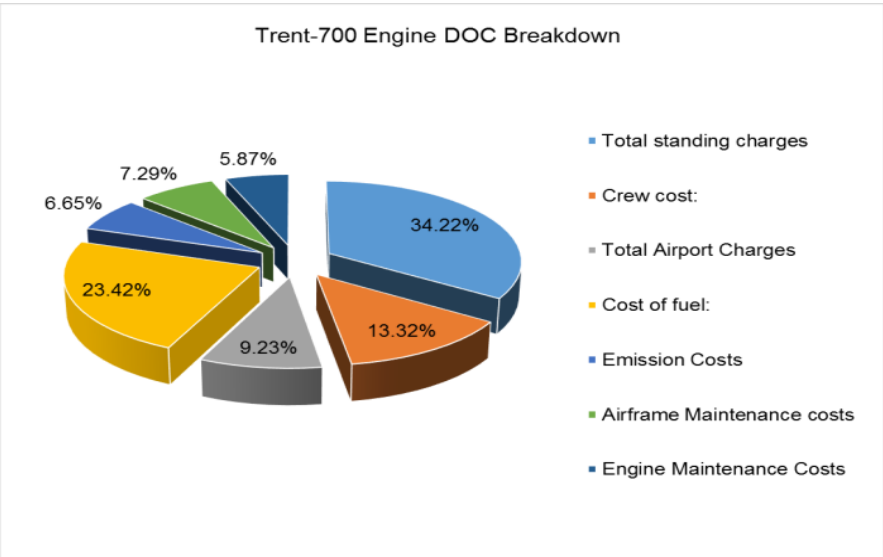


Figure 7-7: Aircraft Direct Operating Cost (DOC) for Trent-700 Engine

The DOC breakdown for the CEUP-7000 and Trent-700 powered aircraft per trip (5011Km mission range) for an average re-engine upgrade conversion cost (K€250) without discount consideration are presented in Figure 7-6 and Figure 7-7, respectively. While there is a decrease in percentage fuel cost, emission and engine maintenance cost of CEUP-7000 due to engine enhanced performance, there is also an apparent increase in percentage total standing charges, total airport charges and airframe maintenance cost due to the increased total engine cost and the overall aircraft weight.

Figure 7-8 show details of CEUP-7000 performance improvement over the baseline in terms of change in DOC, engine maintenance cost and fuel burn per trip for the short, medium and long-range mission. The graph indicates that although there is still fuel burn savings (686Kg) for the short-range mission, it is simply not sufficient to offset the engine maintenance cost penalty thus adversely affecting the trip DOC. Therefore, for the CEUP-7000 re-engined at K€250 conversion cost and zero-discount, short-range flight operations are not economically viable.

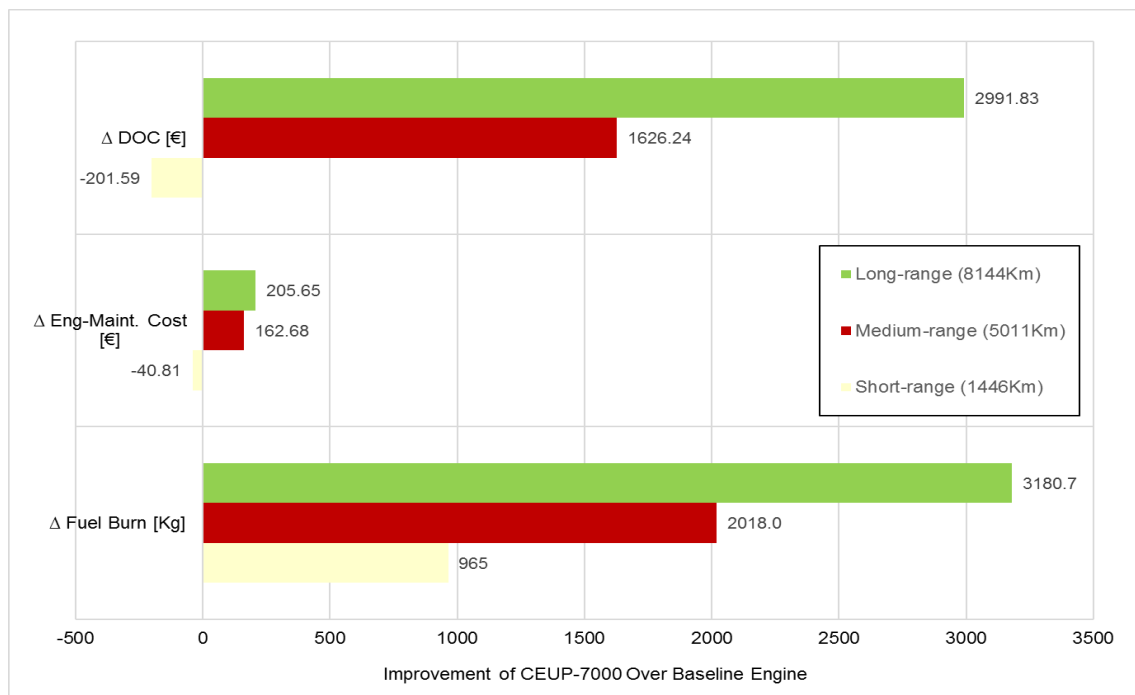


Figure 7-8: Performance Improvement of CEUP-7000 over Baseline

The re-engine upgrade net present value (NPV) for three conversion or modification costs (K€150, K€250, and K€350) and three discount-rate scenarios are presented from Figure 7-9 to Figure 7-11, respectively. The graph affirms the observation made previously in Figure 7-8, that short-range operations with the re-engined upgrade is not profitable except for the conversion cost scenario of K€150 at 5% discount rate as shown in Figure 7-9.

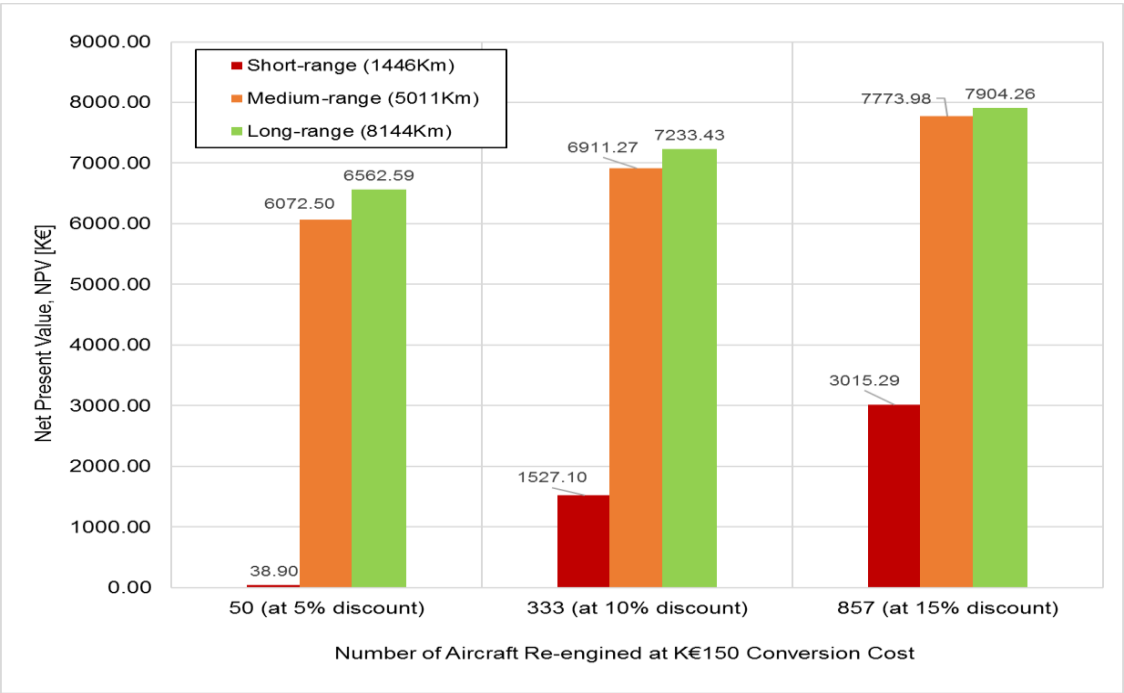


Figure 7-9: NPV for Aircraft Re-engined Upgrade for 150Keuro Conversion Cost

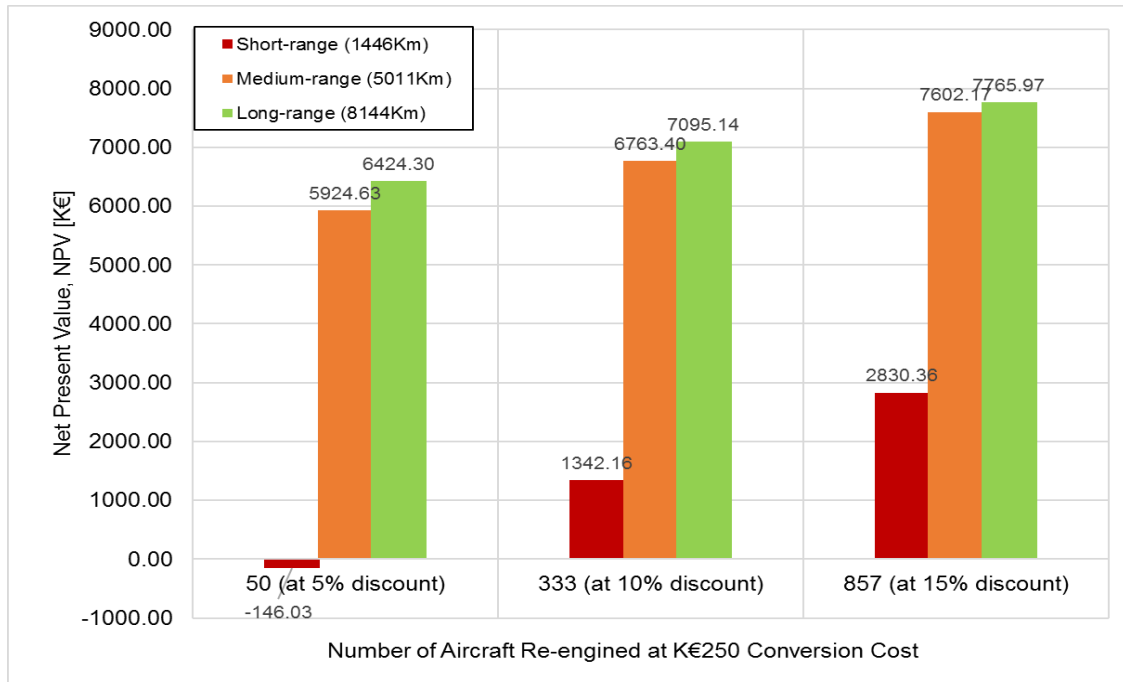


Figure 7-10: NPV for Aircraft Re-engined Upgrade for 250Keuro Conversion Cost

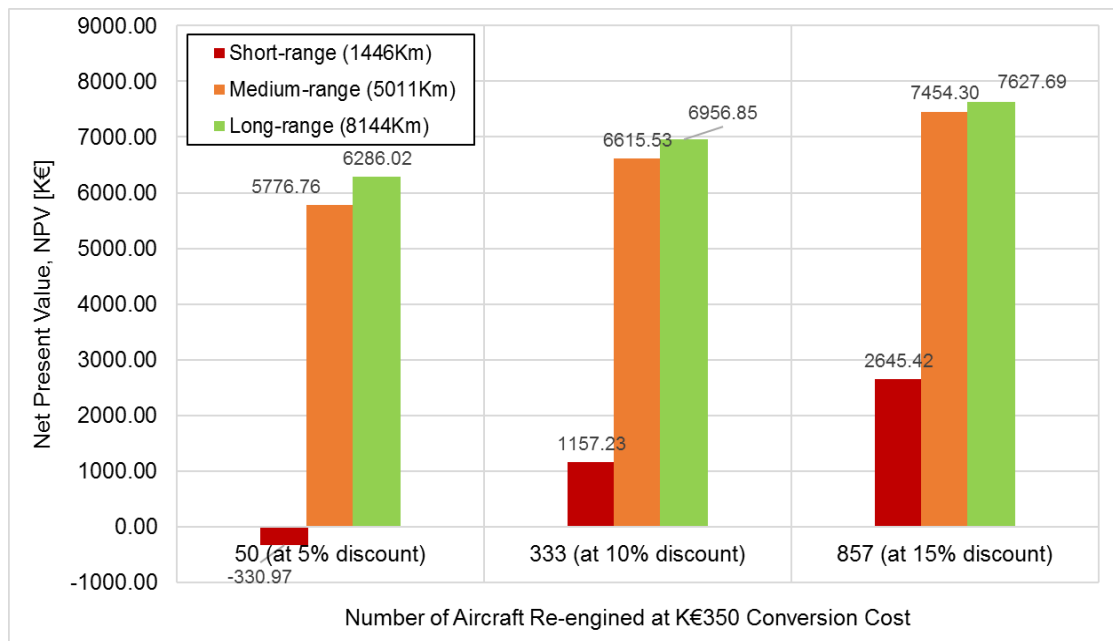


Figure 7-11: NPV for Aircraft Re-engine for 350Keuro Conversion Cost

7.5.1.4 Additional Revenue from Payload Improvement

The same analytical procedure used in section 6.4.7 and 6.4.8 was deployed for this analysis. Figure 7-4 showed that the CEUP-7000 required a 168m shorter takeoff field length (BFL) than baseline engine due to its relative higher takeoff thrust capability. These shorten takeoff BFL capacity can be traded for additional payload capacity limited by the baseline engine BFL. Assuming that the certified maximum weight limit of the airframe is not compromised, a maximum of 7980Kg (equivalent to 76 passengers at 105Kg per person plus luggage) additional weight was possible to carry. Based on the assumptions in Table 6-9, the ticket price per passenger for the 5011Km range mission is estimated as €606.76. The CEUP-7000 potential DOC improvement per trip relative to baseline for the medium-range mission at different cost scenarios is shown in Figure 7-12.

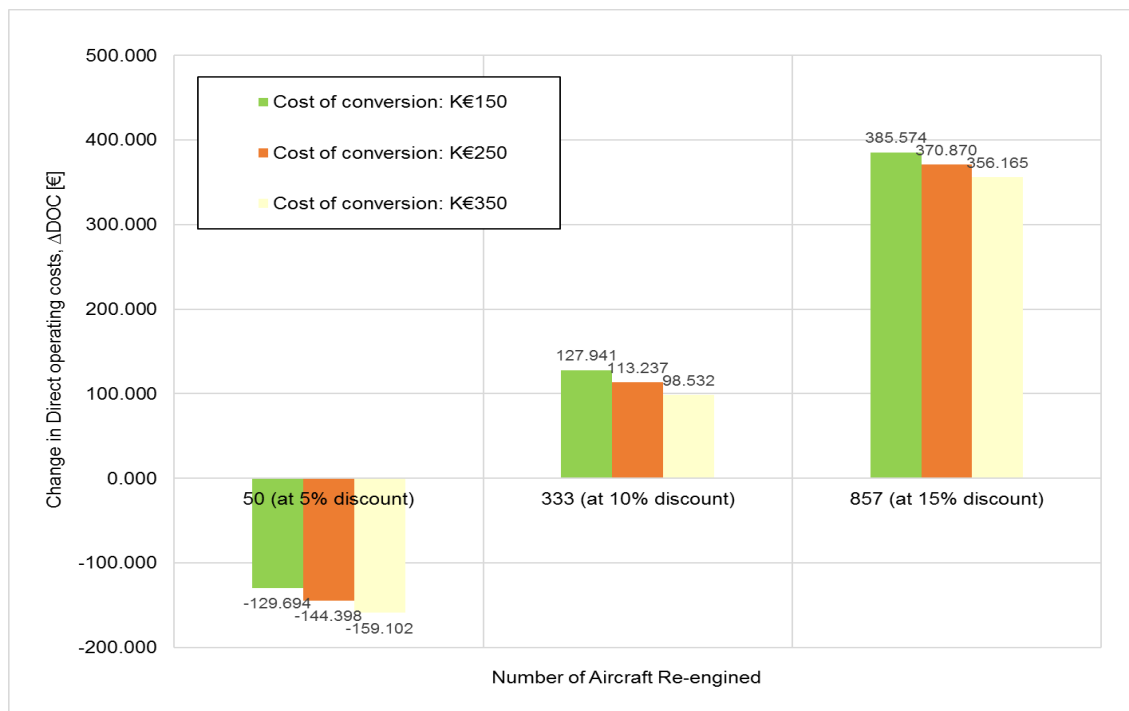


Figure 7-12: CEUP-7000 Potential DOC Improvement for medium-range mission

The 5% discount cost scenario gave a negative ΔDOC , meaning the the DOC for CEUP-7000 was higher than the baseline values. This is because the increased payload carried has caused a 0.154% increase in crew cost, 3.58% fuel cost, 12.1% engine maintenance cost and 35.98% increase in emission cost. Apparently, the effect of 5% discount in engine price could not offset the cumulative impact of those increases in DOC components.

The annual profit/gain is calculated using Equation 6-22, taking into account the extra revenue generated from the 76 additional passengers. As shown in Figure 7-13 the additional revenue earned is sufficiently high to offset the DOC penalty and still make the project profitable for all the upgrade cost scenarios considered. Figure 7-14 shows the NPV of the project following the same trend as the annual profit.

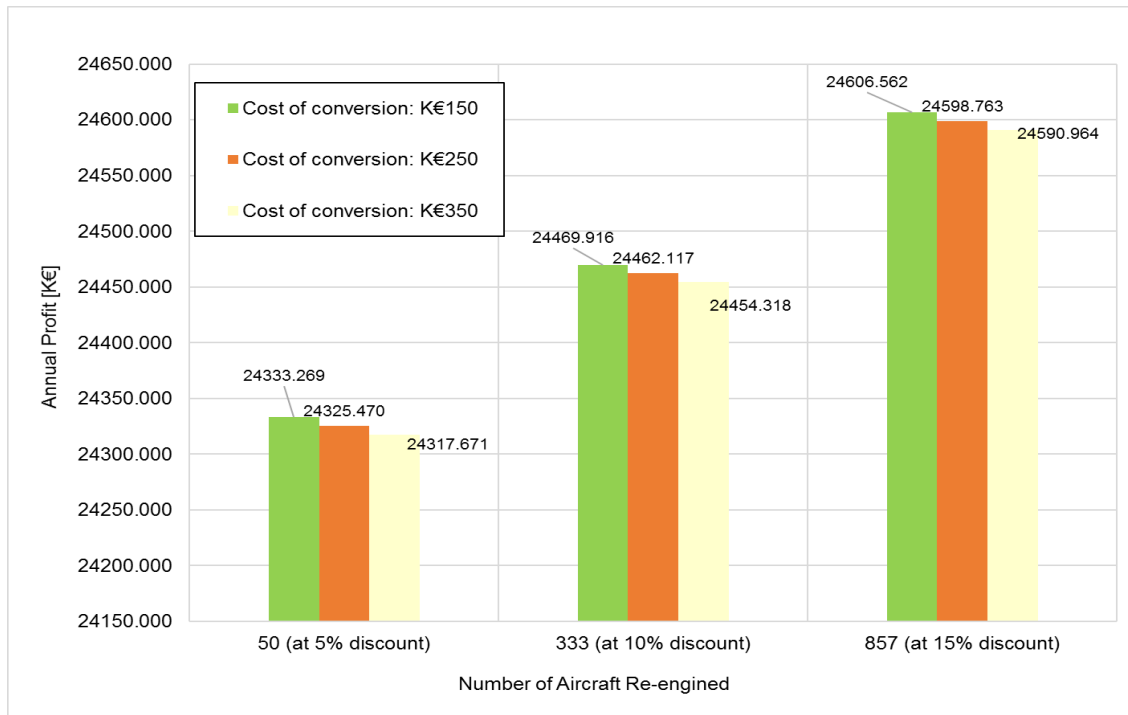


Figure 7-13: Annual profit/gains for medium-range mission

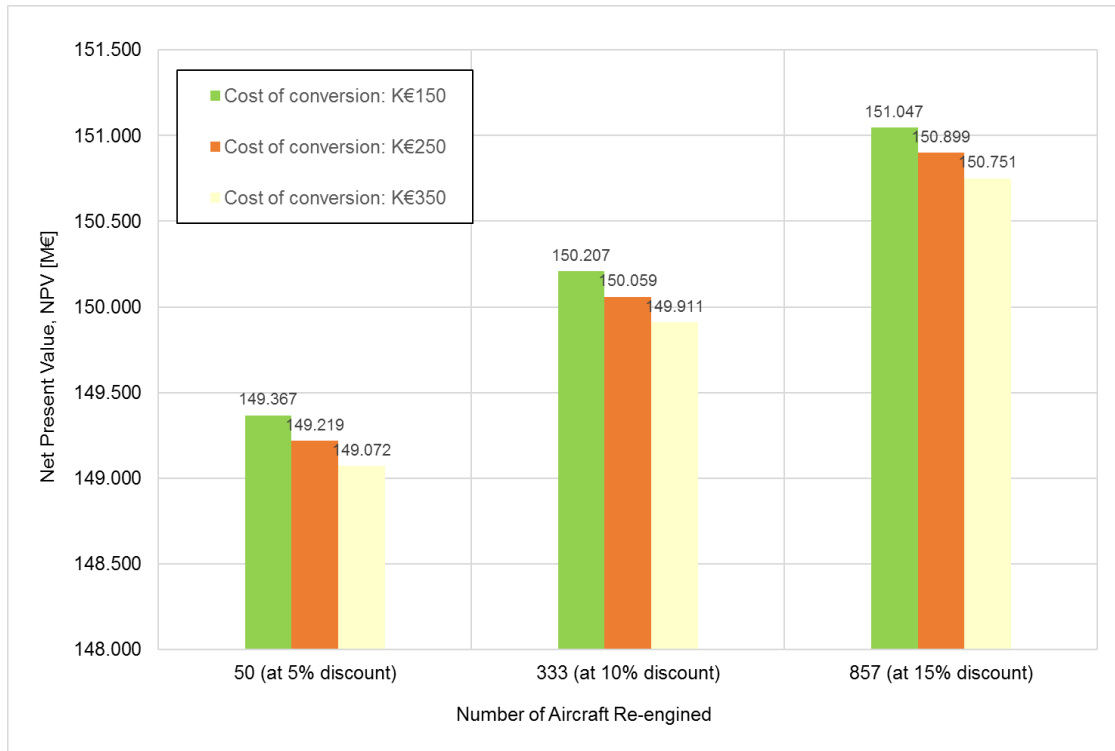


Figure 7-14: Net Present Value (NPV) for medium-range mission

7.6 Chapter Conclusion

The chapter investigates the potential performance and economic merits for an aircraft re-engine upgrade investment. The engine performance and on-wing performance were evaluated and compared with the baseline to quantify the potential fuel burn savings, and its economic impact in terms of DOC and NPV evaluated for the project nominal duration of 10 years. The re-engine upgrade was evaluated for potential costs-saving benefit due to fuel burn reduction brought about by the new higher efficiency engine used for the aircraft re-engining. Since the upgrade/conversion is often a function of performance requirement, age of aircraft, number of aircraft fleet re-engine, and other factors, this work evaluated the economic analysis base on the number of aircraft re-engine and aircraft mission range. To capture the effect of number of re-engine order placed, an engine costs price discount rate of 5% for ≤ 50 engines, 10% for up to 333 and 15% for up to 857 engines, and evaluated for a short (1446Km), medium (5011Km) and long (8144Km) range flight.

Results show performance benefit of 9.5% reduction in engine SFC and 9.2% fuel burn savings relative to baseline performance. Therefore, translating into an economically viable investment with positive investment NPV estimation except for ≤ 50 engine/5% discount rate scenario that is not economically viable. Thus, the methodology provides a cost-benefit analysis of the re-engine upgrade and provides both the operators and OEMs useful insight for re-engining prior to making any commitments.

Chapter Eight

Technology Risk Analysis

8. Introduction

A scenario based technical risk analysis of thermal barrier coating (TBC) upgrade benefit delivery to aircraft engine is of utmost importance to guide both operators and decision-makers on investment in upgrades. This chapter focuses on the risk analysis aspect of the TBC upgrade project implemented within the TERA framework. Techno-economic Environmental Risk Assessment (TERA) framework is a multidisciplinary optimization approach that enables decision support for both traditional and novel technology selection [110]. The TERA takes into consideration performance, environment, economics and risk analysis of the aircraft/engine systems technology. The concept has been applied and proven in the field of aviation, industrial, and marine gas turbine studies [42][35][111]. The aim of this present work is to provide decision support for TBC upgrade investment by analysing the possible risk of technology not meeting its expected benefits and the consequent economic impact on the operator.

The author has described extensively the technical aspect of the research [112], concentrating on the effect of TBC upgrade options on engine performance improvement and life-extension potential for a short-range aircraft mission profile. Alternative benefits of TBC upgrade investment such as payload improvement and runway length reduction were also investigated and quantified, and possible operational variability assessed. Further investigation by the author looked at the techno-economic viability of TBC upgrade investment under different price scenarios. The present chapter however, focuses on the technical risk of the TBC upgrade options and its impact on the economic analysis of the engine/aircraft system.

Although several attempts have been made at quantifying and analysing the technical risk associated with gas turbine engine components [113], there exists very limited work on analysing technical risk of adopting new technology. Khan et al. [114] described a risk model for gas turbine technology selection for natural gas liquefaction (NGL) process based on modified technology readiness level (TRL) scores and mean time between failure (MTBF) analysis. The model attempts to link maintenance scheduling to engine and duty requirement, in order to select the best maintenance routine for the selected engine. The K-sigma model was also discussed by Roth [115] as the best risk-based adaptive technology selection model incorporating both probability distribution and TRL. It evaluates the expected technology benefits as a function of TRL.

However, there is no practical model or framework in public literature that analyses the technical risk of TBC upgrade not delivering the expected benefits. The objective of the present research is therefore to develop a model that links TBC upgrade performance with Technology Readiness Level (TRL), and quantify the technical risk of the technology while assessing its impact on the economics of the system. This will enable decision-maker to make informed judgement on TBC upgrade investment not only based on cost-benefit analysis but also on the potential risk of technology not delivering expected benefits.

8.1 The TERA Framework – Risk Model

The TERA philosophy is an approach that explores the design space to identify potential solutions, thus minimizing cost and computational time. This facilitates decision-making by eliminating unnecessary errors in selecting optimal solutions, and carries out performance optimization and system costs minimization. TERA is a multidisciplinary optimization tool for modelling energy systems performance and asset management [35]. The framework is basically an efficient coupling of engine/aircraft performance module, blade sizing/cooling, engine life prediction, economics and risk analysis modules discussed in previous chapters, and the current architecture presented in Figure 8-1 is an extension to incorporate the risk analysis module. In the present model, the performance module, cooling/upgrade, lifing and economic modules were integrated by setting up a

design of experiment (DOE) to generate approximate models of the design space. The risk module is then integrated and linked to NASA Technology Readiness Level (TRL) in order to estimate the technology risk associated with each TBC upgrade options.

The TERA framework presented in Figure 8-1 shows the risk module receiving data from the cooling/upgrade module before passing it to the lifing and economic modules.

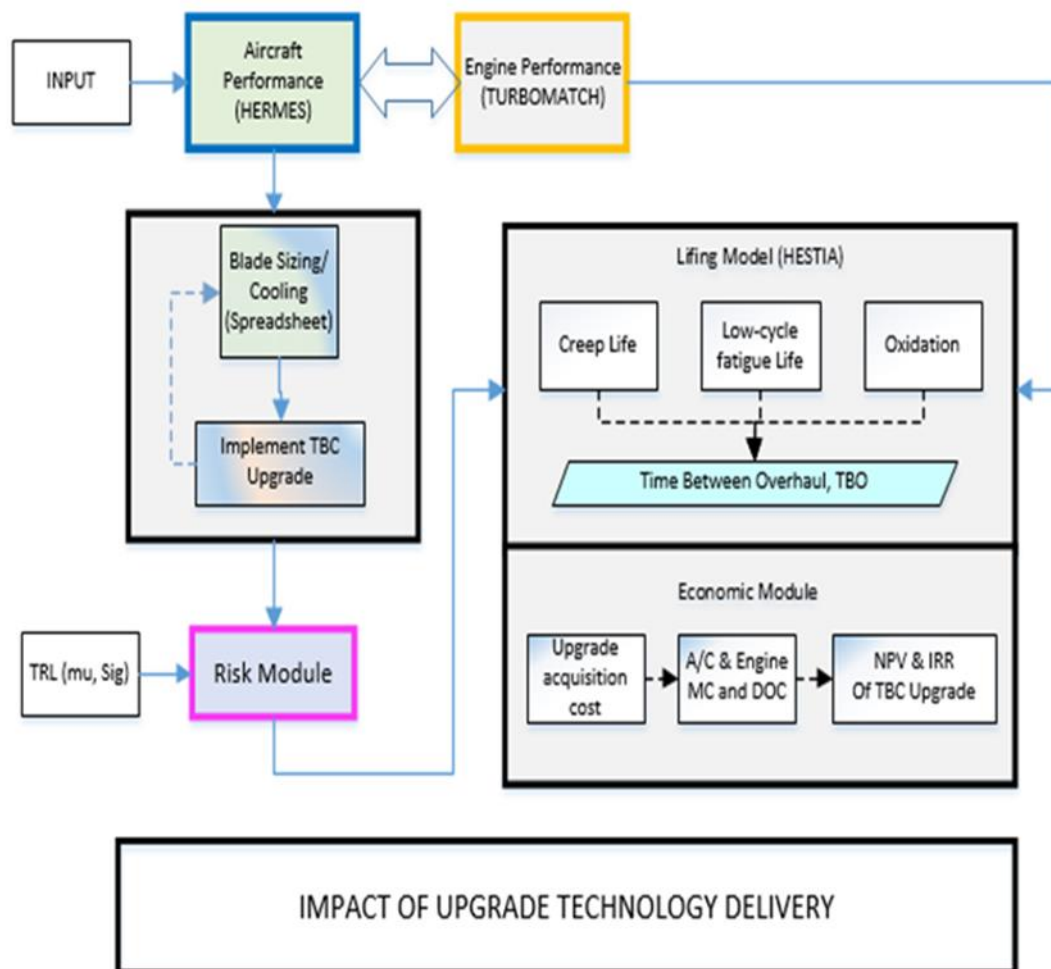


Figure 8-1: TERA Framework for TBC Upgrade Application

Table 8-1: NASA Technology Readiness Level (TRL) Scores

TRL	Description
9	Actual system flight proven on operational flight
8	Actual system tested and flight qualification
7	System prototype demonstrated in flight
6	Model of prototype demonstrated in a relevant environment
5	Component validation in a relevant environment
4	Component validation in a laboratory environment
3	Analytical and/ or experimental proof-of-concept
2	Technology concept formulation
1	Basic principles observed and reported
0	No concept formulation – only basic ideas

In this way, the upgrade technology risk can be evaluated before proceeding to predict the impact of this risk on the engine life and economics of the engine-aircraft system. The risk model uses the change in temperature across TBC, ΔT_{tbc} and overall cooling effectiveness, ε_0 (which are outcomes of cooling/TBC upgrade module), and put them through a Monte Carlo simulation linked to TRL to determine the potential risk associated with each TBC upgrade options. Finally, the impact of the risk associated with each upgrade technology option is quantified and assessed.

8.1.1 Technology Risk Modelling

The evaluation of technology-related risk is often subjective and difficult to quantify [113]. However, it is important to assess and determine the effect of this risk-category on the overall system profitability and return on investment. This is even more interesting as recent trend in aircraft performance enhancement has been through infusion of new propulsion systems technology and major technology advancements [116]. Therefore, a detail risk assessment to predict the potential risk of TBC upgrade technology non-delivery is necessary as it offers useful insight to operators and decision-makers.

8.1.2 Technology Readiness Level

A useful method of analysing the technology risk is the NASA's Technology Readiness Level (TRL). The TRL is a subjective scoring scale that rates technology readiness level from zero to nine, as shown in Table 8-1 [117], with score zero indicating technology with the lowest readiness and highest risk, and nine with the lowest risk and highest readiness. Each score is a reflection of the technology's level of research and development. The disadvantage of TRL scores is that, by themselves do not directly model the technology risk but merely categorizes technologies based on the perceived risk they posed. The TBC upgrade technology option with $K=0.72$ was chosen and a risk profile assigned based on NASA TRL scores, different levels of technology development and presented in Table 8-2. These scores have been derived based on the authors extensive review of literature in public domain on TBC development progress.

Table 8-2: TBC Upgrade Technology Score in NASA TRL Scale

$K_{tbc}=0.72W/m.K$	
Risk Profile	TRLScore
Class-A	9
Class-B	8
Class-C	7
Class-D	6
Class-E	5
Class-F	4

8.1.3 Risk Model Connected with TRL

The present work utilizes the **k- σ risk model** proposed by Kirby and Mavris [118], which matches probability distribution of technology benefits with TRL score. Hence, the risk of technology non-delivery was estimated through Monte Carlo simulation of technology benefits using Weibull distribution. The distribution is chosen because of its flexibility and ability to mimic the characteristics of other distributions such as normal, exponential, or Rayleigh. The Weibull distribution for a given x random variable, can be expressed as:

$$f(x; \alpha, \beta, \gamma) = \begin{cases} \frac{\beta}{\alpha} \left(\frac{x - \gamma}{\alpha} \right)^{(\beta-1)} \exp \left[- \left(\frac{x - \gamma}{\alpha} \right)^\beta \right] & x \geq L \\ 0 & x \leq L \end{cases} \quad \text{Equation 8-1}$$

Where α is the scale parameter, β is the shape parameter, and γ is the location parameter of the distribution. The random variable x considered in this study is the TBC upgrade technology outcome; change in temperature across TBC, ΔT_{tbc} , which is randomly generated within a defined bound through Monte Carlo simulation. The TRL of each technology option is incorporated within the technology bounds of uncertainty distribution through the scale parameter defined as [118]:

$$\alpha(\gamma_i; \gamma_i = \Delta T_{tbc}) = 30\% \gamma_i - (TRL - 1) \frac{(30\% \gamma_i - 5\% \gamma_i)}{8} \quad \text{Equation 8-2}$$

Table 8-3 Scale Parameter of the TBC Upgrade Technologies with different risk profile (TRL)

Risk Profile	$\gamma_i = \Delta T_{tbc}$		$\beta = 20$	
	TRL Score	Scale Parameter α	Mean μ	Std.Dev σ
Class-A	9	2.20730	220.598	0.109890
Class-B	8	3.31095	220.532	0.165364
Class-C	7	4.41460	220.468	0.217709
Class-D	6	5.51825	220.411	0.269239
Class-E	5	6.62190	220.336	0.328943
Class-F	4	7.72555	220.278	0.375387

In order to assess the effect of TRL on technology risk or outcome uncertainty, the Weibull scale parameter was computed for several TRL scores using Equation 8-2, and their corresponding mean and standard deviation determined as presented Table 8-3. This model efficiently captures the technology risk or non-delivery of expected technology benefit or outcome. Consider the risk of the upgrade technology at different levels of maturity or development stage depicted by its TRL score and the technology delivering expected benefit of

$\Delta T_{tbc}=220.7296\text{K}$ for 10,000 runs, Figure 8-2 shows the expected outcome of baseline technology assuming different TRL scores. The higher the TRL value the better the chances of more runs producing expected benefit. However, as the value reduces the distribution is increasingly skewed towards the left, which means less runs are likely to meet target value with high risk profile. Figure 8-3 shows the probability of technology runs delivering expected benefit.

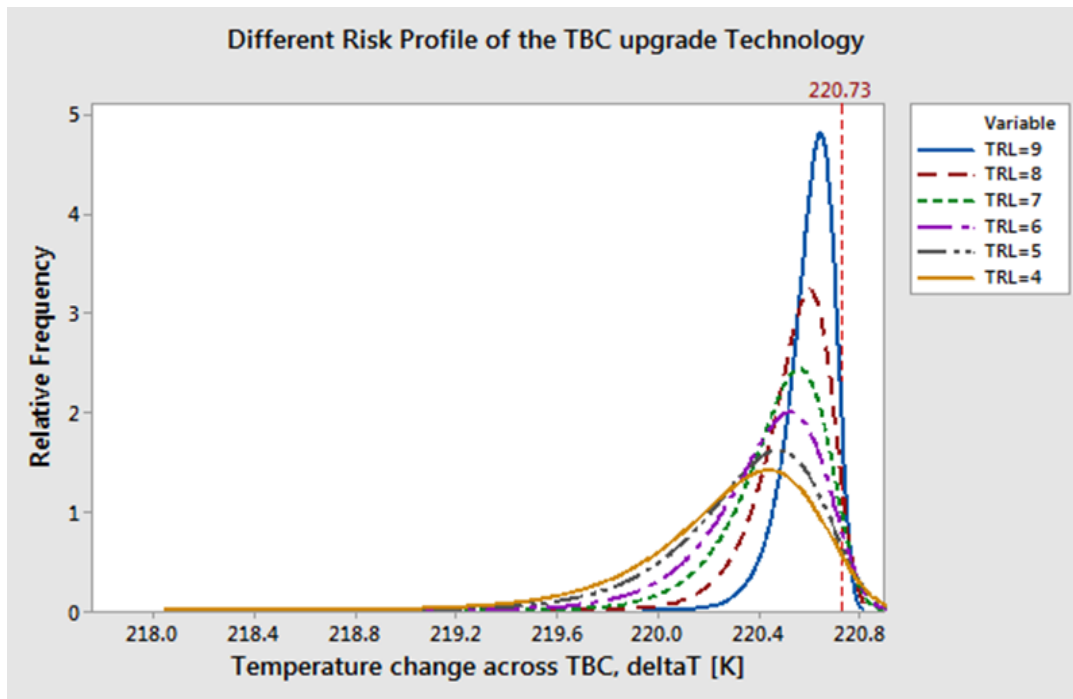


Figure 8-2 Relative Frequency of Temperature change across TBC

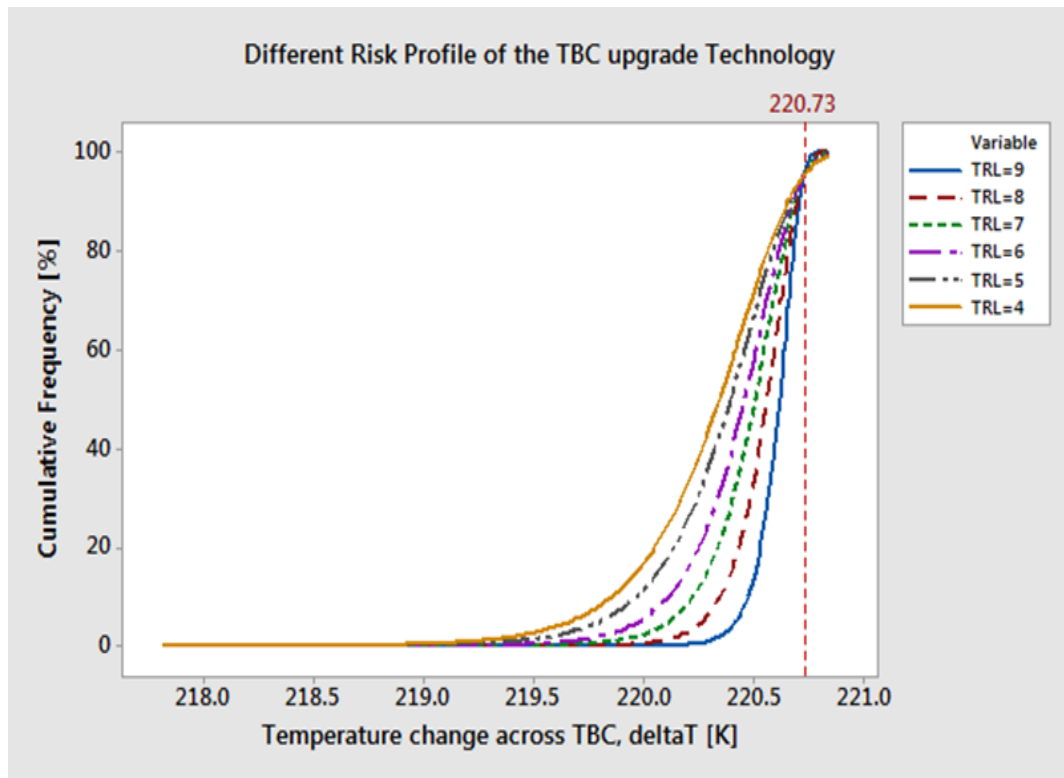


Figure 8-3 Cumulative Frequency of Temperature Change across TBC

8.2 Method for Risk Assessment

The procedure begins by deterministically evaluating the benefits associated with the TBC upgrade technologies using the TERA methodology. This upgrade comprise of six TBC options with different K-values (1.62, 1.44, 1.26, 1.08, 0.9, and 0.72) representing improvement in TBC technology, from baseline or commercially available technology ($K_{tbc}=1.8$) to advance future technology ($K_{tbc}=0.72$), only existing as concepts or prototypes in research laboratories [89]. These improvements are implemented within the cooling module of the TERA framework, and one of the module outputs, temperature change across TBC, is used as the primary benefit for assessing technology improvement. The impact of technology risk on aero-engine TBO extension, engine maintenance costs (EMC) and aircraft direct operating costs (DOC) were investigated in this study.

8.2.1 Design of Experiment (DOE)

Response surface models (RSM) were constructed based on the design of experiment (DOE) results acquired through the central composite approach, corresponding to the space exploration bounds defined in Table 8-4. The derived models are presented as shown:

$$\text{TBO} = -209073 + 413433 X_1 + 670 X_2 - 161908 X_1^2 - 0.4239 X_2^2 - 544 X_1 X_2$$

$$\text{EMC} = 2376 - 4038 X_1 - 6.532 X_2 + 1898 X_1^2 + 0.004898 X_2^2 + 6.286 X_1 X_2$$

$$\text{DOC} = 13118 - 8057 X_1 - 13.031 X_2 + 3786 X_1^2 + 0.009773 X_2^2 + 12.541 X_1 X_2$$

Where,

X_1 = Overall cooling effectiveness, ϵ

$$X_2 = \Delta T_{tbc}$$

Small variation in engine benefit output (for both RSM and simulation) can be attributed to the relative error associated with the development of the RSM, and can be found to generally less than 2% as presented in Table 8-5 and Table 8-6.

8.2.2 Monte Carlo Simulation (MCS)

In order to assess the potential impact of the risk of each upgrade technology option on the aero-engine, a Monte Carlo simulation technique was utilized to evaluate the engine upgrade benefits (TBO extension, EMC and DOC reduction) based on the distribution of input parameter (temperature change across TBC) variation. The values of the input variable were randomly generated for 10,000 runs based on the defined distribution and TRL score discussed in previous section, and their variation mimics the different level of risk associated with each technology.

Table 8-4 Space Exploration Bound within Which RSM is Accurate

Space Parameter	Lower Bound	Upper Bound	Units
TBC	0.72	1.8	W/m.K
ϵ	0.63	0.65	%
ΔT	145.88	220.73	K
Constraints for implementing RSM			
TET _{TO}		1620	K
T _{Amb}		288.15	K

Table 8-5 Response Surface Model Relative Error from Simulation Result

RSM relative error from Simulation Result					
Upgrade	RSM	Simulation	Units	RSM rel. error %	
Baseline	25,767.0	25,864.54	Hrs	- 0.38	
Type-A	27,211.3	27,084.71	Hrs	+0.47	
Type-B	28,802.9	28,623.30	Hrs	+0.63	
Type-C	30771.1	30,604.81	Hrs	+0.54	
Type-D	33,256.9	33,202.51	Hrs	+0.16	
Type-E	36,467.2	36,608.04	Hrs	-0.39	
Type-F	40,679.9	40,719.72	Hrs	-0.10	

Table 8-6 Response Surface model relative error from simulation result

RSM relative error for baseline technology benefit				
Benefit	RSM	Simulation	Units	RSM rel. error %
TBO	25,767.00	25,864.54	hr	- 0.38
EMC	313.98	313.60	€	+0.12
DOC	9,003.78	9,002.09	€	+0.02

Table 8-7 Scale parameter, mean and standard deviation of baseline technology due to TRL

TRL	$\gamma_i = \Delta T_{tbc}$		$\beta=20$	
	ΔT_{tbc}	Scale	Mean	Std.
	[K]	parameter α	μ	Dev σ
9	151.28	7.56	152.57	3.49
8	158.07	12.84	157.28	5.96
7	166.85	18.77	162.53	8.69
6	178.65	25.68	168.65	11.88
5	195.34	24.18	176.14	15.83
4	220.73	45.53	186.21	21.04

Therefore, the calculated scale parameters from the equations above for each TBC upgrade type assuming a specific TRL score that reflects the technology risk category, along with their mean and standard deviation values are presented in Table 8-7. The Weibull shape parameter β , which determines the distribution shape and failure behaviour, in this case the behaviour of technology non-delivery was set at twenty (20) indicating that the distribution mimics the characteristics of a distribution with left skewed tail to capture the risk of the technology and stage of development. The scale parameter was estimated based on ΔT_{tbc} value for that TRL score. The parameter depicts the distribution spread or error margin, and has been illustrated in Table 8-7, the inherent risk (or error margin) widens as the value of TRL decreases.

8.3 Aircraft/Engine Configuration

The aircraft/engine system utilized for the short-range flight analysis is of the CEUP56 type engine with thrust rating of 121.43KN at S.L.S condition and a Cranboe-737 aircraft. Detail description and verification of engine performance is presented in chapter 4. The aircraft mission simulation for this study has been modelled to follow international flight regulations as stipulated in F.A.R part 121, and assumes standard assumptions on fuel reserves, diversion fuel and contingency fuel. The aircraft mass and balance has been modelled for an all-

single class seating with 177 passengers, and is validated against public literature data and have good payload-range performance.

The short-range mission is simulated for London Heathrow (LH) to Malpensa Italy (MI) flight route with 938Km range and local standard atmosphere (L.S.A) for summer, spring and winter is assumed. The mission follows the typical take-off, climb, cruise, and descent, including approach and landing configuration. The mission cruise segment is simulated at design cruise speed of 0.8 Mach and 10668m altitude. To calculate the block fuel and time additional standard 9min of taxiing time and equivalent fuel was added to the mission time and fuel respectively. Also standard reserves of 6096km diversion range, hold at 457m for 20min and 5% of block fuel.

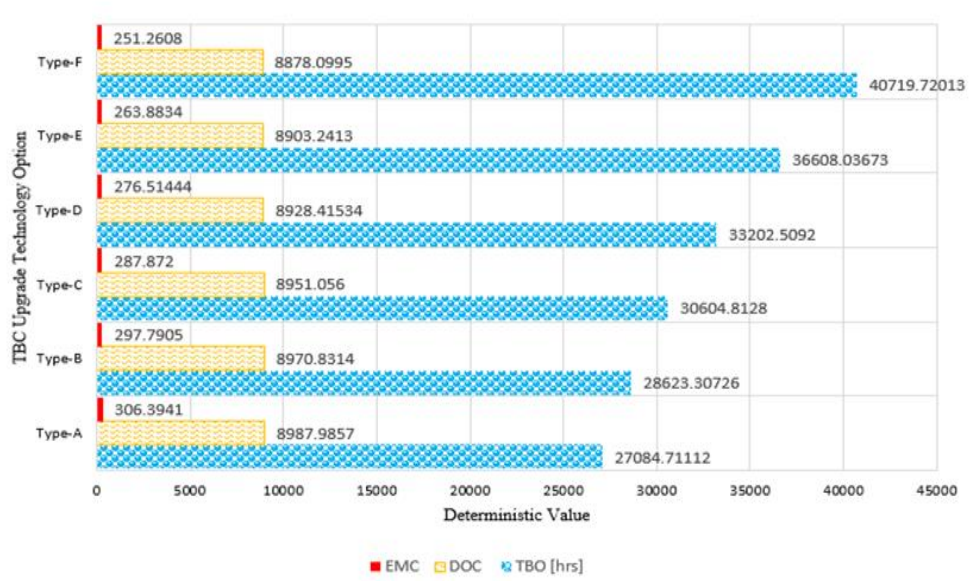


Figure 8-4 TBC upgrade technology deterministic values for performance and economics

8.4 Results and Discussion

8.4.1 Performance Results

The deterministic values of the performance and economic results for criteria selection for the evaluation of the risk associated with the TBC upgrade technology is shown in Figure 8-4. Six TBC upgrades were analysed to determine their potential benefits in terms of time between overhaul (TBO), engine maintenance costs (EMC) and aircraft direct operating costs (DOC). These benefits were estimated based on the TERA methodology discussed previously in chapter 5. Result proves that as improvements in TBC upgrade increases so does their potential benefits, and it's further corroborated by values presented in Figure 8-4. The baseline engine utilized for this work (with TBC k-value of 1.8), had approximately 25864 hours of operations, the engine maintenance cost (EMC) per flight is €313.6 and the aircraft direct operating costs (DOC) per flight reported stood at €9002.088. In Figure 8-4, the upgrades appear to produce more attractive benefits, with the most attractive being TBC Type-F upgrade (with TBC K-value of 0.72), extending engine operations to 40719 hours, and reducing EMC and DOC to €251.2608 and €8878.0995 respectively. The reduction in EMC and DOC as TBC effectiveness increases reveals significant opportunity for costs savings, which in turns improves profit and the investment Net present value (NPV).

8.4.2 Impact of Risk on Engine TBO

The decision to invest on technology upgrade most often is not only based on cost-benefit analysis, but also on the risk associated with technology delivery uncertainties. However, the present study shows the sensitivities of upgrade potential benefits to uncertainties in technology output delivery base on the technology risk profile of TRL scale. Figure 8-5 presents the result of the cumulative probability distribution of TBO for the six TBC upgrade options considered. Figure 8-5 can simply be considered as a risk-analysis oriented version of Type-F upgrade in Figure 8-4 with regards to TBO from technology

development stage in the laboratory (TRL=4) to technology maturity (TRL=9). It is worth mentioning here that for deterministic appraisal of project viability, decision-making is basically based on the project costs-benefit analysis: that is, what are the potential benefits of the investment relative to baseline, what is the additional cost required relative to baseline, and are the potential derivable benefits worth the extra investment costs of the project.

However, risk-analysis provides valuable insight for decision-makers about the risk-benefit profile of the investment, which may significantly influence investment decision [119]. The final decision is mostly subjective and depends on the risk-tolerant level of the investor.

Figure 8-8 shows the cumulative probability distribution of the different technology options with their TRL risk profile. It also provides the Weibull parameters that fits the distribution with a 10,000 simulation runs. Figure 8-8 (a) to (f) depicts the cumulative probability distribution of TBO corresponding to their respective TRL scores and the risk profile. For the Class-A profile with TRL of 9 shows that 91.3% of the simulation runs are likely to fail on technology delivery of TBO = 40679.9 hours, 92.8% for Class-B, 93.5% for Class-C, 93.7% for Class-D, 94.0% for Class-E and 94.2% for Class-F. Figure 8-8 clearly reveals that as the TRL decreases, reflecting higher risk of technology delivery. It simply means that from the development stage in laboratory to production stage only 2.9% additional runs can attain the upgrade performance target (TBO=40679.9 hrs) set originally at development.

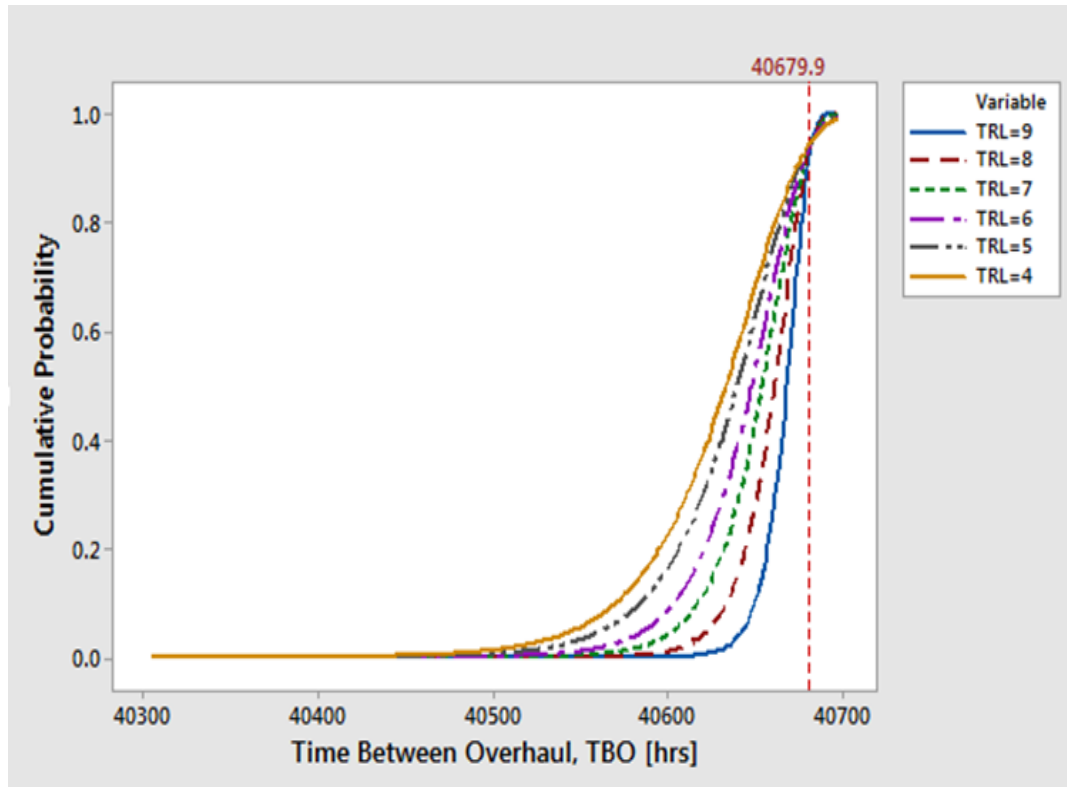


Figure 8-5 Cumulative distribution of TBC upgrade TBO

8.4.3 Impact of Risk on Engine Maintenance Costs

Similarly, Figure 8-6 shows the cumulative probability distribution of the EMC for the considered TBC upgrade technology corresponding to their respective TRL stages as discussed previously. The figure illustrates the potential EMC reduction relative to upgrade Type-F deterministic value (€251.261) and their risk profile indicated by the width of the distribution curve. Individual upgrade technology EMC risk characteristics are presented in Figure 8-9. Each graph (a) to (f) quantify the risk of technology non-delivering for a 10,000 simulation runs on the expected EMC achievable for the TBC upgrade investment. The estimated risk profile for EMC benefits are 2.2% for Class-A, 6.6% for Class-B, 8.7% Class-C, 10.1% for Class-D, 3.7% for Class-E and 5.5% for Class-F. The results followed expected trend of increasing risk exposure with decreasing TRL scores.

8.4.4 Impact of Risk on Aircraft Direct Operating Costs

The direct operating cost (DOC) remains a very importance parameter to the operator, as it constitutes different costs categories relating to flying, fuel and emission. It is often used as a figure-of-merit for aircraft engine economic trade-off and optimization studies. As it strongly influences the profit and general economics of an investment project, hence, have been deployed for assessing the technology risk of TBC upgrade technology non-delivery.

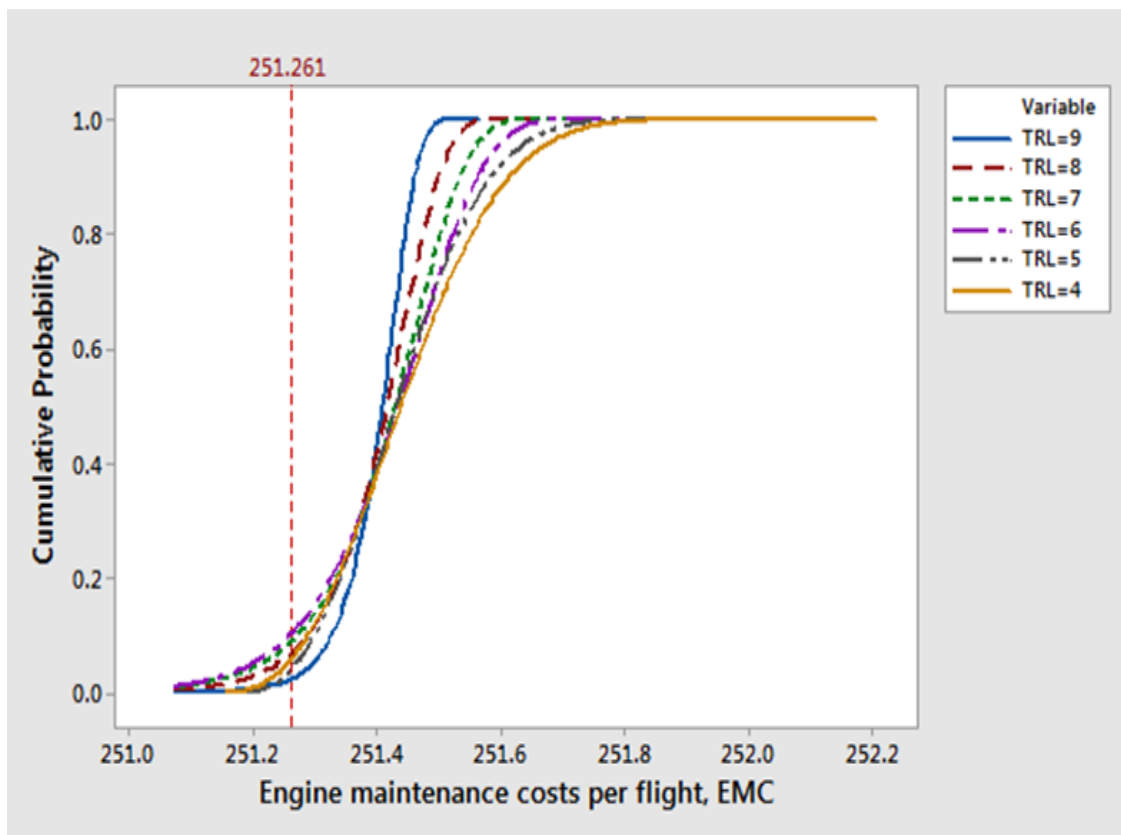


Figure 8-6 Cumulative distribution of TBC upgrade EMC

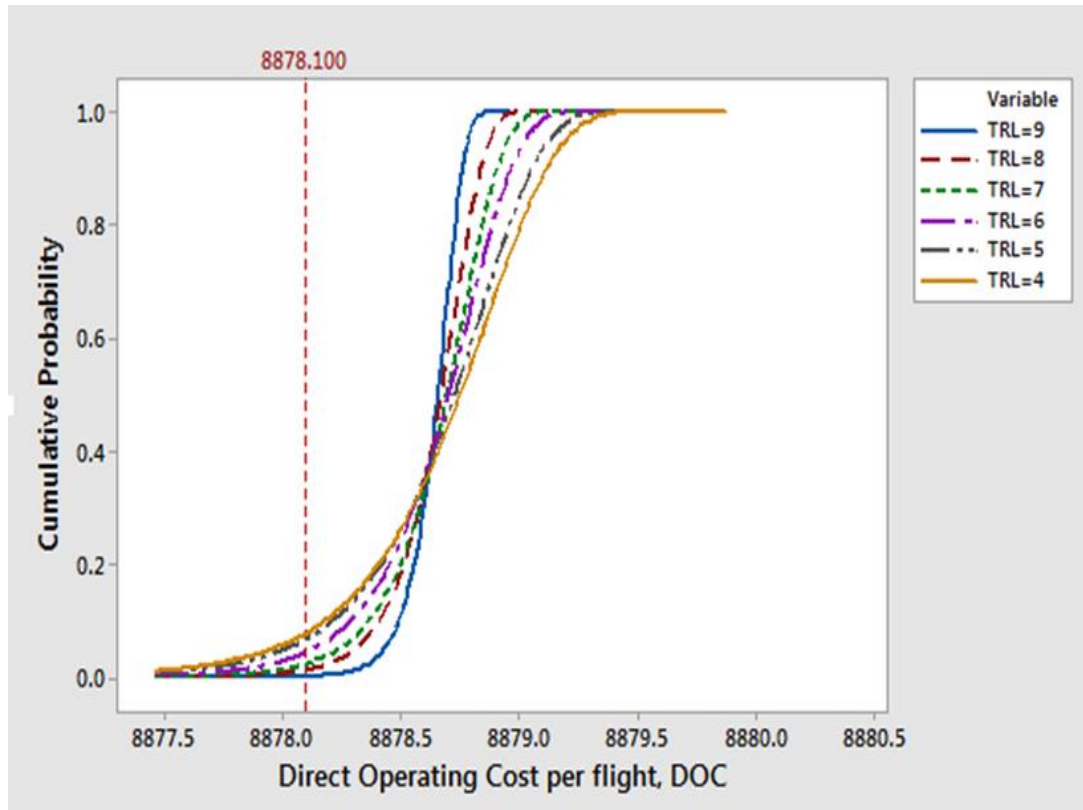
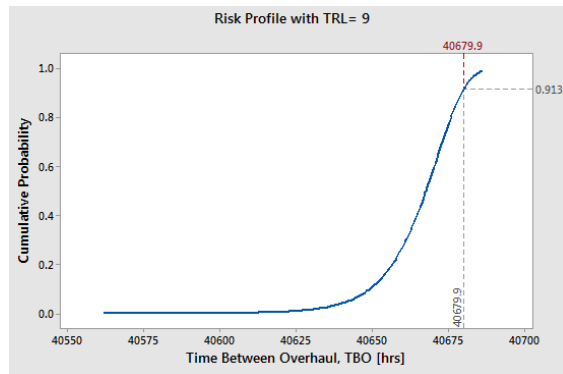
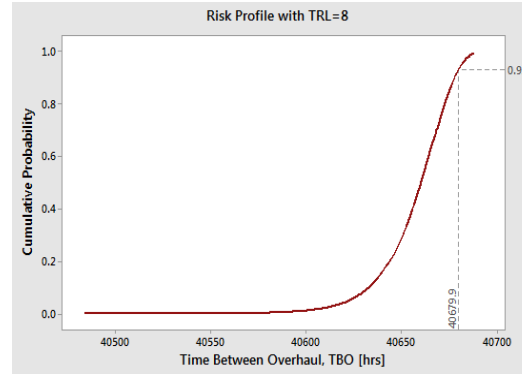


Figure 8-7 Cumulative distribution of TBC upgrade DOC

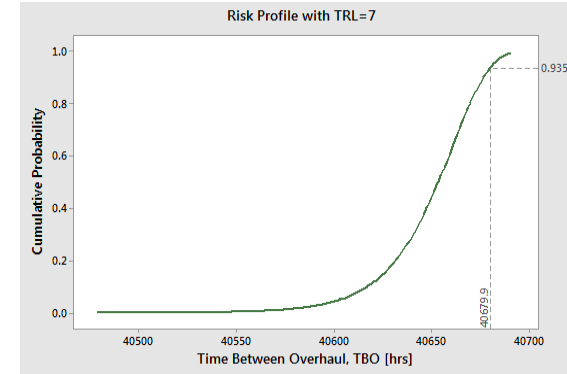
Figure 8-7 shows the cumulative probability distribution of DOC for different TBC upgrade technology. It clearly illustrates that reduction in DOC increases with the higher TRL score and reflecting their consequent risk profile. As mentioned earlier the width of the curve indicates the risk or error margin. For detail investigations, the DOC distribution for each upgrade technology is presented in Figure 8-10. The estimated risk of DOC benefits non-delivery for the upgrade technology as presented in (a) to (f), are 0.1% for Class-A, 1.1% for Class-B, 2.3% for Class-C, 4.3% for Class-D, 6.7% for Class-E and 7.8% for Class-F.



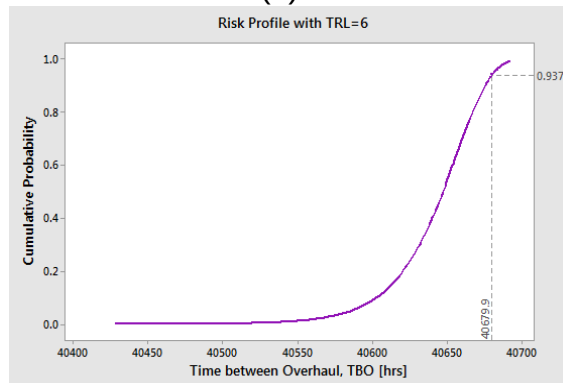
(a)



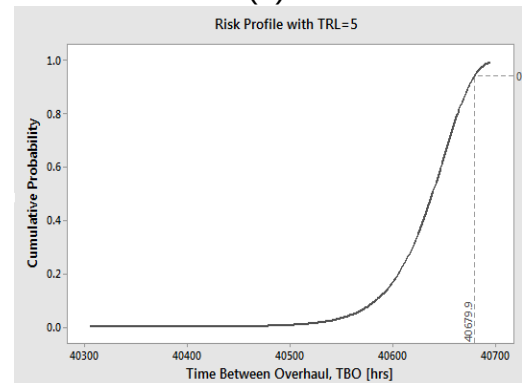
(b)



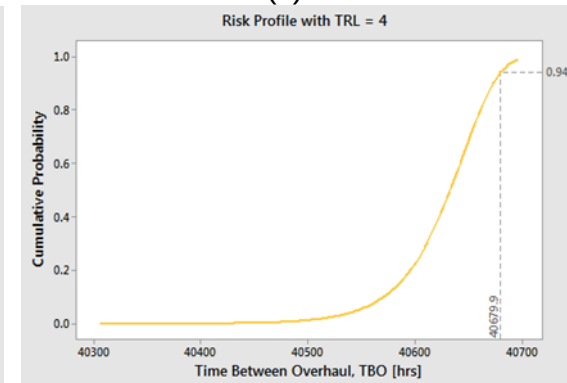
(c)



(d)



(e)



(f)

Figure 8-8 Probability distribution of Time Between Overhaul with Risk Profile (a) TRL=9, (b) TRL=8, (c) TRL=7, (d) TRL=6, (e) TRL=5, (f) TRL =4

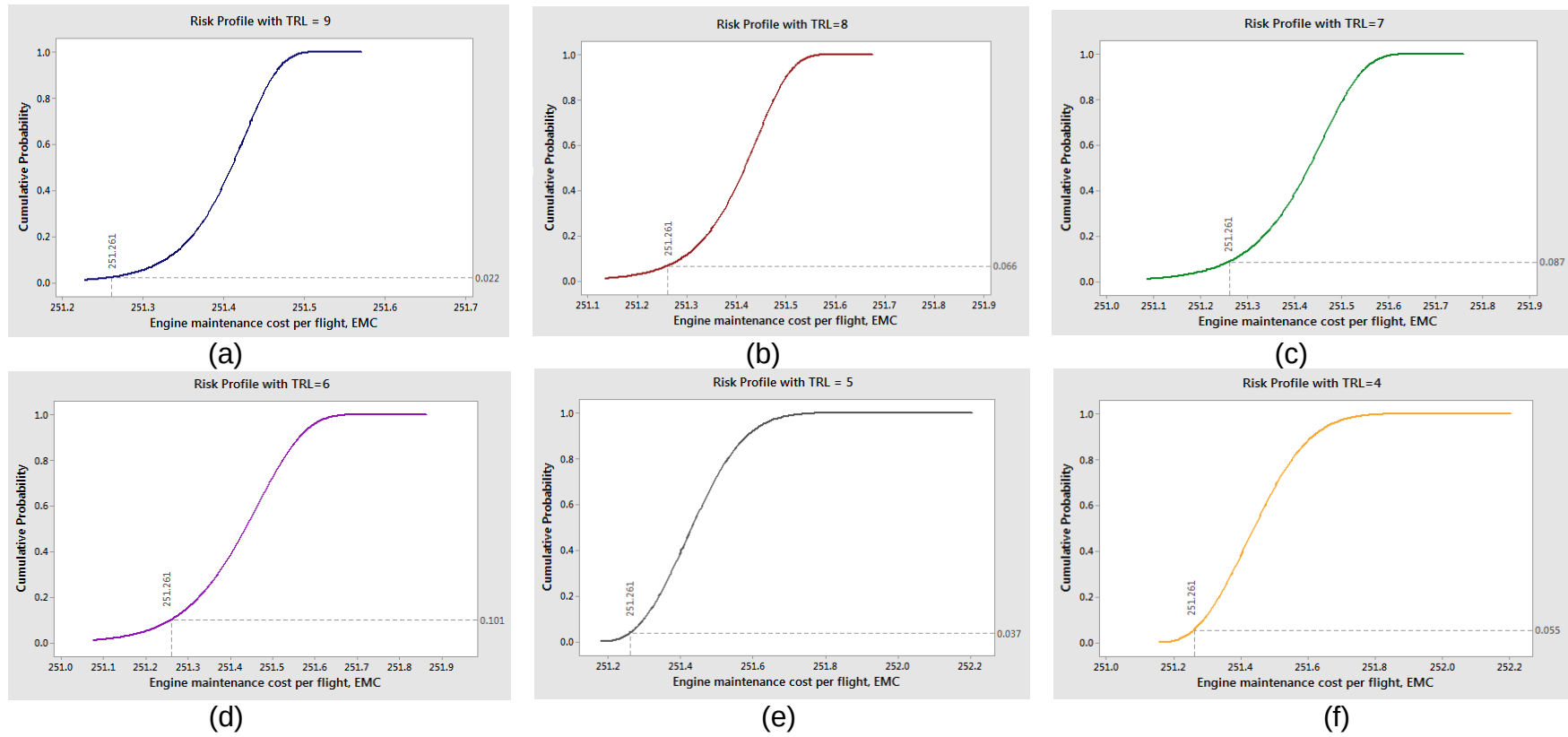


Figure 8-9 Probability distribution of Engine maintenance cost per flight with Risk Profile (a) TRL=9, (b) TRL=8, (c) TRL=7, (d) TRL=6, (e) TRL=5, (f) TRL=4

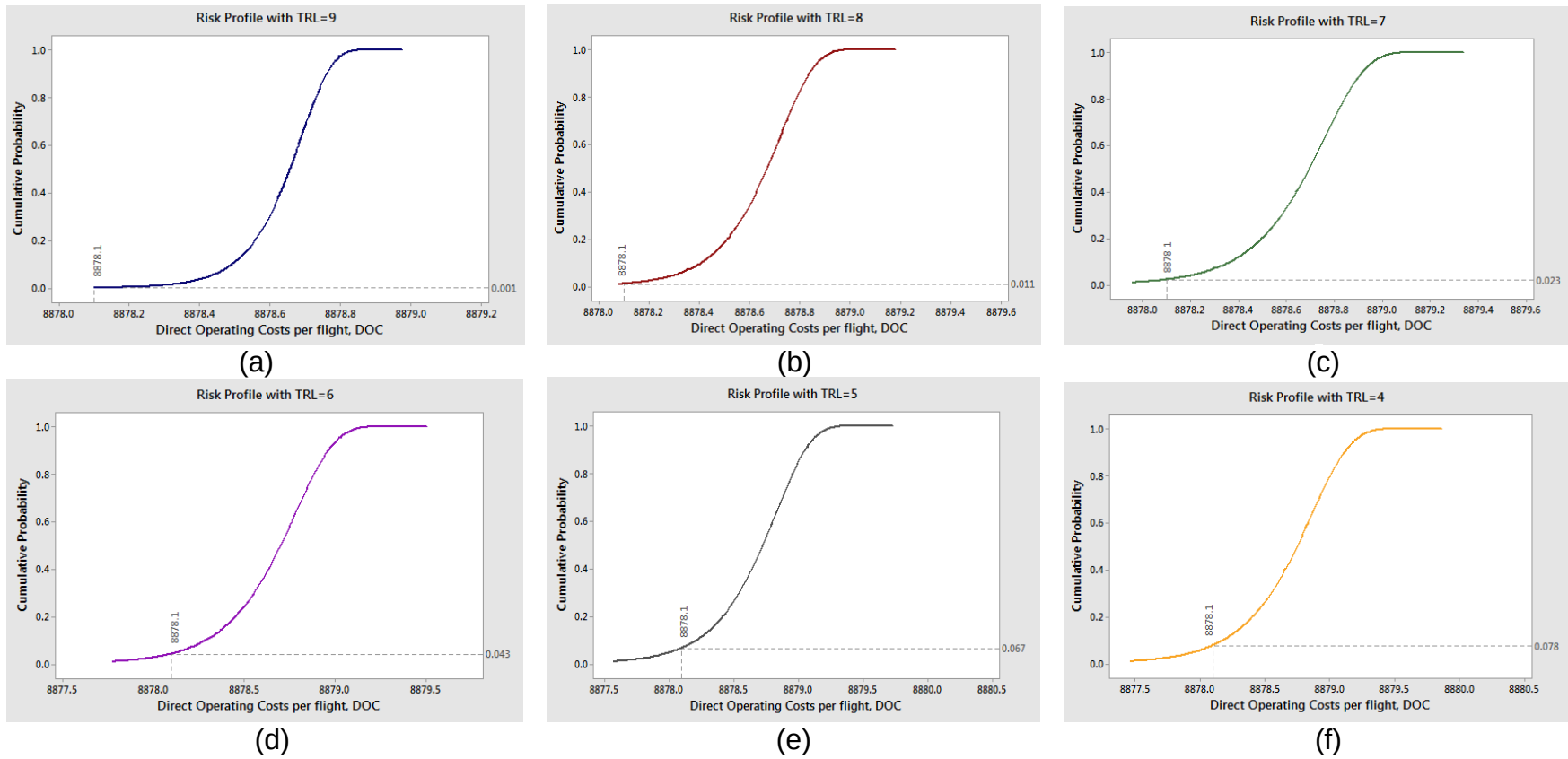


Figure 8-10 Probability distribution of Direct Operating Cost per flight with Risk Profile (a) TRL=9, (b) TRL=8, (c) TRL=7, (d) TRL=6, (e) TRL=5, (f) TRL=4

8.5 Chapter Summary

This chapter presents a risk-evaluation of TBC upgrade technology benefits non-delivery and serves as an investment decision support tool for technology selection for performance and economic optimization. The study deployed the $k-\sigma$ risk model proposed by Kirby et al to evaluate the risk of upgrade technology not delivering on expected benefit by linking the Technology Readiness Level (TRL) and probability distribution function. The change in temperature across TBC, ΔT_{tbc} was used as the technology output parameter for assessing the risk of the technology based on three upgrade benefit parameters; time between overhaul (TBO), engine maintenance costs (EMC) and aircraft direct operating costs (DOC). To approximate the resulting potential risk of technology non-delivery, a full factorial design of experiment (DOE) was deployed to construct surrogate models that coupled the upgrade technology output parameter and the evaluated benefit parameters. The six hypothetical TBC upgrade technologies, Type-A to Type-F, with potential risk classification of TRL score from 9 to 4, based on technology maturity were assessed for the upgrade benefit parameters. TBO seems the most sensitive parameter to variations in ΔT_{tbc} with significantly higher risk exposure with increasing upgrade effectiveness. The EMC and DOC gave a rather moderate risk profile and trend consistency.

The aim of this research is to provide further insight to the operators about the potential risk of technology non-delivery and therefore help selection decision from the technology risk perspective. The procedure predicts the expected trend of results but the technology output parameter, ΔT_{tbc} used in the distribution have been selected for this hypothetical study even though in reality this effect is a combine influence of many parameters. The results therefore show the risk and sensitivity of performance and economic parameters to the upgrade technology maturity level. Although the final decision on an investment depends on the investment risk tolerance of the operator, the authors see this as a crucial and integral step towards a comprehensive analysis for selection decision

Chapter Nine

9. Conclusions

The research presented in this thesis evaluates and quantifies the potential benefits derived from investing in aero-engine upgrades from both the operator's (user's) and manufacturer's perspective, and serves as a useful decision making guide for aero-engine upgrade users (aircraft owners), policy makers and financiers of upgrade investments. The main aim is creating an effective cost-benefit analysis methodology for pre-evaluating upgrade offers/investments prior to making any decision or financial commitment. In this study, the multi-disciplinary TERA approach was utilized for these investigations, with sensitivity-based risk analysis. The TERA framework enables decision support for both traditional and novel engine technologies assessment, accounting for the technical (performance), economics, environmental and risk impact of such technologies on the aero-engine/aircraft system combination. The suitability and adaptation of this approach for the assessment of the different aero-engine upgrade technologies studied in this work, is because the concept has been applied and proven in the field of aviation, industrial and marine gas turbine studies [4][37][43][120]. The methods are appropriately suitable for evaluating aero-engine upgrades from the airline operator, manufacturer's and supplier's perspective. The limits of these TERA-Upgrade methods are largely associated with the lack of real-life data for modelling and validating the results. However, these can be further develop in future work using real data from the OEMs, airline operators and suppliers to improve results confidence.

Four proposed aero-engine upgrade cases were investigated and analysed. They include the thermal barrier coating (TBC) upgrade for HPT blade metal temperature reduction, TBC upgrade for coolant airflow reduction, increased engine fan diameter upgrade, and the aircraft re-engined upgrade. Evaluation of each upgrade entails different procedure but essentially the same overall TERA framework, which consist mainly of the engine and aircraft performance models,

engine sizing/cooling, weight, life, and economic models. To quantify any potential benefits associated with the implementation of the proposed aero-engine upgrade, several aircraft and engine configuration were modelled in TURBOMATCH, based on Boeing 737-900 and Airbus A330 aircrafts, and CFM56-7B27, CF6-80E1A3 and Trent-700 engines specification. The thrust and SFC of these engine models were verified against publically available data.

The thermal barrier coating (TBC) upgrade for HPT blade metal temperature reduction case-study was evaluated based on six hypothetical TBC upgrade options with different values of thermal conductivity ($K_{tbc}=1.62, 1.44, 1.26, 1.08, 0.90$, and 0.72W/mK), representing TBC upgrade effectiveness. The assumed K_{tbc} values of the hypothetical TBC were based on reviews of past and present researches on TBC improvements. The TBC upgrade options were utilized for engine life extension and payload improvement benefit. Results obtain show a maximum engine life improvement of 36.5% increase relative to baseline, 19% decrease in engine maintenance cost (EMC) and up to 1.3% decrease in flight DOC is possible with upgrade Type-F technology, which is the most advanced TBC upgrade considered. The economic attractiveness of TBC upgrade for engine life-extension purpose, evaluated as the cost-benefit analysis for the TBC active operating life (years) presented a profitable investment in terms of both the return on investment and NPV estimation. Utilizing TBC upgrade for increase engine payload capacity also gives very attractive economic prospects from generating revenue from additional 33 passengers or 3465Kg payload capacity.

The re-engining upgrade of existing airframe with new advance turbofan engine presents a potential viable solution for gains in fuel efficiency (or fuel savings) over the original engine, as a market response to the long delays associated with new aircraft development programs. In this case a double-aisle Cranbus A330 aircraft similar to airbus A330-300 is re-engined with with CEUP-7000 engine model, producing a fuel burn reduction of 9.2%, 6.5%, and 6.31% relative to baseline for the short (1446Km), medium (5011Km) and long-range (8144Km) missions. Although fuel burn is a component of total DOC, the low engine

maintenance costs (EMC) due to increase engine life for aircraft operating on long mission length significantly affects the total DOC. Beyond the obvious fuel efficiency gains associated with re-engining an aircraft, there are other tradeoffs, such as nacelle-drag, engine weight and upgrade/conversion costs. The economic merits of re-engining upgrade was evaluated considering the impact of the number of engine upgrade (attracting discounts on engine price) on potential cost savings and NPV of the project.

Increased engine fan diameter upgrade was also investigated for potential performance and economic benefits. The analysis was performed for both fuel burn gains and increased payload capability, with results showing significant benefits for both scenarios.

9.1 Recommendation for Further Work

The study being a techno-economic risk assessment of aero-engine upgrades can be further developed in the following ways:

- Further development of the upgrade acquisition costs (or pricing) models base on real life data from OEMs, MROs and airline operators.
- Development of a robust automated coded coupling all the different models of the TERA-Upgrade study, in order to eliminate any potential error during handling data between models, and hence significantly improving result quality.
- In order to reduce unnecessary assumptions and maximize the benefits of the TERA-upgrade methodology, real life data from the industry or OEMs should be used for the purpose of validation.
- The impact of engine/aircraft aging on the potential benefit of the upgrade for the operator can be further investigated.
- Further work can be done on the impact of multiple upgrades and their interactions with one another on the aero-engine and aircraft system.
- Further work on the upgrade technology risk of non-delivery can be developed to give a more holistic analysis of the upgrade to the investor, financier or policy-maker.

- The optimization of engine-aircraft systems can be carried out for optimum mission specific operations and business best case scenario.
- Reasonable assumptions were made in this work where actual industry data or publicly available information were limited. However, the result confidence of the model can be improved in future work by using information from real-life data.
- The increased engine fan diameter upgrade can be further developed by performing a CFD analysis on the impact of the small increase in fan diameter on engine airflows (performance) and carry out engine internal inlet aerodynamic optimization the match the new fan diameter.

REFERENCES

- [1] statista (2018) *Annual growth in global air traffic passenger demand from 2005 to 2018*. Available at: <https://www.statista.com/statistics/193533/growth-of-global-air-traffic-passenger-demand/>.
- [2] HHH Saravanamuttoo, GFC Rogers, H Cohen, P. S. (2009) *Gas Turbine Theory*. 6th Editio.
- [3] Air Force Studies Board (2007) *IMPROVING THE EFFICIENCY OF ENGINES FOR LARGE NONFIGHTER AIRCRAFT*. Wasington, D. C.
- [4] Kyprianidis, K. (2010) 'Multi-disciplinary conceptual design of future jet engine systems'. Available at: <https://dspace.lib.cranfield.ac.uk/handle/1826/8041>.
- [5] Birch, N. T. (2000) '2020 Vision: the Prospects for Large Civil Aircraft Propulsion', *Aeronautical Journal*, 104(1038), pp. 347–352.
- [6] Benzakein, M. J. (2014) 'What does the future bring? A look at technologies for commercial aircraft in the years 2035–2050', *Propulsion and Power Research*, 3(4), pp. 165–174. doi: 10.1016/j.jprr.2014.11.004.
- [7] Walsh, P. P. and Fletcher, P. (2004) *Gas Turbine Performance*, *Business*. doi: 10.1002/9780470774533.
- [8] Haselbach, F., Newby, A. and Parker, R. (2015) 'Next Generation of Large Civil Aircraft Engines - Concepts & Technologies', in *European Turbomachinery Conference*, pp. 23–27.
- [9] Mohd Tobi, A. L. and Ismail, A. E. (2016) 'Development in Geared Turbofan Aeroengine', in *IOP Conference Series: Materials Science and Engineering*. doi: 10.1088/1757-899X/131/1/012019.
- [10] J AVIER M ARTÍN D ÍAZ (2016) *ECONOMIC IMPACT OF THE IMPLEMENTATION OF AIRWORTHINESS DIRECTIVES AND SERVICE BULLETINS ECONOMIC IMPACT OF THE IMPLEMENTATION OF*.
- [11] CFM International website (1996). Available at:

www.cfmaeroengines.com/engines/ (Accessed: 13 August 2017).

[12] Daly, M. and Gunson, B. (2011) *Janes Aero Engines Issue 29*. Assoc. Ed. Surrey: IHS Janes.

[13] Liu, Y., Sun, X., Sethi, V., Nalianda, D., Li, Y. G. and Wang, L. (2017) 'Review of modern low emissions combustion technologies for aero gas turbine engines', *Progress in Aerospace Sciences*, pp. 12–45. doi: 10.1016/j.paerosci.2017.08.001.

[14] Lefebvre, A. H. and Ballal, D. R. (2010) 'Gas turbine combustion: Alternative Fuels and emissions', in *Gas Turbine Combustion*, pp. 443–511. doi: 10.1201/9781420086058-c10.

[15] GE Aviation (no date o) *CFM Receives Order for 31 CFM56-3 Additional Upgrade Kits, Offering Additional Kit Options for Added Flexibility*. Available at: <https://www.geaviation.com/press-release/jv-archive/cfm-receives-order-31-cfm56-3-advanced-upgrade-kits-offering-additional-kit>.

[16] GE Aviation (2002) *Air China Places \$6 Million Order For CFM56-3 Engine Upgrade Package*. Available at: <https://www.geaviation.com/press-release/services/air-china-places-6-million-order-cfm56-3-engine-upgrade-package>.

[17] CFM (2009) *CFM TECH INSERTION BRINGING LOWER FUEL BURN, LONGER ON-WING LIFE*. Available at: <https://www.cfmaeroengines.com/press-articles/cfm-tech-insertion-bringing-lower-fuel-burn-longer-on-wing-life-506/>.

[18] *Aircraft Commerce* (2008) 'Owner's & Operator's Guide A330-200/-300', p. Issue No. 57.

[19] Doyle, A. (2013) *Paris: Rolls-Royce rolls out legacy Trent upgrades, Flight Global*. Available at: <https://www.flightglobal.com/news/articles/paris-rolls-royce-rolls-out-legacy-trent-upgrades-386958/>.

[20] Goold, I. (2013) 'Rolls-Royce Trent 700 Benefits From Technology Development Flow-Back', *AIRonline PARIS AIR SHOW*. Available at:

<https://www.ainonline.com/aviation-news/air-transport/2013-06-18/rolls-royce-trent-700-benefits-technology-development-flow-back>.

[21] Haselbach, F. and Parker, R. (2012) 'Hot end technology for advanced, low emission large civil aircraft engines', in *28th Congress of the International Council of the Aeronautical Sciences 2012*, pp. 2479–2490.

[22] Rolls-Royce (2005) *The Jet Engine*. Rolls-Royce Plc.

[23] Bunker, R. S. (2010) 'Gas Turbine Engines: Turbine Cooling', *Encyclopedia of Aerospace Engineering*, pp. 1–12. doi: 10.1002/9780470686652.eae093.

[24] Sciubba, E. (2015) 'Air-cooled gas turbine cycles - Part 1: An analytical method for the preliminary assessment of blade cooling flow rates', *Energy*, 83, pp. 104–114. doi: 10.1016/j.energy.2015.01.107.

[25] Moran, J., Spooner, M. and Sherwood, D. (2006) 'Developments in low emissions combustion technology for aero engine applications', in *ICAS conf.* Hamburg, Germany.

[26] Xu, L., Bo, S., Hongde, Y. and Lei, W. (2015) 'Evolution of Rolls-royce Air-cooled Turbine Blades and Feature Analysis', in *Procedia Engineering*, pp. 1482–1491. doi: 10.1016/j.proeng.2014.12.689.

[27] Feuerstein, A., Knapp, J., Taylor, T., Ashary, A., Bolcavage, A. and Hitchman, N. (2008) 'Technical and economical aspects of current thermal barrier coating systems for gas turbine engines by thermal spray and EBPVD: A review', *Journal of Thermal Spray Technology*, pp. 199–213. doi: 10.1007/s11666-007-9148-y.

[28] *High Temperature Coatings* (2013) *University of Virginia*. Available at: <http://www.virginia.edu/ms/research/wadley/high-temp.html> (Accessed: 20 August 2017).

[29] Padture, N. P., Gell, M. and Jordan, E. H. (2002) 'Thermal barrier coatings for gas-turbine engine applications.', *Science (New York, N.Y.)*, 296(5566), pp. 280–4. doi: 10.1126/science.1068609.

- [30] Abu, A. O., Laskaridis, P. and Singh, R. (2013) 'Integrated approach for stress based lifing of aero gas turbine blades', *School of Engineering, Cranfield University*, p. 214. Available at: <http://dspace.lib.cranfield.ac.uk/handle/1826/8405>.
- [31] Sanjay, S., Uwe, S., Maria, O. J. and Seiji, K. (2012) 'Processing science of advanced thermal-barrier systems', *MRS Bulletin*, 37(10), pp. 903–910.
- [32] *PLASMA SPRAY PROCESS* (2011). Available at: <http://engg-learning.blogspot.co.uk/2011/03/plasma-spray-process-inert-gas-such-as.html> (Accessed: 20 August 2017).
- [33] Momberg, S. D. (2015) *Towards the development of a techno-economic based decision support system for High Pressure Turbine blade TBC upgrades*, MSc Thesis. Cranfield University. doi: 10.1017/CBO9781107415324.004.
- [34] Backman, D. G. and Williams, J. C. (1992) 'Advanced Materials for Aircraft Engine Applications', *Science*, 255(5048), p. 1082. doi: 10.1126/science.255.5048.1082.
- [35] Ogaji, S., Pilidis, P. and Hales, R. (2007) 'TERA - a tool for aero-engine modelling and management', *Second World Congress on Engineering Asset Management and the Fourth International Conference on Condition Monitoring*, (June), p. 12.
- [36] Vicente, E. (1994) *Effect of Bypass Ratio on Long Range Subsonic Engines*. Cranfield University.
- [37] Gayraud, S. (1996) *Technical and Economic Assessments for Industrial Gas Turbines Selection*. Cranfield University.
- [38] Whellens, M. W., Singh, R., Pilidis, P. and Taguchi, H. (2003) 'Genetic Algorithm based Optimization of Intercooled Recuperated Turbofan Design', *41st Aerospace Sciences Meeting and Exhibit*, (January). doi: 10.2514/6.2003-1210.
- [39] Celis, C., Moss, B. and Pilidis, P. (2009) 'Emissions Modelling for the Optimisation of Greener Aircraft Operations', *Proceedings of the Asme Turbo*

Expo 2009, p. 167–178. doi: 10.1115/GT2009-59211.

[40] Apostolidis, A., Sampath, S., Laskaridis, P. and Singh, R. (2013) 'WEBENGINE - A WEB-BASED GAS TURBINE PERFORMANCE SIMULATION TOOL', in *Proceedings of ASME Turbo Expo 2013*. San Antonio, Texas, USA, pp. 1–11.

[41] Laskaridis, P., Pilidis, P. and Kotsiopoulos, P. (2005) 'An Integrated Engine-Aircraft Performance Platform for Assessing New Technologies in Aeronautics', *Isabe 2005*, pp. 1–13.

[42] Pascovici, D. S., Colmenares, F., Ogaji, S. O. T. and Pilidis, P. (2007) 'An Economic and Risk Analysis Model for Aircrafts and Engines', in *ASME Turbo Expo 2007: Power for Land, Sea, and Air (GT2007)*, pp. 103–116.

[43] Nind, A. D. (2016) *A Technoeconomic Risk Assessment of Conventional Aero- Gas Turbines: Technological Limits and Future Directions*. Cranfield University.

[44] Colmenares, F. (2009) *TECHNO-ECONOMIC AND ENVIRONMENTAL RISK ASSESSMENT OF INNOVATIVE PROPULSION SYSTEMS FOR SHORT -RANGE CIVIL AIRCRAFT*. Cranfield University.

[45] Kyprianidis, K. G., Grönstedt, T., Ogaji, S. O. T., Pilidis, P. and Singh, R. (2011) 'Assessment of Future Aero-engine Designs With Intercooled and Intercooled Recuperated Cores', *Journal of Engineering for Gas Turbines and Power*, 133(1), p. 011701. doi: 10.1115/1.4001982.

[46] Boggia, S. and Rud, K. (2005) 'Intercooled recuperated gas turbine engine concept', in *41st AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit*, pp. 1–11. doi: 10.2514/6.2005-4192.

[47] Misirlis, D., Vlahostergios, Z., Flouros, M., Salpingidou, C., Donnerhack, S., Goulas, A. and Yakinthos, K. (2017) 'Optimization of Heat Exchangers for Intercooled Recuperated Aero Engines', *Aerospace*, 4(1), p. 14. doi: 10.3390/aerospace4010014.

- [48] Kyprianidis, K. G., Grönstedt, T., Ogaji, S. O. T., Pilidis, P. and Singh, R. (2011) 'Assessment of Future Aero-engine Designs With Intercooled and Intercooled Recuperated Cores', *Journal of Engineering for Gas Turbines and Power*, 133(1), p. 011701. doi: 10.1115/1.4001982.
- [49] *IATA Technology Roadmap Technical Annex* (2008).
- [50] Ziemianski, J. A. and Whitlow, J. B. (1988) 'NASA / Industry Advanced Technology Program', *Nasa Technical Memorandum*.
- [51] EU (2016) *validation of Radical Engine Architecture systems*. Available at: http://ec.europa.eu/research/transport/projects/items/dream_en.htm.
- [52] Snecma (2013) 'Snecma Continues Open Rotor Aircraft Engine Tests', *Aviation analysis wing*.
- [53] Cranfield University (2009) *HERMES v5 and TURBOMATCH Calls: User Manual*.
- [54] Jenkinson, L. R., Simpkin, P. and Rhodes, D. (2003) *Civil Jet Aircraft Design*. Available at: <http://www.getcited.org/pub/100419933>.
- [55] Rubini, P. (2008) 'Turbine blade cooling', *Cranfield University MSc Course Note*, b, p. 15. doi: 10.1615/AtoZ.b.BLACOO.
- [56] Torbidoni, L. and Horlock, J. H. (2005) 'A New Method to Calculate the Coolant Requirements of a High-Temperature Gas Turbine Blade', *Journal of Turbomachinery*, 127(1), p. 191. doi: 10.1115/1.1811100.
- [57] Ghafir, M. F. Bin (2011) *PERFORMANCE BASED CREEP LIFE ESTIMATION FOR GAS TURBINES APPLICATION*. CRANFIELD UNIVERSITY.
- [58] Vigna, S. O. (2006) *A FLEXIBLE LIFING MODEL FOR GAS TURBINES: CREEP AND LOW CYCLE FATIGUE APPROACH*. Cranfield University.
- [59] Pascovici, D. S. (2008) *Thermo Economic and Risk Analysis for Advanced Long Range Aero Engines*. Cranfield University.

- [60] Webster, G. . and Ainsworth, R. . (1994) *High Temperature Component Life Assessment*. London: Chapman & Hall.
- [61] Walston, W. S., O'Hara, K. S., Ross, E. W., Pollock, T. M. and Murphy, W. H. (1996) 'Rene N6: Third Generation Single Crystal Superalloy', *Superalloys 1996*, pp. 27–34. doi: 10.7449/1996/Superalloys_1996_27_34.
- [62] Eshati, S. (2012) 'An Evaluation of Operation and Creep Life of Stationary Gas Turbine Engine', *PhD Thesis, Cranfield University, Bedfordshire, UK*, pp. 2011–2012.
- [63] Zhao, L. (2011) *THE EFFECT OF THERMAL BARRIER COATING ON HIGH PRESSURE TURBINE BLADE LIFE ESTIMATION*. CRANFIELD UNIVERSITY.
- [64] Meggiolaro, M. A. and Castro, J. T. P. (2004) 'Statistical evaluation of strain-life fatigue crack initiation predictions', *International Journal of Fatigue*, 26(5), pp. 463–476. doi: 10.1016/j.ijfatigue.2003.10.003.
- [65] Khan, R. S. R. (2012) *TERA for Rotating Equipment Selection*. CRANFIELD UNIVERSITY.
- [66] Nalianda, D. K., Kyprianidis, K. G., Sethi, V. and Singh, R. (2015) 'Techno-economic viability assessments of greener propulsion technology under potential environmental regulatory policy scenarios', *Applied Energy*, 157, pp. 35–50. doi: 10.1016/j.apenergy.2015.07.017.
- [67] Gowon, S. (2016) *Investigation of Integrated Rotorcraft-Engine Performance In Airborne Contaminated Environment*. Cranfield University.
- [68] Harris, F. D. (2005) 'An Economic Model of U . S . Airline Operating Expenses', *NASA-CR-213476*, (December). Available at: <http://halfdome.arc.nasa.gov/publications/files/HarrisCR-2005-213476.pdf>.
- [69] Harris, F. D. (2005) 'An Economic Model of U . S . Airline Operating Expenses', *NASA-CR-213476*, (December).
- [70] Roskam, J. (1990) *Airplane Design-Part VIII:Airplane Cost Estimation:Design, Development,Manufacturing and Operating*. Kansas:

DARcorporation.

[71] Kang, M. and Ogaji, S. (2008) 'An Approach to Maintenance Cost Estimation for Aircraft Engines', *ASME Turbo Expo 2008: Power for Land, Sea, and Air*.

[72] Doulgeris, G. (2008) *Modelling & Integration of Advanced Propulsion Systems*. Cranfield University.

[73] Gerend, R. (1970) 'Correlation of Gas Turbine Engine Weights and Dimensions', in *AIAA 6th Propulsion Joint Specialist Conference*. San Diego, California.

[74] Palmer, J. R. (1990) *The TURBOMATCH scheme for aero/industrial gas turbine design point/off-design performance calculation*. Cranfield, UK.

[75] EASA (2014) *ICAO Aircraft Engine Emission Databank*. Available at: <https://www.easa.europa.eu/document-library/icao-aircraft-engine-emissions-databank> (Accessed: 12 August 2017).

[76] Sagerser, D. A., Lieblein, S. and Krebs, R. P. (1971) 'Empirical Expressions for Estimating Length and Weight of Axial-Flow Components of Vtol Powerplants', *Nasa Technical Memorandum X-2406*, 5(3), pp. 45–67.

[77] Pilidis, P. (2014) *Gas Turbine Theory and Performance Course Notes*.

[78] Pera, R. ., Onat, E., Klees, G. . and Tjonneland, E. (1977) 'A Method to Estimate Weight and Dimensions of Aircraft Gas Turbine Engines', *NASA CR-135170*, (May 1977).

[79] Aero Expo (2016) *Airliner turbofan/with axial compressor*. Available at: <http://www.aeroexpo.online/prod/ge-aviation/product-169836-877.html> (Accessed: 2 May 2016).

[80] Onat, E. and Klees, G. . (1979) 'A method to estimate weight and dimensions of large and small gas turbine engines', *NASA CR-159481*.

[81] Rukshan, N., Navaratne, R., Camilleri, W., Najafi, E., Sethi, V. and Pilidis, P. (2013) 'PRELIMINARY AERO ENGINE LIFE ASSESSMENT VIA TECHNO-ECONOMIC ENVIRONMENTAL RISK ANALYSIS', in *ASME Turbo Expo 2013*:

Turbine Technical Conference and Exposition, pp. 1–10. doi: 10.1115/GT2013-94830.

[82] Tong, M. T., Halliwell, I. and Ghosh, L. J. (2004) 'A Computer Code for Gas Turbine Engine Weight and Disk Life Estimation', *Journal of Engineering for Gas Turbines and Power*, 126(2), p. 265. doi: 10.1115/1.1691980.

[83] Ackert, B. S. (2013) 'Aircraft Payload-Range Analysis for Financiers', *Aircraft Monitor*, April Vers.

[84] Guha, A., Boylan, D. and Gallagher, P. (2013) 'Determination of optimum specific thrust for civil aero gas turbine engines: A multidisciplinary design synthesis and optimisation', *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, 227(3), pp. 502–527. doi: 10.1177/0954410011435623.

[85] Airbus (2005) 'Airport and Maintenance Planning Code Descriptions of Change', *Customer Services, Airbus*.

[86] Boeing (2013) 'Commercial Airplane Characteristics for Boeing 737', (September).

[87] Gleeson, B. (2006) 'Thermal Barrier Coatings for Aeroengine Applications', *Journal of Propulsion and Power*, 22(2), pp. 375–383. doi: 10.2514/1.20734.

[88] Nicholls, J. R. (2003) 'Advances in Coating Design for High-Performance Gas Turbines', *MRS Bulletin*, 28(09), pp. 659–670. doi: 10.1557/mrs2003.194.

[89] J. R. Nicholls, K. J. Lawson, A. J. and D. S. R. (2015) 'METHODS TO REDUCE THE THERMAL CONDUCTIVITY OF EB-PVD TBC's', *Surface and Coatings Technology, Volumes 151-152, 1 March 2002, Pages 383-391*, 1(March), pp. 383–391. doi: 10.1017/CBO9781107415324.004.

[90] Nicholls, J. R., Simms, N. J., Chan, W. Y. and Evans, H. E. (2002) 'Smart overlay coatings - Concept and practice', *Surface and Coatings Technology*, 149(2–3), pp. 236–244. doi: 10.1016/S0257-8972(01)01499-2.

[91] Leyens, C. (2004) 'Advanced Materials and Coatings for Future Gas Turbine

Applications', *24th International Congress of the Aeronautical Sciences*.

[92] Raymer, D. P. (2006) *Aircraft Design: A Conceptual Approach Fourth Edition*, *Aircraft Design: A Conceptual Approach: Fourth Edition (AIAA Education Series)*.

Available at:

http://search.proquest.com/docview/29012266?accountid=14116%5Chttp://en-sor.lib.strath.ac.uk/sfxlcl41?url_ver=Z39.88-

[2004&rft_val_fmt=info:ofi/fmt:kev:mtx:book&genre=book&sid=ProQ:Mechanical+%2526+Transportation+Engineering+Abstracts&atitle=&title=Aircraft+De.](http://search.proquest.com/docview/29012266?accountid=14116%5Chttp://en-sor.lib.strath.ac.uk/sfxlcl41?url_ver=Z39.88-2004&rft_val_fmt=info:ofi/fmt:kev:mtx:book&genre=book&sid=ProQ:Mechanical+%2526+Transportation+Engineering+Abstracts&atitle=&title=Aircraft+De.)

[93] (2013) 'Long-term CFM56-7B maintenance costs', p. Issue 87.

[94] Morrell, P. and Dray, L. (2009) 'Environmental aspects of fleet turnover, retirement and life cycle Final Report', *Omega*.

[95] easyJet (no date cq) *easyJet Airline Company Ltd*. Available at:

<https://www.easyjet.com/en/buy/flights?isOneWay=off&pid=www.easyjet.com>

(Accessed: 10 February 2017).

[96] IATA (2017) *Jet Fuel Price Monitor*.

[97] Fasching, W. A. (1979) 'CF6 Jet Engine Performance Improvement Program - Task 1 Feasibility Analysis', *NASA-CR-159450*.

[98] US Air force (2007) 'Improving the efficiency of engines for large nonfighter aircraft', *NAP*. Available at: www.nap.edu.

[99] Gad-Briggs, A., Haslam, A. and Laskaridis, P. (2013) 'Effect of change in role of an aircraft on engine life', *Aeronautical Journal*, 117(1196), pp. 1053–1070.

[100] Hamlin, G. (no date cv) *To Re-Engine...or Not*, *Aviation Week and Space Technology*. Available at: <http://atwonline.com/opinions/re-engine-or-not>

(Accessed: 5 September 2017).

[101] Wyman, O. (2010) *To Re-Engine or Not to Re-Engine: That is the Question*, *SpeedNews*. Available at: <http://speednews.com/article/6950> (Accessed: 5 October 2017).

[102] Rolls-Royce (2017) *Trent 7000 Engine*. Available at: [https://www.rolls-](https://www.rolls-royce.com)

royce.com/products-and-services/civil-aerospace/airlines/trent-7000.aspx#/
(Accessed: 25 October 2017).

[103] Rolls-Royce (2017) *Trent 7000 Engine*.

[104] EASA (2014) *TYPE-CERTIFICATE DATA SHEET*. Available at:
[https://www.easa.europa.eu/system/files/dfu/Trent 700 series issue 03.pdf](https://www.easa.europa.eu/system/files/dfu/Trent_700_series_issue_03.pdf).

[105] Aircraft commerce (2017) 'Widebody engine in-service performance', *Issue No. 113*.

[106] Rolls-Royce (2014) *Rolls-Royce wins Trent 7000 order worth \$455M from Hawaiian Airlines*. Available at: <http://www.rolls-royce.com/media/press-releases/yr-2014/pr-181214b.aspx> (Accessed: 10 September 2017).

[107] Knecht, M. (2011) *D4.2 - Cost-benefit studies of possible future retrofit programmes*.

[108] SESAR Consortium (2008) *The ATM Deployment Sequence*. Frankfurt.

[109] Avibroker (2010) *Aircraft For Lease Immediate Availability*.

[110] Ogaji, S. O. T., Pilidis, P. and Sethi, V. (2009) 'Advanced Power Plant Selection: The TERA (Techno-economic Environmental Risk Analysis) Framework', in *ISABE 2009*, p. 1115.

[111] Doulgeris, G., Korakianitis, T., Pilidis, P. and Tsoudis, E. (2012) 'Techno-economic and environmental risk analysis for advanced marine propulsion systems', *Applied Energy*, 99, pp. 1–12. doi: 10.1016/j.apenergy.2012.04.026.

[112] Igbon, D., Osigwe, E., Gray, I. and Pilidis, P. (2017) 'Technoeconomic Evaluation of An Aircraft Engine Upgrade Part 1- Aircraft Performance Outcomes', *ISABE 2017*.

[113] Grace, D. and Scheibel, J. (2003) 'Technical risks and mitigation measures in combustion turbine project development', *Journal of Engineering for Gas Turbines and Power*, 125(1), pp. 228–235. doi: 10.1115/1.1496771.

[114] Khan, R. S. R., Lagana, M. C., Ogaji, S. O. T., Pilidis, P. and Bennett, I.

(2011) 'Risk Analysis of Gas Turbines for Natural Gas Liquefaction', *Journal of Engineering for Gas Turbines and Power*, 133(7).

[115] Roth, B. A., Graham, M. D., Mavris, D. N. and Macsotai, N. I. (2004) 'Adaptive Selection of Aircraft Engine Technologies in the Presence of Risk', *Journal of Engineering for Gas Turbines and Power*, 126(January 2004), pp. 40–44. doi: 10.1115/1.1639006.

[116] *Aviation Week and Space Technology (New York)* (2017) 'Continuous Technology Upgrade Through Engine Lifecycles'. Available at: <http://aviationweek.com/continuous-technology-upgrades-through-engine-lifecycles>.

[117] Mankins, J. C. (1995) 'Technology readiness levels: A white paper', ANSA, pp. 1–5. Available at: http://www.hq.nasa.gov/office/codeq/trl/trl.pdf%5Cnfile:///d:/Technology/Techn readns levels/Techn Radnss lvls_white papr.pdf.

[118] Kirby, M. R. and Mavris, D. N. (1999) 'Forecasting Technology Uncertainty in Preliminary Aircraft Design', *World Aviation Conference*, p. 14. doi: doi:10.2514/6.1999-5631.

[119] Savvides, S. C. (1994) 'Risk Analysis in Investment Appraisal', *Project Appraisal*, 9(1), pp. 3–18. doi: 10.2139/ssrn.265905.

[120] Maccapani, M., Khan, R. S. R., Burgmann, P. J., Di Lorenzo, G., Ogaji, S. O. T., Pilidis, P. and Bennett, I. (2014) 'A TERA Based Comparison of Heavy Duty Engines and Their Artificial Design Variants for Liquefied Natural Gas Service', *Journal of Engineering for Gas Turbines and Power-Transactions of the Asme*, 136(2). doi: 10.1115/1.4025474.

APPENDICES

Appendix A Engine Off-Design (OD) Point Simulations

A.1 Off-Design Point (OD) Simulation Plots of CEUP6-80 Engine

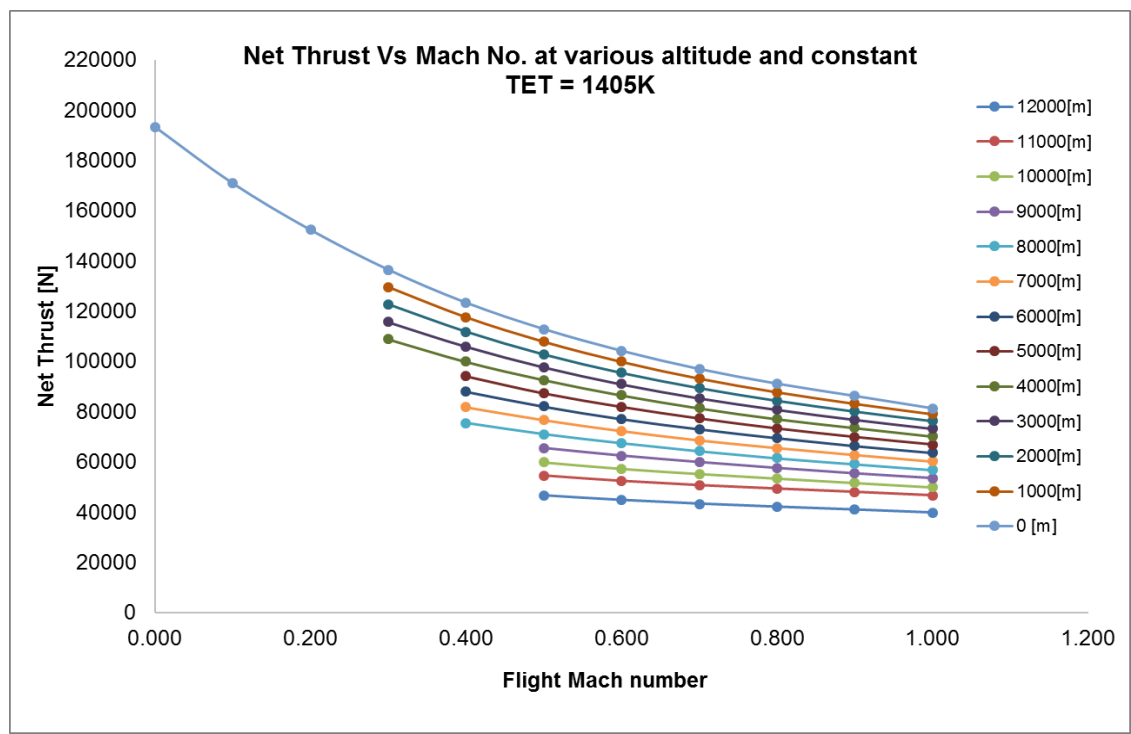


Figure A 1: Thrust Vs Flight Mach No at different altitudes

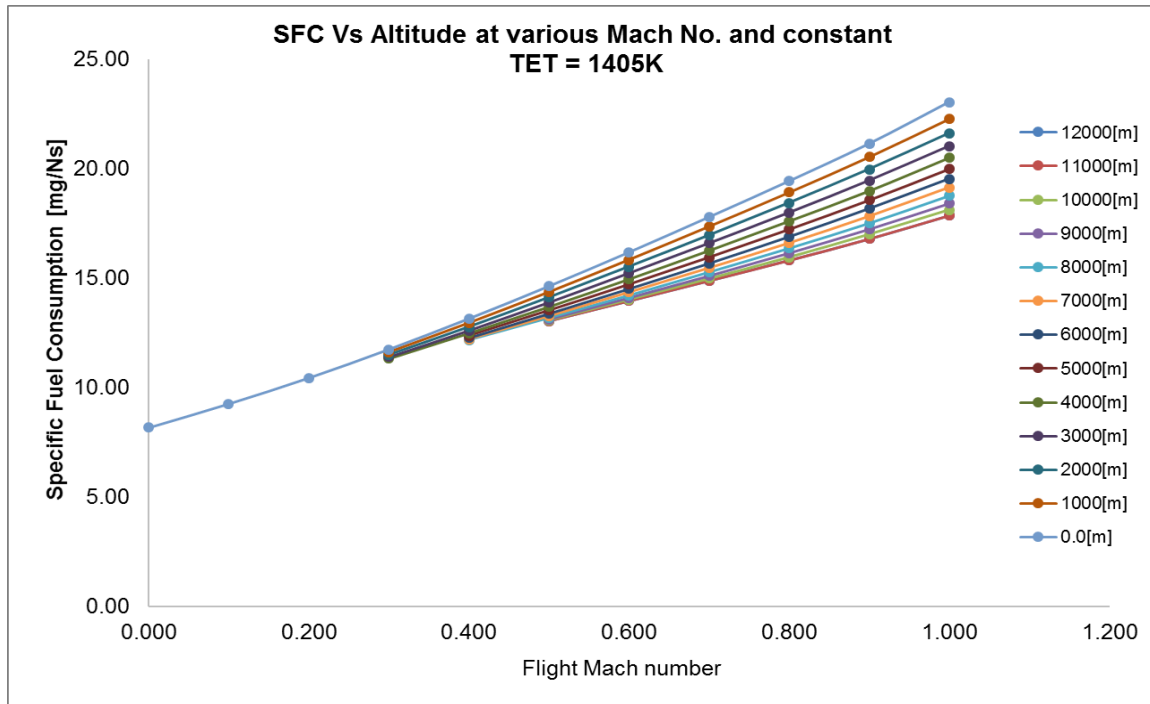


Figure A 2: SFC Vs Flight Mach No at different altitudes

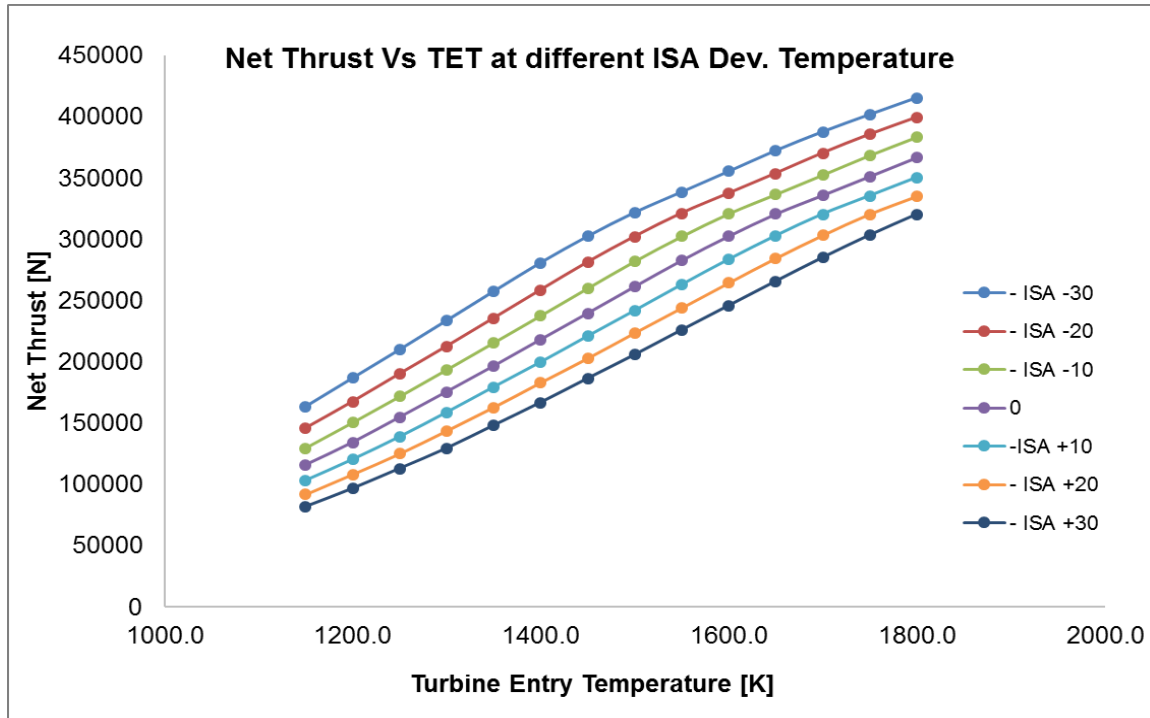


Figure A 3: Thrust Vs TET at different ISA Dev. Temperature

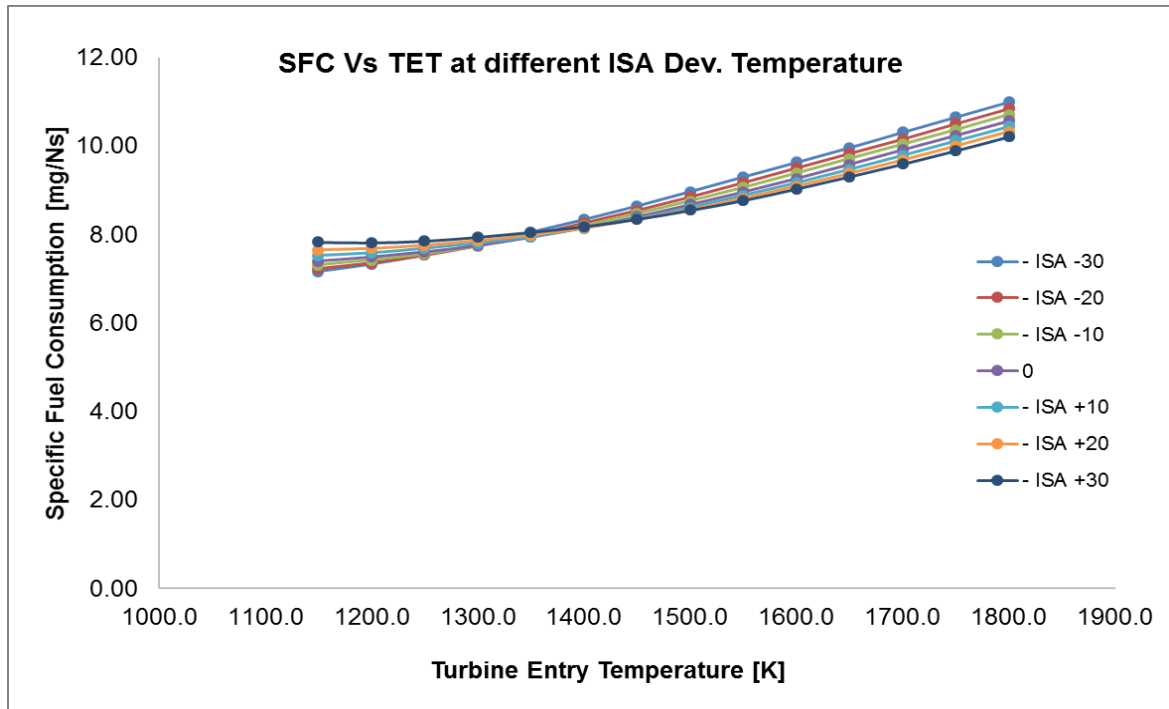


Figure A 4: SFC Vs TET at different ISA Dev. Temperature

A.2 Off-Design Point (OD) Simulation Plots of CEUP-7000 Engine

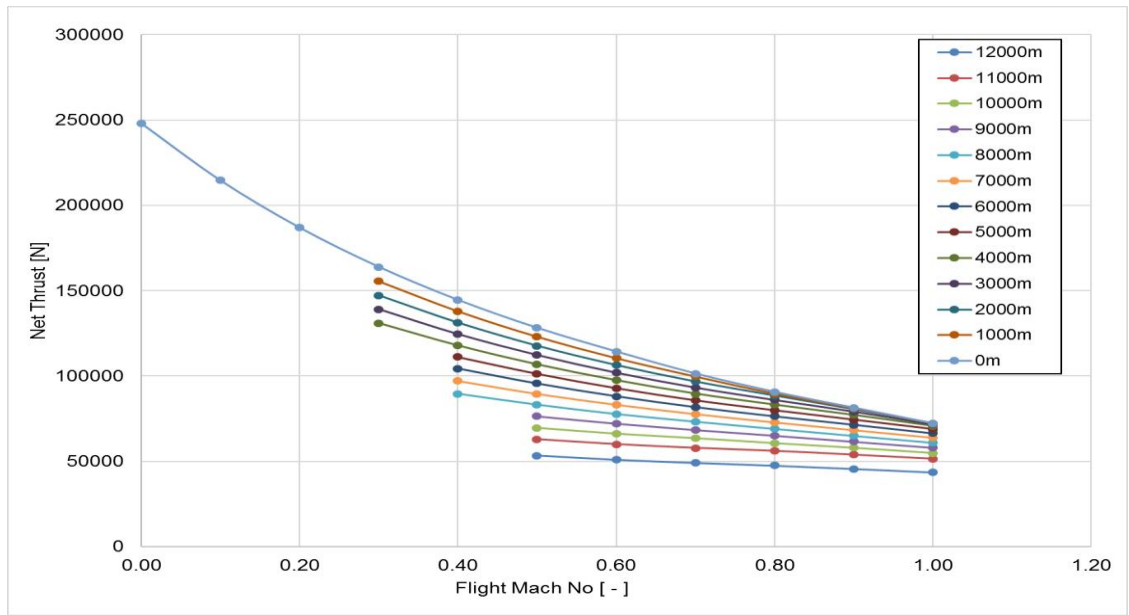


Figure A 5: Flight Mach No Vs Net Thrust at different altitudes

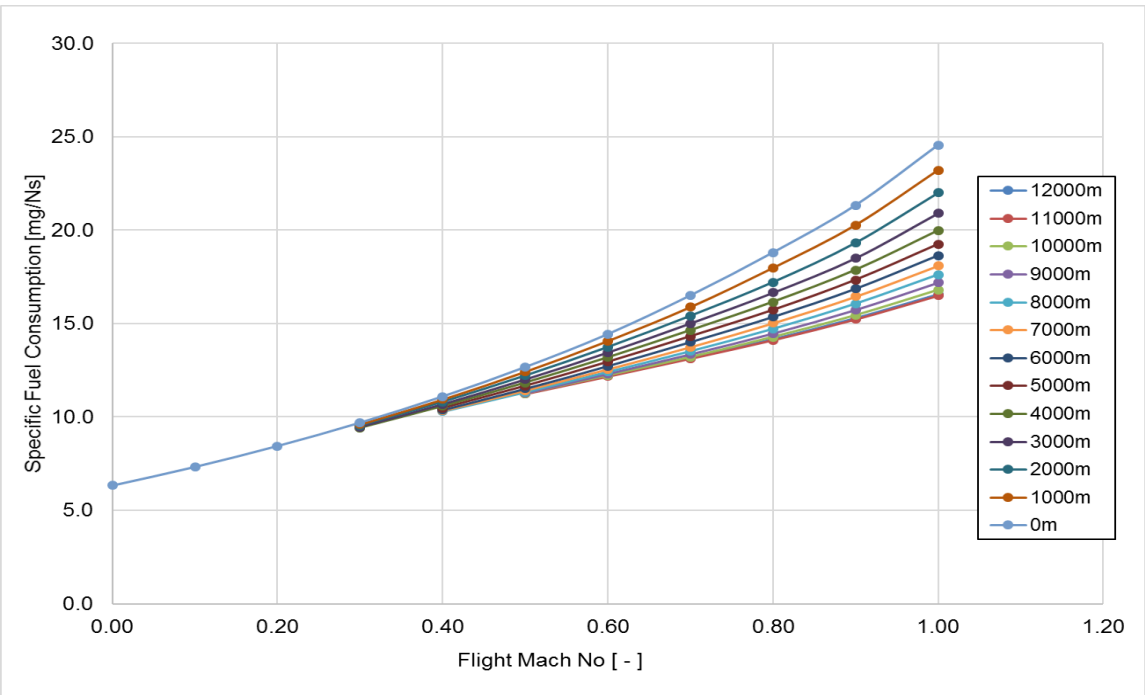


Figure A 6: Flight Mach No. Vs SFC at different altitudes

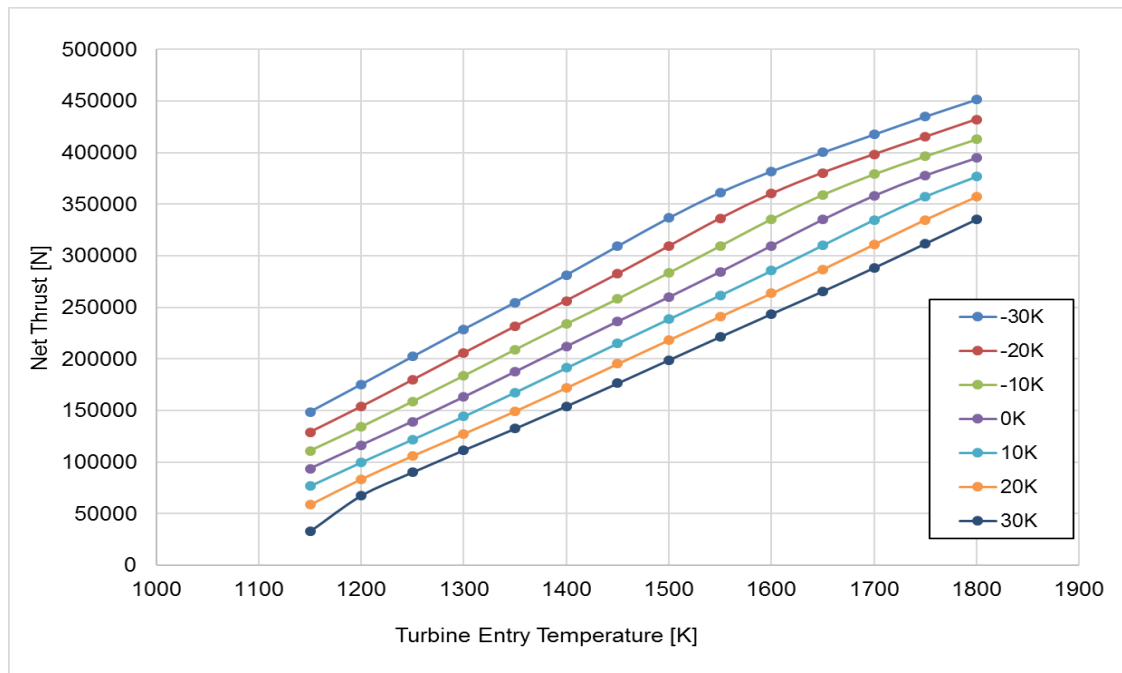


Figure A 7: TET Vs Net Thrust at different ISA Dev. Temperature

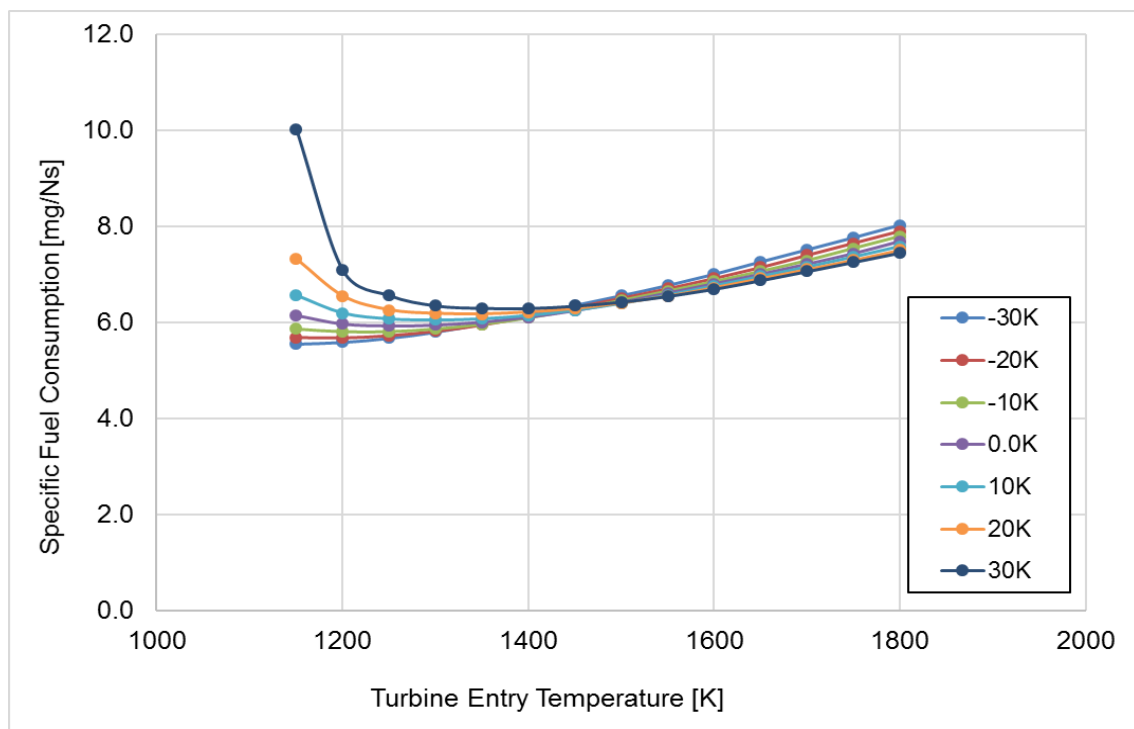
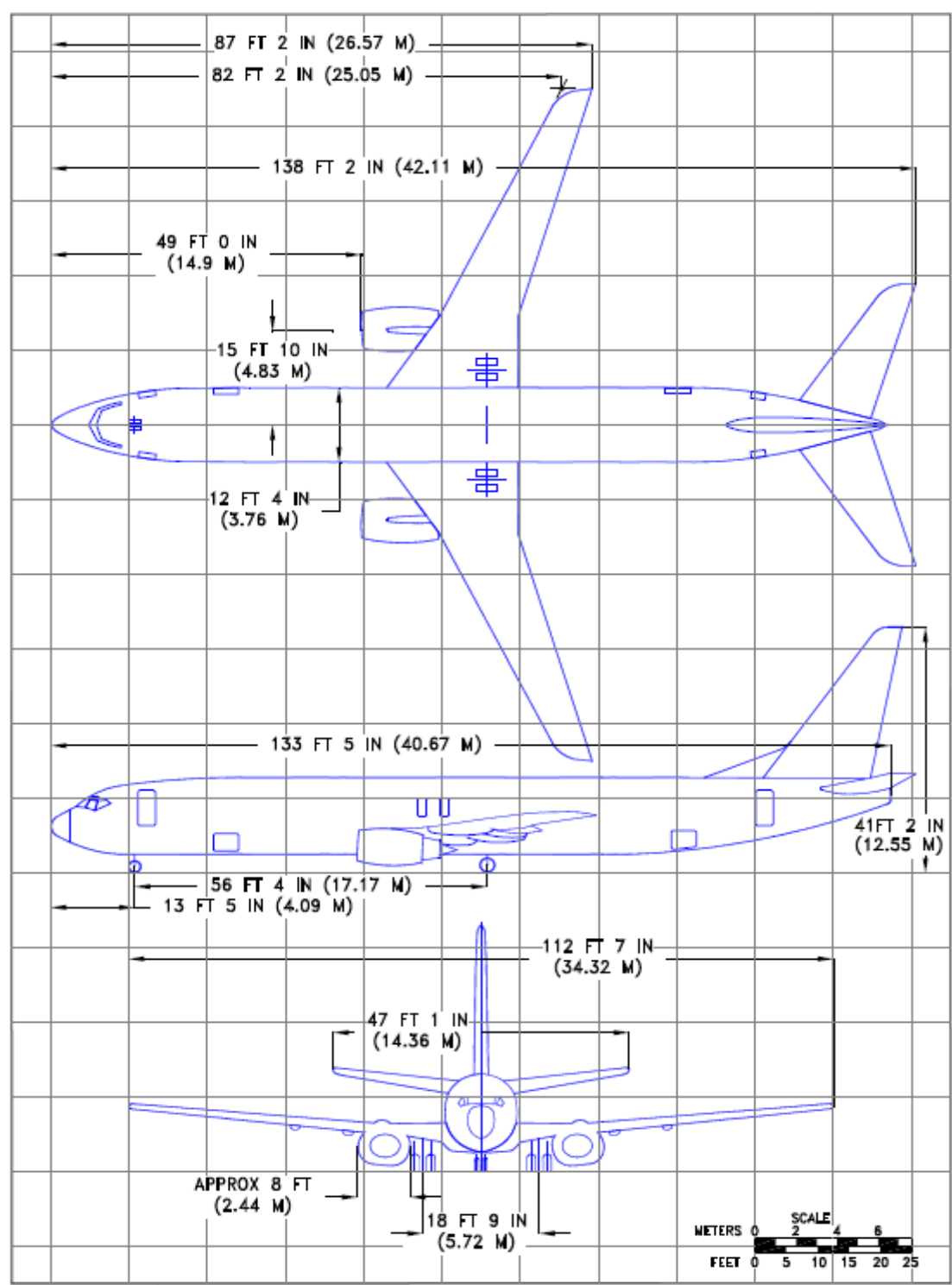
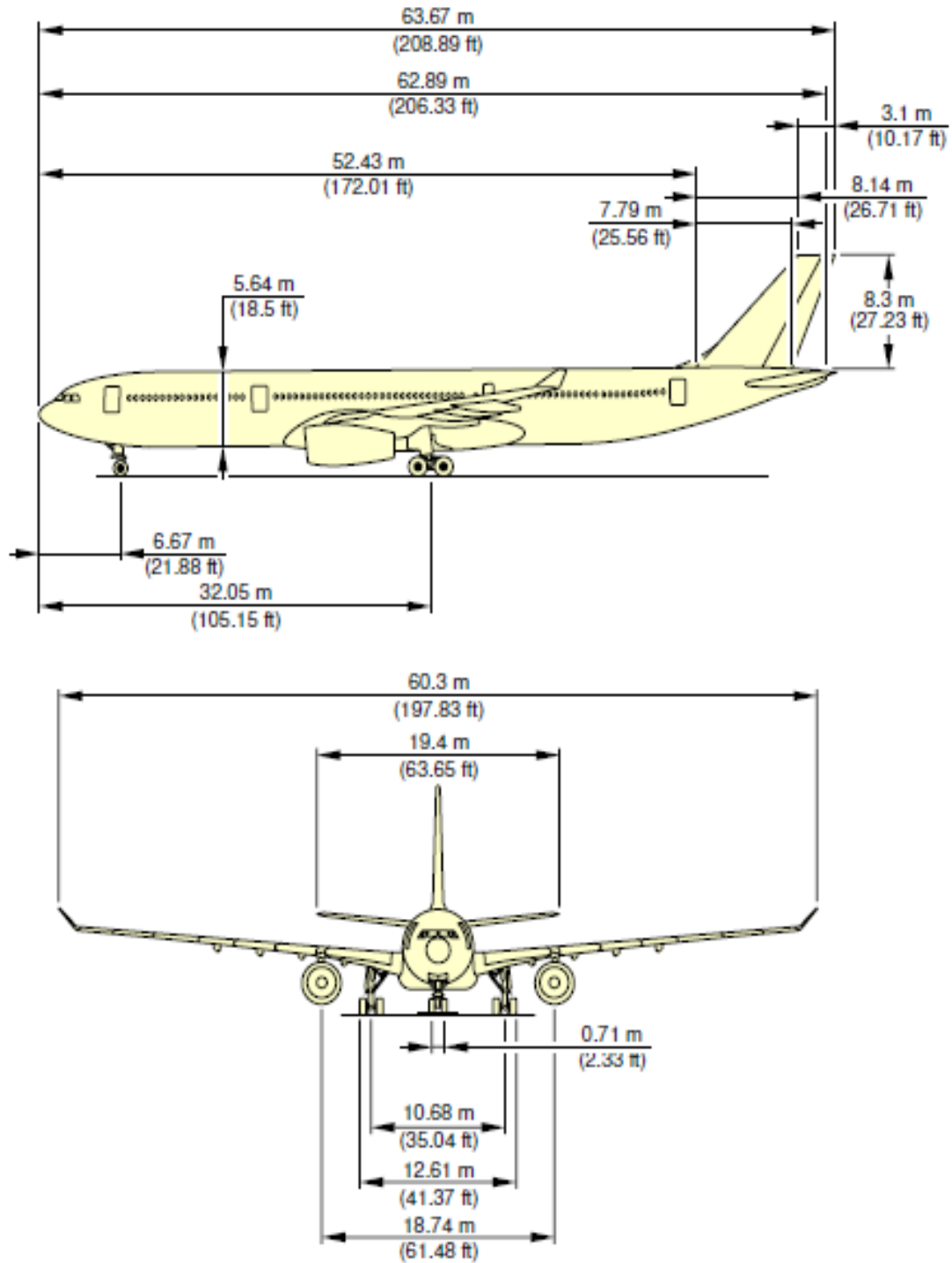


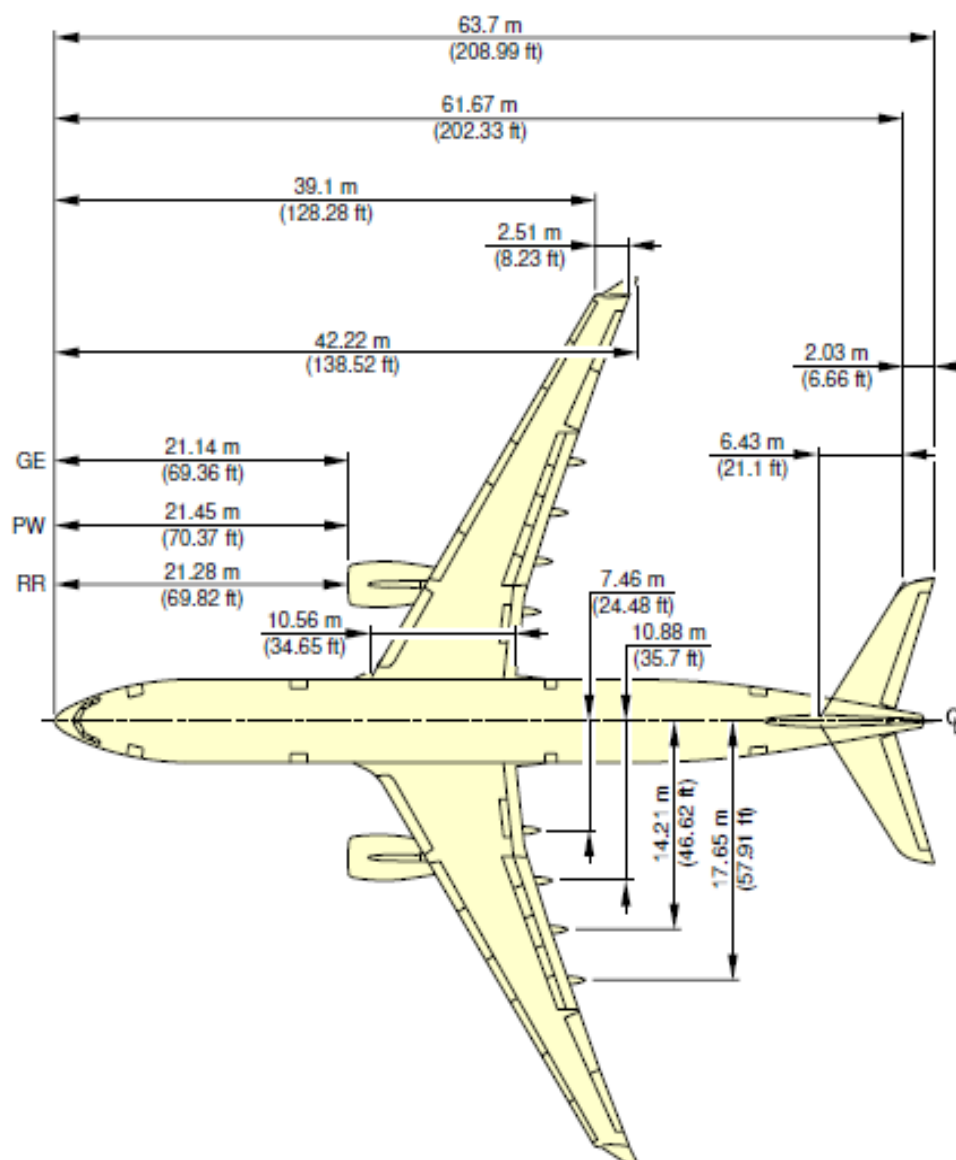
Figure A 8: TET Vs SFC at different ISA Dev. Temperature

Appendix B Boeing B737-900 Aircraft Configuration



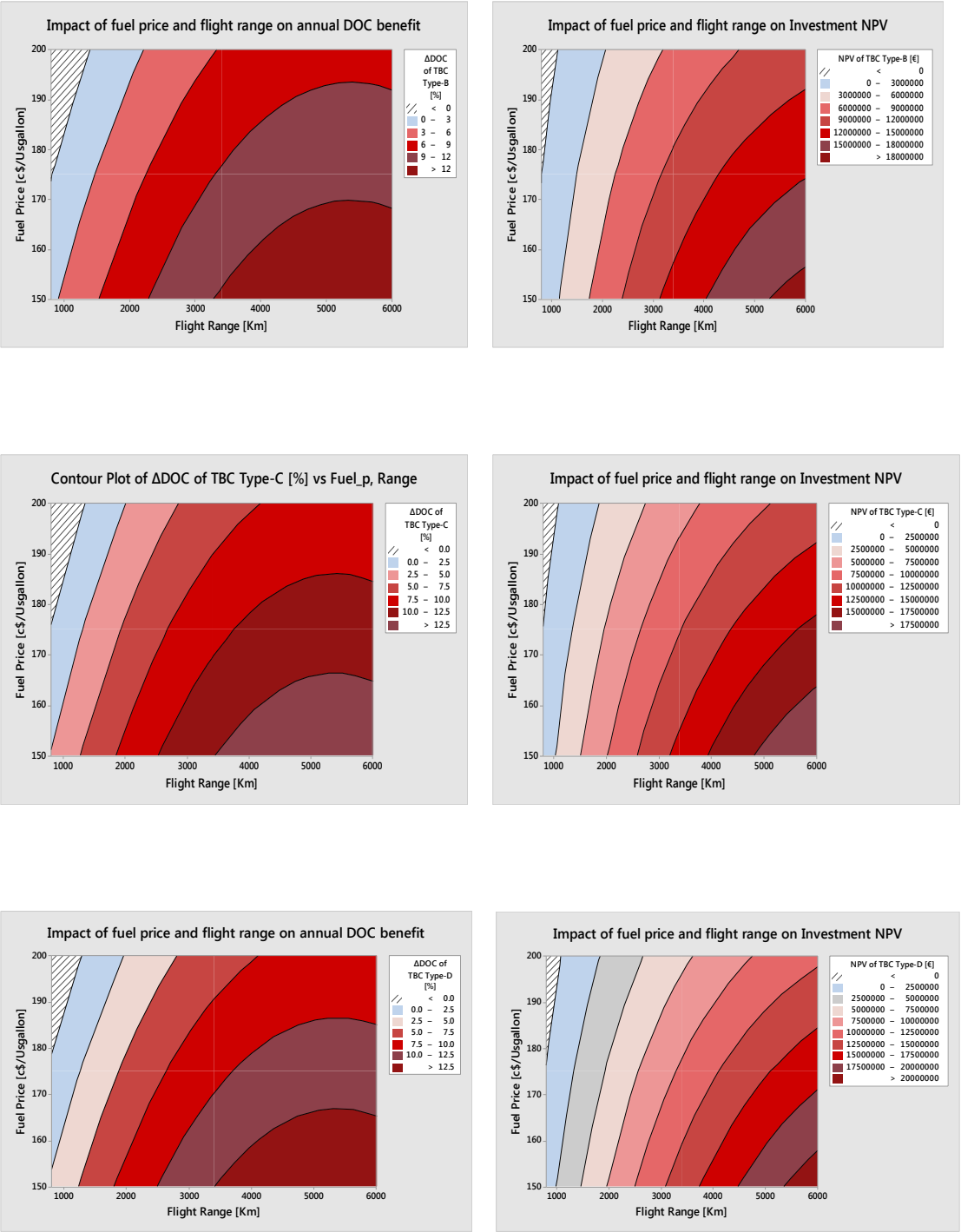
Appendix C Airbus A330-300 Aircraft Configuration

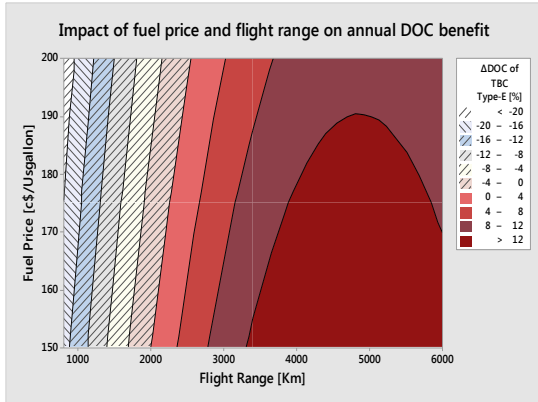
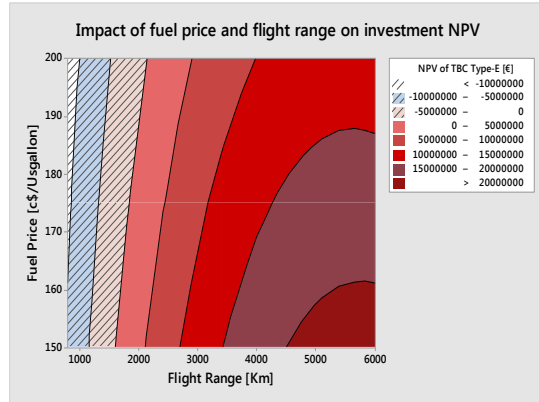




Appendix D TBC Upgrade Sensitivity Analysis

D.1 Flight Range Vs Fuel Price





D.2 Increase in TBC Upgrade Vs Fuel Price

