OPTIMIZATION OF CRUISE SPEED AND ALTITUDE FOR MINIMIZATION OF DIRECT OPERATING COST

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

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ABSTRACT

OPTIMIZATION OF CRUISE SPEED AND ALTITUDE FOR MINIMIZATION OF DIRECT OPERATING COST

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The objective of the study is to carry a parametric analysis on an airliner model to enhance performance and minimize direct operating costs. The cost-minimization approach is based mainly on the determination of optimal speed and altitude and maintains them during the cruise. A comprehensive nonlinear performance model of Airbus A320 is developed as an algorithm using Matlab and then validated to carry out simulation for different study cases. The model is built based on information provided by basic aircraft data BADA, and the method selected to be applied for the optimization is sequential quadratic programing SQP, which is found to be suitable for this study. The minimization of direct operating cost is a function of operational and atmospheric parameters. As an example of atmospheric effects, the effect of variable ambient temperature during the cruise phase is discussed. The results show that the variations in fuel consumption and flight duration are affected by daily and seasonally temperature variations, but the flight time is noticed to be more sensitive to temperature variations. Also, some operational parameters were examined such as the effect of selection of cost index on the amount of fuel and time consumed en route, and the effect of aircraft small amounts of weight reduction, these effects are evaluated and presented in terms of savings in direct operating cost for individual flights and the entire fleet for a hypothetical airline. For more realistic insightful results the model also used to for more complex conditions which are performing flights with the presence of time and operational constraints, those study cases give a very good perspective of challenges encountered in daily flight operations and how to make the optimal decision against them for minimization of direct operating costs.

Keywords: Aircraft fuel consumption, Speed and altitude optimization, Direct operating cost, Meet-time of arrival, Weight minimization, sequential quadratic programing

ÖZ

DOĞRUDAN İŞLETME MALİYETETİNİN MİNİMİZASYONU İÇİN SEYİR SÜRATİ VE İRTİFA ENİYİLEMESİ

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Bu çalışmanın amacı, performans iyileştirmek ve doğrudan işletme maliyetlerini minimize etmek için bir havayolu modelinde parametrik analiz yürütmektir. Maliyet minimizasyonu yaklaşımı, optimal sürat ve irtifanın belirlenmesi ile bu değerlerin seyir boyunca sürdürülmesi esasına dayanmaktadır. Airbus A320'nin doğrusal olmayan kapsamlı bir peformans modeli MATLAB kullanılarak bir algoritma şeklinde geliştirilmiş ve farklı inceleme durumları için simülasyon yürütülerek doğrulanmıştır. Bu model temel uçak verisi BADA tarafından sağlanan bilgiye dayalı olarak geliştirilmiş olup eniyileme için uygulanmak üzere seçilen yöntem ise bu çalışmada kullanılması uygun bulunan SQP'dir (sıralı karesel programlama). Doğrudan işletme maliyetinin minimizasyonu, işletme ve atmosfer ile ilgili parametrelerin bir fonksiyonudur. Atmosferik etkilere örnek olarak, seyir safhasındaki değişken çevre sıcaklığının etkisi irdelenmiştir. Sonuçlar, yakıt tüketimindeki ve uçuş süresindeki değişimlerin, günlük ve mevsimlik sıcaklık değişimlerinden etkilendiğini ve özellikle uçuş süresinin sıcaklık değişimine daha duyarlı olduğu göstermiştir. Ayrıca, maliyet indeksi seçiminin rota için harcanan yakıt miktarı ve süre üzerindeki etkisi veya uçak ağırlığının küçük miktarlarda azaltılmasının etkisi gibi bazı işletme parametreleri de incelenmiştir. Bu etkiler değerlendirilmiş ve hipotetik bir havayolunun bütün filosundaki tekil uçuşlar için doğrudan işletme maliyetindeki tasarruf cinsinden sunulmuştur.

Daha realistik aydınlatıcı sonuçlar için, bu model, zaman ve işletme ile ilgili kısıtları içeren uçuşların gerçekleştirildiği daha karmaşık koşullarda da kullanılmıştır. Bu inceleme durumları, günlük uçuş operasyonları esnasında karşılaşılan zorlayıcı koşullar için başarılı bakış açılarını ve doğrudan işletme maliyetlerinin minimizasyonu için bu koşullar altında nasıl optimal karar alınabileceğini açıklamıştır.

Anahtar Kelimeler: Uçak yakıt tüketimi, sürat ve irtifa eniyilemesi, doğrudan işletme maliyeti, varış zamanı, ağırlık minimizasyonu, sıralı karesel programlama

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ABBREVIATIONS	
APM	Aircraft Performance Model
CI	Cost Index
DOC	Direct Operating Cost
FCOM	Flight Crew Operating Manual
FF	Fuel Flow
IATA	International Air Transport Association
IOC	Indirect Operating Costs
ISA	International Standard Atmosphere
SAR	Specific Air Range
LRC	Long-range Cruise Speed
FMS	Flight Management System
SQP	Sequential Quadratic Programming
TOC	Top of Climb
TOD	Top of Descent point
ATC	Air Traffic Control
BADA	Base of Aircraft Data
CCO	Continuous Climb Operations
ConOps	Current Concept of Operations

MRC	Maximum Range Cruise
ECON	Economy Cruise Speed
VSM	Vertical Separation Minima
RVSM	Reduced Vertical Separation Minima
SWC	Significant Weather Charts
ATM	Air Traffic Management
TEM	Total Energy Model
TFM	Turbo Fan Model
CW	Weight Coefficient
CCI	Cost Index Coefficient
VSM	Vertical Separation Minima
CEO	Current Engine Option
TEM	Total Energy Model
ECCF	Economy Cruise Cost Function
FMC	Flight Management Computer

LIST OF SYMBOLS

SYMBOLS

g_0	Gravitational Force [m/s^2]
V_∞	Free stream Velocity [m/s]
C_D	Drag coefficient
C_L	Lift coefficient
C_T	Thrust coefficient
D	Drag Force [N]
GS	the ground speed [m/s]
L	Lift Force [N]
m	Aircraft Mass [kg]
r	Flown Ground Distance [NM]
TAS	True Airspeed
Th	Thrust Force [N]
W	Weight [N]
S	Aircraft Wing Reference Area,
P_0	Pressure at Sea Level [bar]
M	Mach Number
C_T	Thrust Coefficient
m_{mref}	Aircraft Reference Mass[kg]
H_p	Geopotential Pressure Altitude [feet]
R	Real Gas Constant for Air [m^2/(K·s^2)]
LR	Lapse Rate [K/m]
CF	Cost of Fuel [$]

CT	Cost of Time [$]
C_t	Total Flight Cost [$]
C_v	Variable Costs [$]
C_{fx}	Fixed Costs [$]
C_{Lmax}	Maximum Lift Coefficient
γ	Adiabatic Index of Air
δ	Pressure Ratio
ρ	Air Density [kg/m^3]
δ_T	Thrust Parameters
θ	temperature ratio

CHAPTER 1

INTRODUCTION

1.1 Motivation

The sector of air transportation has shown rapid growth and development over the past five decades. The accompanied development in aerospace technology has been magnificent, leading to a significant reduction in the costs of building and operating airplanes, which motivated the growing demand for air transportation services. In general, technology-based industries that have rapid and continuous development in the need for their products have a large increase in their revenues. Contrary to this, the air transportation sector usually has a lower profit than the other sectors [1], [2].

Recently, reducing the amount of fuel consumed by airlines has become an increasingly central factor in saving costs for air transport companies, due to the high cost of fuel. The fluctuating prices of jet fuel in the last few years is very significant, it was 33.4% of the airline cost structure in 2015 and drop to 17.7% in 2019 according to IATA reports [3]. Despite this the cost of fuel is still one of the largest divisions of airlines operating costs, as a result, aircraft operators seek to developing and searching for new techniques to minimize operational costs [4] , [5] [6] , [7].

According to the International Air Transport Association (IATA), the fuel cost was approximately $180 billion in the year 2018 (which about 23.5% of total operational costs at $73 per barrel Brent). This increase is 20.5% higher than the year 2017 estimations and is about twice the $91 billion fuel cost for the year 2005, which is corresponding to 22% of operational costs at $54.5 per barrel Brent. In the year 2018, the fuel cost was raised and found to be $200 billion, estimated to be about 24.2% of operating costs based on $65 per barrel Brent [8] . Those values are significantly affected by the variable price jet fuel worldwide.

In general, businesses are work to minimize the costs of service or products, so that selling prices can be profitable, which is the only way to compete in the market. The air transportation sector is categorized as a dynamic business, with dynamic and fast changes in many of its components. As a matter of this fact, decision-makers need a wide perspective and a full understanding of how to manage and minimize the costs [9].

Considering Turkish Airlines, as a good example for a rapidly growing airline, the growth in the number of its flights in the year 2017 was 10.4% in the domestic flights and 8.5% in the international flights and, rate of increasing flights since the year 2013 was about 28% [10]. According to this research estimation, in the year 2019, the cost of fuel for the national airlines operating in Turkey was about $4 billion.

The high bill of fuel motivates researchers to enhance the performance efficiency of the air transportation. Attempts to upgrade air fleets are delayed by the costs and time needed to develop and produce new aircraft based on new concepts [11].

Airline's biggest challenge is the reduction of the costs of operations which is a subject of crucial importance to the operators. The cost of fuel is not always the dominant factor in cost fractions; rather the time of operations is also a strongly effective factor [12]. In general, fuel cost is considered as a significant segment of the Direct Operating Cost (DOC), which comprises all costs related to operating the aircraft. The fuel cost is calculated based on jet fuel prices in the region of the operation. In addition to this, the Indirect Operating Costs (IOC) must be considered also, which includes other costs than the fuel; these are not measured as a part of direct aircraft operations expenses.

The ICO consists of two divisions, the first part includes ground and system operating expenses, for instance, operating base and ground expenses like, ground crew transport, and handling fees paid to service providers, passenger services like flight crew wages, and passenger insurance, sales, advertisement, and administrative functions [13].

The efficiency of fuel reaches about 14% in the last decade, this percentage is expected to be improved continuously by adopting new methods and improve air operations [14]. In the recent years, airliners pay more attention and effort to develop optimal techniques to minimize fuel cost; mainly those techniques are strictly obeying the recommendations provided by the manufacturer or by specialist service providers [15].

Focusing on vertical flight trajectory is found to be one of the best operational approaches to improve the efficiency of time and fuel of a flight. It can be noticed from the previous literature that most prior researches have focused on optimization of the fuel minimization rather than combining the time as a vitally effective factor; little effort has been done to inspect for a more efficient method to enhance cruising altitude and speed performance based on real flight recoded data with employing directly real atmospheric conditions [16].

The performance of Aircraft is directly related to airspeed and altitude, so modifying those parameters can give improvements to the performance efficiency without major modifications in hardware or by planning better routing. [17]. Technical limitations and operational constraints may also limit such parameters to be used optimally. Estimation of the probable benefit of vertical trajectory improvement strategies would provide a better understanding of the available improvements of these parameters, and could improve short term efforts to enhance efficiency, hence minimizing DOC.

1.2 Objective of the Study

The main objective of this thesis is to perform a parametric study to minimize the direct operating cost DOC of a jet airliner trip during the cruising phase, via speed and altitude optimization at different flight conditions and examine the effect of different parameters on the results.

The following steps were conducted:

Developing an algorithm for an aircraft model by using Matlab, the aircraft chosen is Airbus A320-214. This model can be used to enhance the performance of the flight and give a better understanding for the effect of the real operational parameters, such as the atmospheric conditions, selection of the Cost Index (CI), aircraft gross weight, and the effect of time constraints on the flight cost, etc.

Establish an optimum realistic performance for airline operations by calculating optimum cruise speed and optimum altitude during the cruise.

Evaluate the possible penalties from violating optimal altitude and speed due to Air Traffic Control (ATC) constraints or the operational constraints such as meet time of arrival conditions.

Providing a support decision tool for airlines, which helps in go/no-go decisions in case of time vs. fuel dilemma. Therefore this tool can give a clear answer of the relation between fuel consumption and flying near to the optimal altitude and speed values.

The objective of this research can be concluded as a pursuing trail to provide a set of potential benefits that can be obtained by quantifying the benefits of optimizing cruising speed and altitude values. In this thesis, the advantages are presented in a form of reducing the cost of time and fuel due to speed and/or altitude optimization compared with the actual constrained flight conditions.

The main vision of this thesis is to conduct a comprehensive assessment between real flight scenarios, and equivalent more efficient trajectories, therefore suggesting the most realistic prediction of improvements. The main consideration is to develop an approach that is simple and practical to real flight operations.

1.3 Research Overview

There are two main methods available for minimization of fuel consumption over any segment of the flight, lateral path minimization, and vertical path optimization which can be achieved via enhancement of aircraft performance. Lateral trajectory improvement comprises minimizing the trip distance according to the available routes and wind conditions in those routes, hence potentially reducing the amount of time of flight. Aircraft performance enhancements contain reducing the amount of fuel consumed in the cruising phase, which can be achieved by modifying the airframe aerodynamics to reduce drag, reducing the weight, or by flying closer to the optimum flight conditions. Whereas the effects of structure or aerodynamic shape adjustments and lateral trajectory enhancements are well known for manufacturers and flight dispatchers, little has been done to check the effect of operating an aircraft away from its optimal performance margins.

Air density, temperature, and Mach number have the most significant and direct impact on the performance of aircraft and because of this, they were selected as dimensions to inspect.

The baseline of performance evaluation is set based on potential improvements in speed and altitude. Flight and atmospheric data are implemented in aircraft performance parameters to predict fuel burn on an individual flight basis.

Archived data from the Base of Aircraft Data (BADA) provided by Eurocontrol was used to get aircraft performance information. A custom analysis algorithm is developed to compute variable performance parameters during the cruise phase for Airbus A320-214. This is used as an example for mid-range, mid-size jetliners. The aerodynamic and the propulsive coefficients of this aircraft are obtained from BADA. An Aircraft Performance Model (APM) is developed as an algorithm by using MATLAB programing language. The model takes into consideration the geometry, aerodynamic and propulsive characteristics of Airbus A320-214. The APM is validated for the optimal speed, altitude, fuel burn, and cost calculations, and they were compared with the information provided by the Flight Crew Operating Manual (FCOM) [18], and from real flight data, which is collected from several flights at varıable atmospheric and aircraft configuration [19].

The obtained performance data was used to develop new flight paths based on optimal altitude and speed, and associated fuel and time consumed, then compared with the nonoptimal path fuel quantity and endurance and hence the DOC. These comparisons served as a base for analyzing the outcomes.

The algorithm aimed to inspect the cruise phase for different flight scenarios. The majority of the work involved the design and employment of a robust tool to examine different flight scenarios based on variable flight conditions. The primary evaluation metric was applied to simply reach some savings in DOC, by comparing theoretical analysis results with the actual results to the improved flight scenarios under multiple flight configurations and atmospheric conditions.

In civil aviation many factors affect directly the DOC, this research sheds some light on some of them as discussed in the following paragraphs.

The weather is considered as the major factor affecting aircraft performance and operations, which is responsible for around 75% of the flight delays (Rosenberger, et al., 2000), and causing loses of hundreds of millions of dollars every year for the airlines' revenue [20]. So far, a few researchers have examined the direct impact of changes in weather parameters such as ambient temperature on aircraft operations [21]. Among the other factors, this study investigates the effect of variations of some atmospheric parameters on the performance of the aircraft and on the direct operating cost of airlines.

The atmospheric parameter in focus in this research is the ambient temperature and its impact on the DOC. The temperature variations are expressed in the form of deviations from the International Standard Atmosphere (ISA), those deviations can be above or below the standard temperature which is +15°C. In general, those deviations have a direct effect on Specific Air Range (SAR), True Airspeed (TAS), and Fuel Flow (FF). TAS is directly proportional to Mach number and relative air temperature. When cruising at a constant Mach at a temperature higher than ISA true airspeed will increase which leads to shorter flight time, hence saving time, but with extra fuel consumption [19].

In airline operations the critical decision to be taken is whether to fly higher speed to save time or slower speed to save fuel, in the case of flying faster the fuel consumption will higher, and in case of flying slower the fuel cost will be less but the cost of time will be higher. The best combination is obtained by the Cost Index (CI), which is the base of initial performance calculations, mainly the optimum speed and the optimum altitude [22].

In order to support aircraft operators and planners to predict the minor changes in aircraft performance due to variations in temperature, an accurate aircraft performance model is required to obtain accurate computation of the fuel and the time needed for the flight.

Moreover, the model can help performance departments and policymakers to optimize the future schedule plans for their destinations based on the model outcomes.

It can be noticed from the literature that there is a lack of knowledge about the direct impact of temperature variation on the DOC of the flights. Many studies discuss this issue as fuel-savings or fuel flow optimization, separating this from the savings in flight time which is directly proportional to the DOC [23].

The cruise-only approximation is adopted to simplify the analysis of fuel burn calculations, as the cruise is the longest phase of flight excluding very short-range flights, which are beyond the scope of this thesis [24]. Some researches consider the factors responsible for fuel consumption, such as the wind, temperature, aircraft aging, gross weight, CG position, and altitude, etc. however, it is not stated the direct impact of change in temperature on fuel consumption. Wickramasinghe et al., explained the correlation between fuel consumption, flight time, and the CI, considering the time constraints and optimum flight trajectories [25]. Franco discussed the minimization of DOC at a constant altitude during the cruise phase, they found that the cost was minimal at a specific CI and fuel consumption for given flight time. The study also considers the effect of the wind on the DOC [26].

According to the literature review from the previous studies, it can be noticed that most of those studies discussed the optimization of flight trajectory for optimum fuel consumption; some others consider the effect of flight time on the DOC with or without considering the wind. However, deep investigation of the direct impact from the other weather conditions is not covered in detail. This work aims to employ the developed APM to estimate the changes in the DOC due to variations in temperatures as discussed in detail in section 5.1.

As mentioned earlier the CI value selection is the base of the optimum performance calculations which is computed by the aircraft Flight Management System (FMS). The selection of CI and its effect on the optimum cruise speed and altitude is has a significant effect on the DOC, as discussed in details based on specific study cases. The results discuss also the consequences of using uncertain estimations of cost indices on the direct operating costs.

Another inspected factor was the effect aircraft gross weight reduction on the performance and as a consequence on the DOC. As a policy, airlines used to set some restrictions and policies to minimize operational costs by reducing weight. Lighter aircraft consumes less fuel that a heavier one. The effect of weight is found to be a very significant factor affecting the performance and cost as discussed in section 5.2 [27] To ensure reducing the weight new strategies were introduced, such as lighter seats, redesigning or reducing the number of lavatories, and minimizing the weight of any other equipment if applicable.

The APM algorithm is used to estimate the economic benefits from small scale weight reductions.

This thesis also discusses aircraft fuel minimization at the cruise phase in the case of flying under time restrictions such as the need for arriving at a certain time at different distances and weights. The method selected for the optimization is the Sequential Quadratic Programming (SQP) algorithm from the MATLAB optimization toolbox to find the effect of meet-time of arrival constraints on fuel consumption. The cruise distance is divided into small intervals according to the flown distance to obtain maximum accuracy of the results, in addition to speed, the altitude is also defined as design variables for the optimization process.

The optimization computes the optimal values for speed and altitude that result in minimum fuel consumption. The optimization is carried out for different flight scenarios under conditions of constrained and non-constrained time. In the case of time-constrained condition which is better known as meet-time of arrival condition, the optimization is conducted for minimum fuel consumption and its effect on the DOC. The APM algorithm is expected to significantly help in making the proper decision for the meet-time of arrival operational issues. [28].

1.4 Thesis Outline

This thesis includes six chapters in addition to the first chapter of the introduction the other chapters are briefly introduced as follows:

Chapter 2: This the background chapter which describes the basics of aircraft performance such as classifications and definitions of speeds and a comparison between them, and the matter of altitude selection and some operational aspects and the atmospheric conditions affecting the flight operations.

Chapter 3: This chapter describes the methodology of discussing the optimization of speed and altitude and the approach used. The chapter includes the data used to develop the mathematical model for the aircraft and the atmosphere. The methodology chapter also explains the sequential quadratic programming technique the one used in this work.

Chapter 4: This chapter discusses the validation of the atmospheric and A320 models to make sure that the developed algorithm is valid and reliable by comparing the outcomes of the models with references such BADA, FCOM, and real flight data collected from real flights. Also, the SQP is used for validation.

Chapter 5: this is the parametric study cases in which the papers were published during the development of this thesis. This includes performing the model to examine the effect of temperature, weight, cost index, and operating under time constraints operations on the cost of the flight.

Chapter 6: This chapter includes concluding remarks as well as recommendations for further research.

CHAPTER 2

BACKGROUND

2.1 Aircraft Performance

The main focus of this research is to develop techniques to improve the performance efficiency of aircraft via enhancing the techniques of aircraft operations. According to this, improved performance is that indicates a decrease in the consumed fuel and reducing flight time if applicable, and correspondingly a decrease in the DOC. Many methods exist to improve aircraft performance. Some approaches to performance enhancement involve major modifications to the aircraft itself. Engine upgrades, modifications of aerodynamic performance, and weight reduction efforts are some examples of enhancement approaches that employ modifying the physics of the aircraft characteristics.

Instead, the technique of operating the aircraft can improve performance without needing any major and expensive modifications to the aircraft. Those practical approaches can potentially make significant financial benefits in the air transport sector.

The literature strongly recommends that improvements in operations are easier and much less costly with a significant effect in the short term than modifying the aircraft itself [11].

2.1.1 Cruise Altitude Selection

The altitude selection represents the selection of vertical trajectory, the trajectory on interest in this research. The cruise starts after the climb phase at a point called Top of Climb (TOC) to the end of the cruise phase after which the aircraft starts the descend at the Top of Descent point (TOD). The cruise can be one altitude or more based on the length of the flight, for a relatively long flight the need for climb to a higher altitude is possible via a procedure called Step Climb (SC), which is a function of the remaining distance and the gross weight of the aircraft.

The selection of an initial flight level which starts at the TOC to commence the cruise phase is based on the aircraft's performance capability at the associated weight, altitude, and air temperature and on the available flight levels for the selected route; it is also a function of the wind speed and direction at different potential flight levels. It is of crucial importance to select a flight altitude that is as near as possible to the optimal computed altitude where the initial gross weight of the aircraft at the TOC is considered. It is also vital to make sure that the aircraft has adequate climb potential at this heavy weight at the TOC. This altitude is called the service ceiling at which the residual rate of climb must be at least 300 fpm. [29]

A good background of real airline operations is essential before any suggestions to improve the operations. Aircraft are designed and built to fly at specific altitudes those dependent mainly on gross weight. As the fuel consumed during cruising the weight is reduced and the optimal altitude becomes higher slightly with every small amount of weight reduction. Both the engine and aerodynamic performance are influenced by altitude as it is a direct function of the air density, on the other hand, only aerodynamic performance is affected by the aircraft gross weight. The lift coefficient (C_L), generally has a constant value at the optimum lift/drag ratio, as it is expressed in Equation 2.1:

$$C_L = \frac{2L}{\rho V_\infty^2 S} \qquad 2.1$$

Here, (L) is the lift force,(ρ) is the air density, and (V_∞) is the free stream velocity, or true airspeed (TAS), and S is the wing area.

Simultaneously, Due to weight reduction during cruise the dynamic pressure is also reduced to conserve the optimum lift/ drag ratio. Consequently, for a given cruise speed, the optimum altitude increases as density decreases. Form the initial results of the APM is it obviously seen that the optimum altitude that is obtained from the highest SAR value is gradually increases with the progressing of the flight, as shown in Figure 2.1

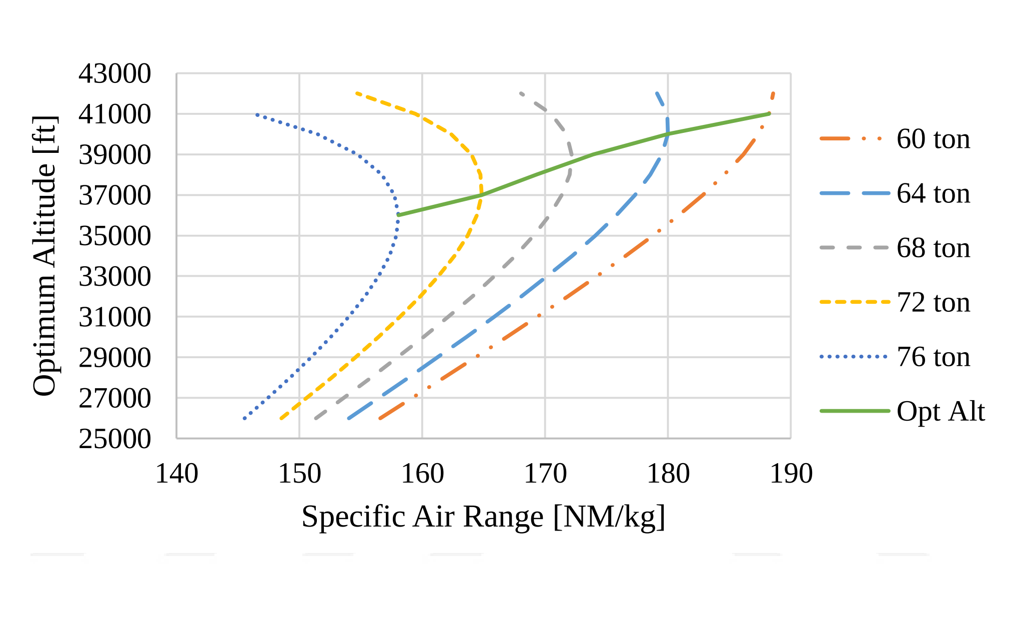


Figure 2.1: Optimum Altitude vs. Specific Air Range

The plotted results are obtained from the APM algorithm at ISA conditions and Mach number of 0.78

These results show the basic concept of an optimum altitude profile. As seen it is increased gradually with reducing weight with a significant increase in SAR. Despite that the optimal altitude might not vary significantly in cruise, the relationship still shows that the optimal cruise altitude can be clearly varying based on the gross weight of the aircraft.

In practice, the optimum altitude is hard to be maintained throughout the flight. The main reason for this is the ATC constraints that prevent the flight from maintaining its optimum altitude because the airway could be busy with another close traffic or the flight distance is short, so the air traffic controllers prefer to keep relatively short flights at lower flight levels so that they will not spend longer time and distance in climb and descent phases, which are unpleasant phases for air traffic controllers, because of the extra attention that must be paid for the maneuvering traffic within the approach or terminal maneuvering area.

The practical operational altitude the aircraft can fly is called the recommended altitude. This is obtained based on ATC rules at which aircraft must maintain a specific constant flight level, those flight levels are separated vertically to certify safe aircraft separation according to their directions.

According to the rules of the air, the semicircular rule applies inside controlled airspace [30] . The standard rule defines an East/West track divided:

Eastbound – Magnetic track 000 to 179° – odd thousands (FL 250, 270, etc.)

Westbound – Magnetic track 180 to 359° – even thousands (FL 260, 280, etc.)

Because of obligatory flight level restrictions, the optimum altitude which is increasing gradually cannot be maintained all along the route, however, the aircraft management system FMS recommend a flight level that is as near as possible to the optimum altitude and/or climb to higher altitudes as a step climb procedure in case of relatively long flights.

Also, it is not yet been confirmed to adopt the Continuous Climb Operations (CCO) at which the ATC will allow the aircraft to continuously chase its optimum altitude with every small segment of fuel consumed at small distance intervals. As illustrated in Figure 2.2 [31]. Because of this, the aircraft will only fly its optimal altitude at one or two points throughout its flight while it is crossing it in level cruise. Strictly speaking, the aircraft is flying all along its journey away from its optimum flight level. The best we can do is to stay as near as possible to the optimum altitude. According to this, the thesis considers the Current Concept of Operations (ConOps) with step climb, if required, to estimate the performance of aircraft in the cruise phase. The step climb is initiated at a point during the cruise which depends on the aircraft's weight for a given Mach number. Tabulated data are published in the FCOM for selected flight level changes for various temperature conditions. The climb is initiated when the optimum altitude, corresponding to the aircraft's weight, is mid-way between the lower flight level and the next higher flight level.

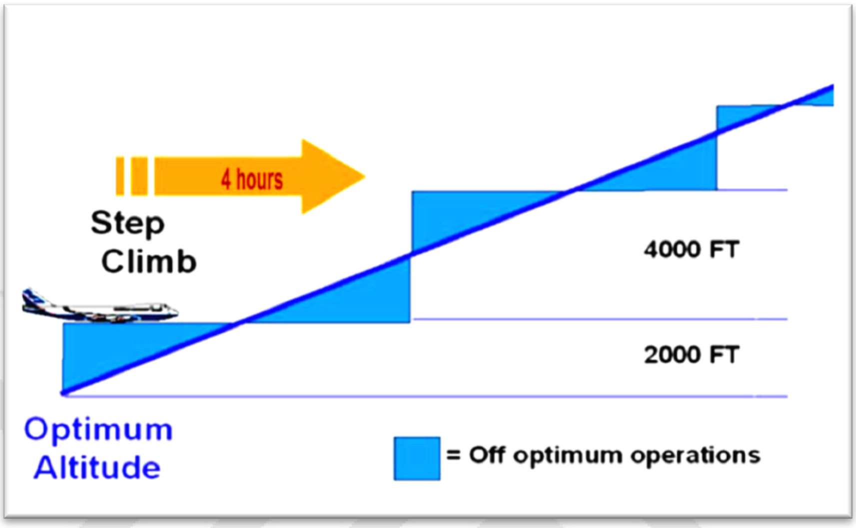


Figure 2.2: Step Climb Altitudes vs. Continuous Climb Operations

2.1.2 Cruise Speed Selection

The other main considered parameter is the cruising speed. This is proved by the dynamic pressure expression; the airspeed is directly related to the altitude, rather defined as the density altitude where the altitude represents the real value of air density. Airspeed has several more sensitive relations with aircraft performance such as the effect on optimal lift/drag ratio.

The conventional commercial jetliners operate in the high subsonic regime (Mach 0.7 – 0.8). Relatively minor changes in airspeed can cause significant variation in drag force, due to compressibility effects in the transonic region, also because the speed is squared in the dynamic pressure formula. In addition to this, the performance of the turbofan engine is also affected by Mach number variations, because airspeed remains constant in zero wind conditions and is not sensitive to weight variations,. However, the quality of aircraft performance for a given flight condition is a function of fuel consumed for flown distance, so winds do have a great influence on optimum airspeed, where, headwinds increase the optimal speed, while tailwinds decrease it; this is expressed in the form of Ground Speed (GS). It is obvious that the tailwind is the preferable wind for the matter of saving fuel and flight time and hence the DOC.

For a better understanding of what speed to maintain during flight and which one shall be used, the speeds are classified as follows:

2.1.2.1 Maximum Range Cruise Speed (MRC)

The maximum range of a flight can be achieved by flying at a specific cruising altitude that gives maximum specific air range SAR. As shown in Equation 2.2. The speed of the aircraft at that yields the greatest SAR is known as the Maximum Range Cruise (MRC) speed. Flying at the MRC speed leads to the minimization of the fuel required to travel a specific cruise distance (in still air). The MRC speed for an aircraft depends on its cruising altitude, the ambient air temperature, and gross weight [29], as shown in Figure 2.3, the MRC is slightly decreasing with a reduction in gross weight as the fuel is consumed during the cruise.

$$\mathrm{SAR} = -\frac{\mathrm{dr}}{\mathrm{dm}} = \frac{\mathrm{GS}}{\mathrm{FF}} \qquad 2.2$$

Where,

r is the flown distance [NM]

m is the aircraft mass [kg]

GS is the ground speed [kt]

FF is the fuel consumption [kg/h]

2.1.2.2 Long-range Cruise Speed (LRC)

The speed of LRC is calculated by sacrificing 1% from the maximum SAR and selecting the higher between MRC and LRC speeds, as shown in

Figure 2.3 [29]. The LRC speed depends only on the performance characteristics of the aircraft, that is, without considering a specific cost related to a specific operator, LRC speeds are calculated and published in the FCOM of the aircraft which is provided by the manufacturer.

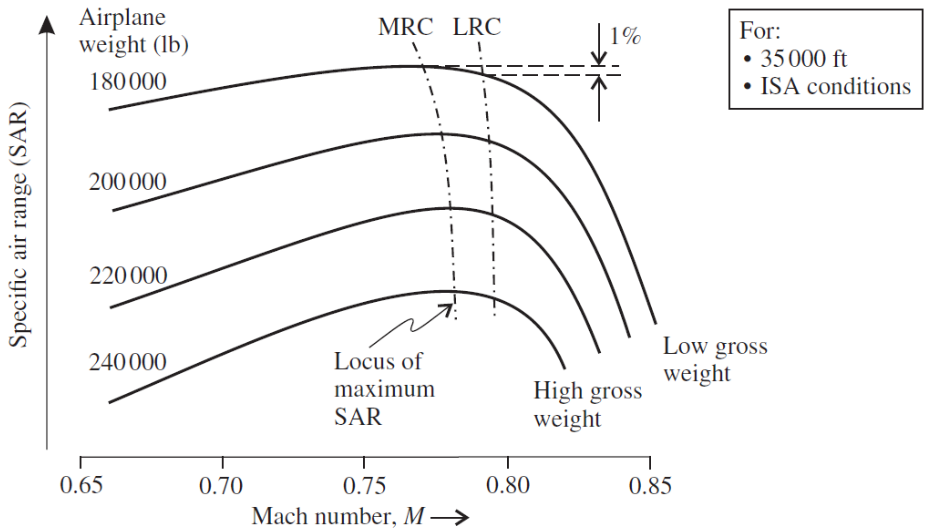


Figure 2.3: Effect of Aircraft Weight and on Maximum Range and Long-range Cruise Speeds

2.1.2.3 Economy Cruise Speed (ECON)

In real operations, airlines prefer to maintain a little higher speed than the MRC speed. This faster speed accounts for extra cost penalty due to greater fuel consumed for a specific flight. The tendency to increase the speed is mainly to fly faster, in other words, to travel in a shorter time, and that is why aircraft has been built. Since time is money, in air transportation time costs money, so that it is intended to be shortened for cost savings. Time-related costs comprise maintenance, aircrew, and operational can be minimized by conduct flight in a shorter time.

The airlines aim to operate their flight at the lowest possible cost at a speed which is higher than MRC speed; this will result in the lowest fuel consumption, hence lower operating cost, that speed is called the Economy Cruise Speed (ECON). The computation of ECON speed is a function of specific cost divisions of an airline, which is calculated based on a given cost index value for a specific aircraft type [29], as illustrated in Figure 2.4The DOC fractions of cost are obtained from the algorithm for a particular weight, altitude, temperature, and cost index. [19]

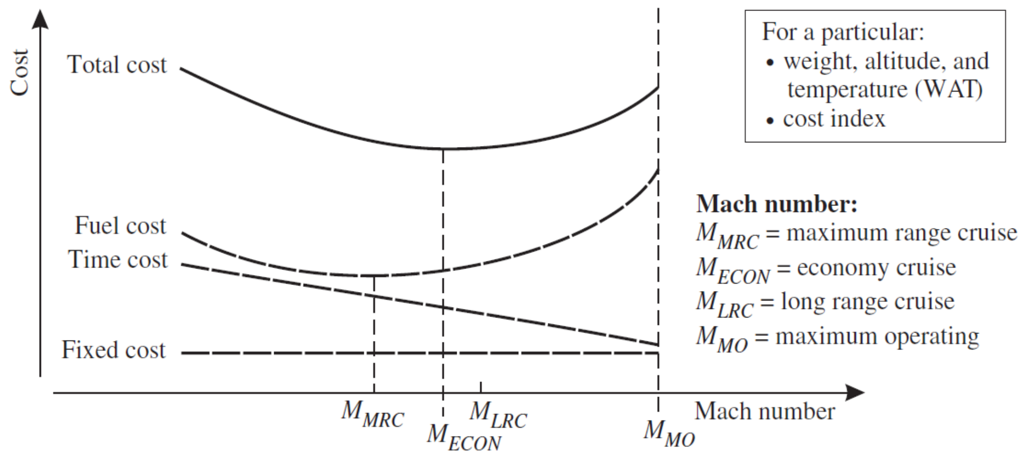


Figure 2.4: Characteristic Mach numbers for cruise according to cost fractions

2.1.3 Comparison of Cruise Speeds

It can be seen from Figure 2.4 Mach number effects fixed cost, time cost, fuel cost, and total cost in the cruise phase. The Mach numbers for the three mentioned cruise speeds (i.e., MRC, LRC, and ECON) are designated as M_{MRC}, M_{LRC}, and M_{ECON}, respectively. M_{MRC} as the name indicates, is a relatively slow speed used in case the airline wants to fly maximum distance with minimum fuel consumption, hence minimum fuel cost but with a longer time, so the time cost will be higher. M_{LRC} is typically 2–5% faster than M_{MRC} for jetliners is based on the weight and the altitude, this speed is used in case saving time is required and its weighing in the cost is more than the cost of fuel, in other words, the delay in arrival time may cost more than extra fuel consumed due to higher speed required [32], [33].

M_{ECON} is the speed of minimum DOC, which is always greater than M_{MRC} when the operation is a function of time cost and it is smaller than M_{LRC} for the cost related to the fuel consumed. It can be seen from Figure 2.4 the difference between those speeds is very small in terms of Mach number but is very sensitive to the DOC which is a function of the selected CI.

2.2 Reasons for Non-Optimal Vertical Flight Trajectories

It can be interpreted from the previous sections that, a minor change in performing flight operations can significantly affect the performance and the cost of the flight. The answer to this question can be classified into airline planning strategies, ATC constraints, and atmospheric/weather conditions.

2.2.1 Airline Flight Planning Strategies

Airlines adopt specific strategies for flight planning based on the type of aircraft and routes flown. The commercial flights are conducted under the control of ATC which provides control and guidance to ensure the safety of air traffic. Also, ATC always tries to provide assistance to the pilots to maintain their optimum flight parameters such as speed or altitude or both in case of available unoccupied corridors or flight levels.

Mainly airline strategies aim to conduct flights with minimum costs by saving fuel and time. Those strategies are based on the accurate estimation of total cost including direct and indirect operating costs. For some airlines the fuel cost is small compared with some others, for other airlines, the cost of time is higher, it could be due to high rates of leasing aircraft for instance, etc.. All of these factors are expressed in the form of CI, which is supplied to the pilot to be inserted in the aircraft's FMS. The CI is the base of all calculations of the aircraft performance which is performed by the FMC, therefore, there will not be many options for the pilot to select the optimum values for the speed and the altitude, however, the pilot must fly as near as possible to those value if the ATC provides the clearance to maintain those optimal values.

The CI exists as a tool to provide a balance between the cost of time and the cost of fuel for a given flight condition. Flying at a speed higher than the optimal economy speed costs greater fuel quantity, however, the cost of time will be less, resulting from a reduction in the operating time, hence maintenance costs because many maintenance programs are based on the calendar or operating hours. Also, in many airlines, flight crews are paid based on block flight time. Airlines aim to minimize costs by flying at the speed provided by the CI.

This cost centric strategy is relatively responsible for conducting flights beyond the performance optimal cruise speed trajectory. An example of this case is the meet time of arrival issue, where the pilot is requested to fly a higher cruise speed to arrive at a specific time to the destination in order to avoid delay penalties. This is dealt with in details as a study case of time constraints operations which are encountered daily by air airlines.

Finally, airlines try to balance many operational considerations for speed and altitude options, such as providing the pilots with alternative CI, altitudes, and speeds in case of the optimum altitude are not available due to ATC constraints.

Airlines are required to create clear strategies and policies to encourage optimal flight trajectories. Developing advanced planning techniques is essential; however, pilots may not be able to enhance the performance because the optimal results provided by FMS are constrained by the CI.

2.2.2 Airspace and ATC Constraints

The capacity of airspace is the main reason for not being able to fly optimal trajectories. The vertical trajectories are harder to be depicted than the lateral ones in the current surveillance systems which limits the situational awareness. In addition, the task of tracking the aircraft in vertical plane becomes difficult and puts air traffic controllers in a higher workload to ensuring safe separation especially when aircraft are in vertical transition during descent or climb. As a result of this, aircraft are preferred to maintain horizontal flight levels on airways, with special attention for monitoring the air traffic in transition across flight levels [34]. In the past the Vertical Separation Minima (VSM) was 2000 feet, nowadays the vertical separation minima have been reduced to be 1000 feet only with the implementation of the Reduced Vertical Separation Minima (RVSM) in many countries. As shown in Figure 2.5 [35]. The direction of traffic is managed according to the semicircular rule which separates the traffic in odd and even flight levels, so any two consecutive flight levels are separated by 2000 feet under RVSM. According to this rule, an aircraft trying to maintain an optimal altitude level in RVSM airspace will have to experience 2000 feet step climbs.

ATC may also have some constraints for the speed of the aircraft which are using the same airway at the same flight level, in this case, the air controllers will have to separate the traffic by ordering the conflicting traffic to reduce or if capable to increase the speed, in both cases, the optimal speed will be violated. At the same time, the lateral or/and vertical separation is requested by the ATC, the speed and/or altitude can be diverted from the optimal margined and as a result, the performance degrades.

The ATC constraints are more significant in less developed airspaces where the procedural separation is applied because of lack of radar coverage, in this case, the capacity of the airways is much less which makes the diversions from the ideal trajectories more demanded.

Airlines advice pilots to keep negotiating with ATC to get as possible nearer trajectories to their optimal ones, some airline tends to give bonuses for saving fuel and time.

The effect of those issues is discussed in the following section by assuming different flight scenarios for Airbus 320-214 aircraft.

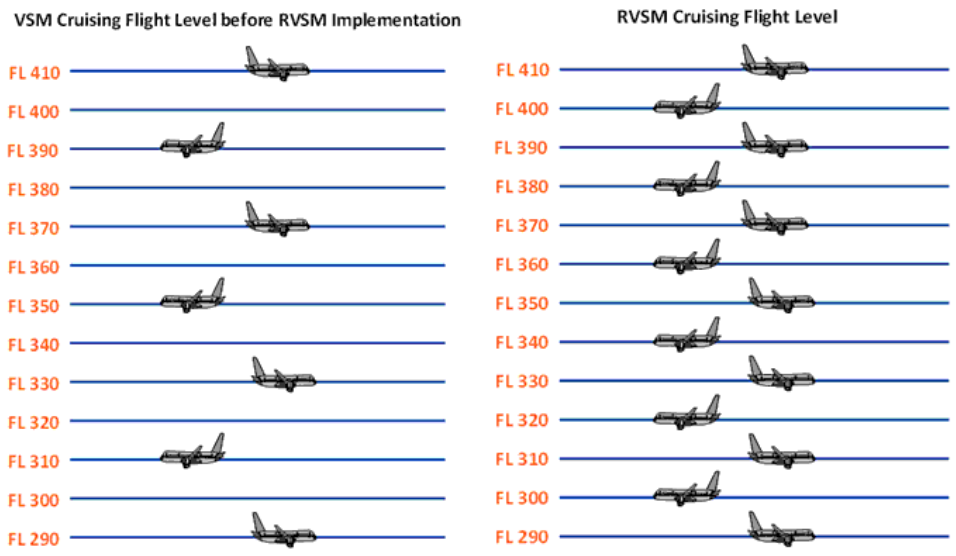


Figure 2.5: VSM vs. RVSM

2.2.3 Atmospheric Conditions

The atmosphere is one of the most direct and observable causes for averting from optimal trajectories. One of the main tasks for the pilot is to avoid the weather and stay away as possible from it. The aircraft may be forced to leave its optimal trajectory to avoid bad atmospheric conditions, better called weather, for safety reasons, or even for passengers comfort in case of turbulence. Most commercial flights are performed above or close to the tropopause where the weather is much less effective especially for the thunderstorms and weather cells; however, severe cumulus clouds can extend to high altitudes and force aircraft to change altitude. Atmospheric weather conditions at the flight level can be also another probable reason for delays, which definitely result in imposing to flying higher speed than optimal in an attempt to meet the time of arrival.

Air turbulence is one of the most challenging weather phenomena. When aircraft encounters massive pockets of rough air at the cruising altitude, in order to avoid unpleasant turbulence condition pilots request decrease or increase altitude in search of smoother air to increased passengers comfort. The degradation in performance is considered worth passengers comfort and also safety in case of severe turbulence.

The effect of temperature variations on performance and DOC is investigated in this thesis. Temperature variations are expressed in the form of deviation from the International Standard Atmosphere (ISA). The ISA deviations occur on daily basis and as a function of the altitude, the other factor affecting temperature variations is the tropopause height where the temperature decreasing rate is paused.

In general, temperature deviation above standard ISA results in a small, but not insignificant, increase in an aircraft’s drag, such an increase in drag would require an increase in thrust to maintain the cruise speed. Maintain constant cruise speed requires higher thrust as a result increase in fuel consumption to compensate for the increase in drag. [29].

CHAPTER 3

METHODOLOGY

Mathematical modeling is a representation of a system in a form of a set of mathematical expressions. Modeling an engineering system such as an aircraft is an effective method to analyze and estimate the parameters affecting the performance of aircraft. This can be achieved by building a mathematical model representing the physics of aircraft motion and geometry. The mathematical model developed for Airbus A320-214 by the assistance of the information about the aircraft type provided by BADA, the model is referred to as APM, which is solely developed for this thesis.

3.1 Base of Aircraft Data BADA

The approach of the aircraft modeling in this work is developed based on the concept of the Base of Aircraft Data BADA, which is provided by EUROCONTROL, via mutual collaboration with aircraft manufacturers and operators. The APM model is developed to estimate the performance of aircraft based on their trajectories for the research and operations of Air Traffic Management (ATM). The APM concept is based on a mass-varying, kinetic approach. This concept considers aircraft as a point and requires modeling of forces involved in the motion of aircraft.

The BADA APM consists of four sub-models: The action model computes the forces applied to the aircraft during the flight (aerodynamic, propulsive, and gravitational). The propulsion model provides an engine model to estimate fuel quantity. Total Energy Model (TEM) is the model that considers the geometrical, kinematic, and kinetic characteristics of the aircraft motion. TEM is used to calculate aircraft performance and path. The operations model provides information about the way the airline is operating the aircraft. The limitations model limits the aircraft actions to keep it within certain safety margin limits.

The BADA mathematical models are expressed in terms of polynomial equations. [6], [36] , [22].

3.2 Selection of Aircraft Model

The aircraft selected for this research is Airbus A320-214. The general view of A320 is shown in Figure 3.1 [18]. A320 family is narrow-body midsize jetliner designed and produced by Airbus. Since 1988 about 9400 unit has been built according to Airbus till June 2020 [37].

A320-214 is the Current Engine Option (CEO) type which is the conventional type of this family including A320 – 212, 214, 231, and 232 based on engine type used and version. This type is equipped with CFM 56-5B4 engine which is used by many other manufacturers such as Boeing for midsize narrow-body aircraft.

The data provided by BADA is fairly enough to build an accurate mathematical model because of the accumulated information from long years of operations within the Eurocontrol. In addition to this, access to operational information from some aircraft operators and very well qualified and expert pilots on this type encourage adopting this specific type of Airbus as a model for the study cases in this research.

It is also worth mentioning that the APM developed in this work is intended to be developed in the future to be used as an assistant tool to estimate the performance of aircraft and to help to solve daily operational issues encountered by the operators of this type.

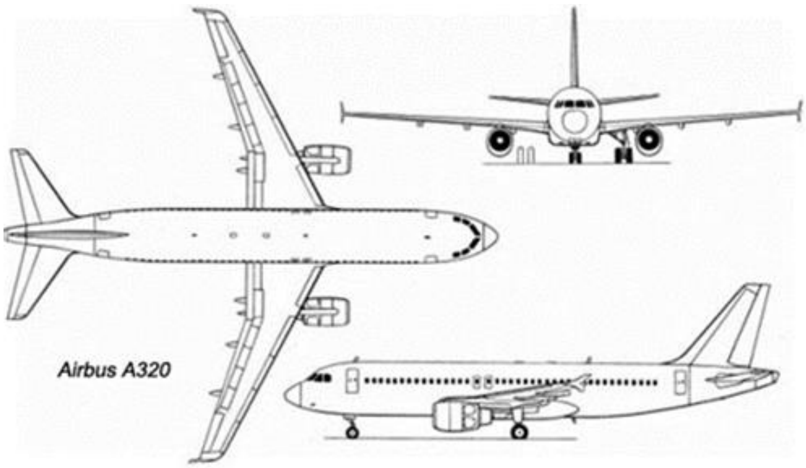


Figure 3.1: Airbus A320 General View

The specifications of the Airbus A320ceo are presented in Table 3.1 [18]

Table 3.1: Basic Data and Specifications of Airbus A320-214

Dimensions	
Length (m)	37.6
Wingspan (m)	34.1
Height (m)	11.8
Wing area (m2)	122.4
Maximum take-off weight (kg)	78000
Maximum landing weight (kg)	66000
Operating empty weight (kg)	42600
Maximum zero fuel weight (kg)	62500
Maximum payload (kg)	16600
Performance	
Range with max payload (km)	6100
Cruise speed (km/h), (M)	840, 0.78
Maximum speed (km/h), (M)	890 , 0.82

Maximum operating altitude (m)	11900
Engines	CFM 56-5B4
Thrust (KN)	2 x 111.2
Passengers capacity (1-class)	180

3.3 Aircraft Performance Model

The algorithm of APM is developed exclusively for this research based on the information provided by the Base of Aircraft Data BADA, which provides data for model specifications and the aircraft database. The aircraft motion model is defined based on the aircraft specifications via data of basic aerodynamic characteristics, propulsion model and, gravitational equations. [36] [22].

APM implements both the empirical data from real flights and from BADA and the analytical data from the mathematical model of the aircraft. This model takes into consideration the effect of all parameters on the performance of the aircraft such as the atmospheric conditions, aerodynamic characteristics, thrust, aircraft mass, wind, etc.

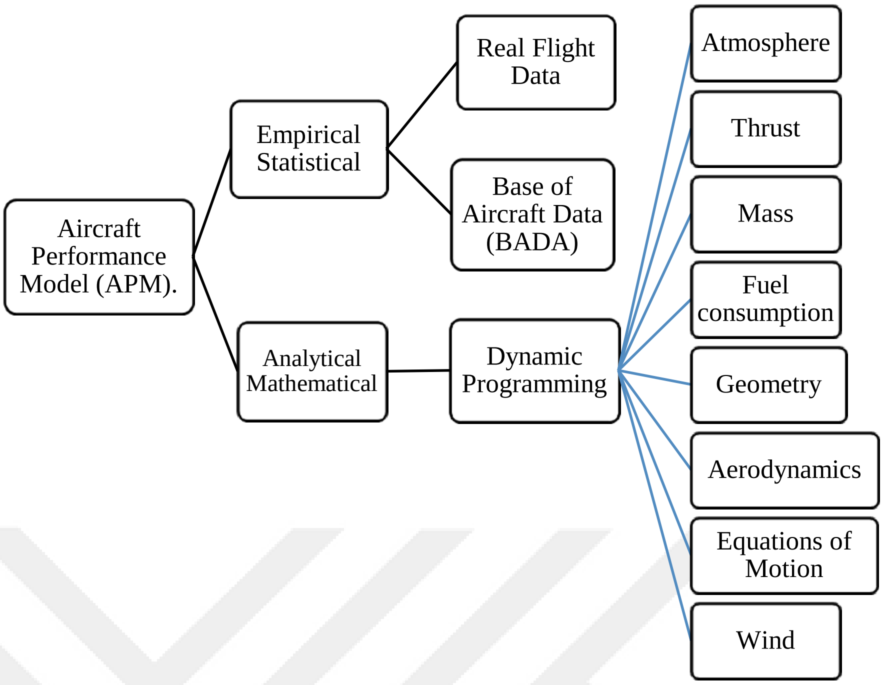


Figure 3.2: APM Diagram

The APM algorithm uses aircraft equations of motion based on Total Energy Model TEM concept, which balances the rate of increase in potential and kinetic energy with the rate of work done by forces acting on the aircraft, as shown in Equation 2.1

$$(Th\text{-}D).\ TAS = m\ .\ g_0 \left(\frac{dh}{dt}\right) + m\ .\ TAS\ \left(\frac{dTAS}{dt}\right) \qquad 2.1$$

Where,

Th is the thrust force,

D is the drag force,

$\left(\frac{dh}{dt}\right)$ is the rate of climb, The aerodynamic forces are the most significant forces affecting the aircraft flight; they are subjected to counties changes all along the flight path, those changes are mainly due to reduction in aircraft gross weight due to fuel consumption, changes in speed and/or altitude, changes in atmospheric conditions and wind speed and direction, etc. In this research, only cruising phase is considered, at which the altitude is constant, in this case, the model is governed by the following equations, where the lift is equal to weight and thrust is equal to drag:

$$L=W \tag{3.1}$$

$$Th=D \tag{3.2}$$

$$L= 0.5 .\delta. \gamma. P_0. S. M^2 .C_L \tag{3.3}$$

$$D = 0.5 .\delta. \gamma. P_0. S. M^2 . C_D \tag{3.4}$$

Where,

L is the lift force,

W is aircraft weight,

δ is the pressure ratio,

γ is the Adiabatic index of air,

P_0 is the pressure at sea level,

S is the aircraft wing reference area,

M is Mach number,

C_L is the lift coefficient, and

C_D is the drag coefficient.

At cruise phase the aerodynamic configuration considered as clean configuration where landing gear and high-lifting devices are not deployed.

As can be seen from Equations 3.5 and 3.6 Lift and drag equations are expressed as a function of Mach number M and pressure ratio δ [36] [22].

The lift coefficient C_L is obtained from Equation 3.5.

$$C_L = \frac{2.L}{\delta.\gamma.P_0.S^2.M.C_L} \qquad 3.5$$

BADA method specifies the drag coefficient, C_D, as a function of the lift coefficient C_L and the Mach number M. as shown in Equation 3.6 .

$$C_D = \text{scalar } [C_0+(C_2+ C_L^2)+(C_6.C_L)] \qquad 3.6$$

The drag coefficient C_D is modeled as a polynomial of lift coefficient C_L, Where, C_0, C_2 and C_6 are coefficients depending on Mach number provided by BADA according to available aircraft type and configuration.

The BADA is obtained from the Propulsive Forces Model (PFM), which depends on the type of engine, Turbo Fan Model (TFM), is the model used for A320. the thrust is provide in each model as a function of reference atmospheric parameters, aircraft gross weight, and thrust coefficient C_T, as shown in Equation 3.7.

$$Th = \delta \,.\, W_{mref}.\, C_T \qquad 3.7$$

Where W_{mref} is the reference weight of the aircraft, for Airbus A320 it is given as 77000 kg [18].

The thrust coefficient C_T of this model considers aircraft configuration in cruise as a function of Mach number, throttle parameter δ_T and thrust parameters a_n, which are provided by BADA [36] [22], as shown in Equation 3.8.

$$C_T = f\,(a_{1\text{-}36}, \delta_T, M) \qquad 3.8$$

Where,

$$\delta_T = f\,(b_{1\text{-}36}, \delta, M) \qquad 3.9$$

Where, $a_{1\text{-}36}$ and $b_{1\text{-}36}$ are the parameter sets that are provided by BADA for a specific flight phase and aerodynamic configuration [36].

The algorithm calculates the fuel consumption as a rate of fuel flow, based on Equation 3.10, resulting from data inputs of the flight such as aircraft weight, altitude, true airspeed and atmospheric conditions including the effect of the wind.

$$FF = \delta.\sqrt{\theta}.W_{mref}.a_0.L_{HV}^{-1}.C_F \qquad 3.10$$

The fuel flow FF formula is expressed in Equation 3.10, the fuel consumption is affected directly by the pressure ratioδ, temperature ratio θ, and aircraft reference weight, which are directly related to the selected altitude and temperature. FF is also directly related to standard speed of sound (a), fuel low heat value LHV, which is the factor defined as the amount of heat can be released from the specific amount of fuel, and the fuel coefficient C_F.

As expressed in Equation 3.11 the fuel coefficient is provided as a function of Mach number where, C_T and fuel coefficients f_n which are 25 parameters provided in BADA database. The propulsive coefficients used for A320 APM are obtained from CFM 56-5B4 turbo fan engine model [6] [36] [22].

$$C_F = f\,(M, C_T, f_{1\text{-}25}) \qquad 3.11$$

The coefficients presented in the previous equations are non-linear coupled multivariate coefficients.

BADA introduces a generic aircraft modeling method that can be applied for different aircraft types based on engine type, aerodynamic configuration, and thrust level setting, and fuel consumption for each specific aircraft.

Those equations and coefficients are implemented to develop an algorithm in Matlab. This algorithm which is referred to as an APM is used for performance calculations for different study cases presented in this thesis.

3.4 Atmosphere Model

The atmosphere plays a major role in aircraft performance and operations. The model provides equations for the properties of the atmosphere, such as density, temperature, pressure, and speed of sound as a function of geopotential altitude, based on the International Standard Atmosphere ISA. These equations are essential for performance calculations, as well as calculations of Calibrated Air Speed (CAS), True air Speed TAS, and Mach number M. The model of the atmosphere is expressed in Matlab by the equations governing the relations between atmospheric parameters such as pressure, temperature, density, tropopause height, and their rate of change with changing altitude [36]. Also, the model can handle any temperature deviations from standard ISA.

3.4.1 International Standard Atmosphere ISA

The conditions of the standard atmosphere are defined as those occur in the International Standard Atmosphere ISA at the point where the geopotential pressure altitude Hp is zero or at sea level.

The main parameters are introduced as T_0, p_0, ρ_0, and a_0 with the values listed in Table 3.2

Table 3.2: ISA parameters at MSL

Standard atmospheric	T_0 =	288.15	[K]
Standard atmospheric pressure	P_0 =	101325	[Pa]
Standard atmospheric density	ρ_0 =	1.225	[kg/m^3]
Standard speed of sound	a_0 =	340.29	[m/s]
Real gas constant	R =	287.05	[m^2/(K·s^2)]
Gravitational acceleration	g_0 =	9.806	[m/s^2]
Lapse Rate	LR =	- 0.0065	[K/m]
Specific heat	γ =	1.4	-

3.4.2 Real Non-ISA Atmosphere

In the actual flight operations, the ISA parameters are rarely met, the most off-standard parameters are the temperature, and pressure, the deviation of those parameters from the standard is expressed as temperature differential at Mean Sea Level (MSL). The difference between ISA temperature at MSL and non-ISA temperature is denoted as (ΔT), for the pressure it is (ΔP).

For more realistic calculations that resemble the real daily flight operations, the values of ΔT and ΔP are individually identifying any non-ISA atmospheric condition. Therefore, deviations from a non-ISA atmosphere are expressed for the atmospheric pressure, density, and temperature as functions of the geopotential altitude H_P.

3.4.3 Geopotential Pressure Altitude (Hp)

The pressure altitude is defined as the geopotential altitude H that occurs in the ISA atmospheric conditions corrected for any deviation from the standard values.

The difference between geopotential altitude and pressure altitude depends on the temperature deviation ΔT and the pressure altitude H_p. The expression that describes this is expressed in Equation3.12

$$H = H_p - \frac{R\,\Delta T}{g_0} \ln\left[1 + \frac{LR\,H_p}{T_0}\right]^{\frac{-g_0}{RLR}} \qquad 3.12$$

For aircraft performance it is also known as density altitude which is the real physical altitude sensed by aerodynamics and the power plant.

In conclusion, it is evident that in hot weather conditions (i.e., when ΔT is positive), the pressure Altitude will be higher and vice versa if the deviation is negative. As a result it will affect the density at that altitude which has direct influence on the aerodynamic and propulsion forces.

3.4.4 Tropopause Height

The tropopause is a thin layer separation two different layers: the lower one is the troposphere, where most of the weather conditions happen, and the upper layer which is the stratosphere. The standard height of the tropopause is 11,000 km (36089 feet), however, to more realistic calculations the actual instantaneous value of the tropopause height must be considered.

The height of the troposphere is an essential input for flight performance calculations which is one of the basic inputs in the aircraft’s FMS. Pilots or dispatchers usually use the significant weather charts SWC, which is valid for 24 hours, to find out what is the value of the instantaneous tropopause altitude along the route of the flight. At the tropopause the rate of decreasing temperature with increasing altitude will be zero, hence lapse rate is zero at that layer and beyond, which will result in constant ambient temperature. The variation of tropopause height in medium-range route can be about 10,000 feet.

3.4.5 Speed of Sound and Mach Number

The mathematical expressions provided by BADA are expressed as a functıon of Mach number which implements the speed of sound (a) and true airspeed TAS based on atmospheric inputs. The relations are expressed in Equations 3.13 and 3.14.

$$a=\sqrt{\gamma\ R\ T} \qquad 3.13$$

$$M=\frac{TAS}{a} \qquad 3.14$$

3.5 Cost Analysis

In the air transport industry, the direct operating cost DOC is summed up from fixed cost, fuel cost, and time-related costs. which are those related to timely accounted activities such as scheduled maintenance, crew active duty time, and aircraft or equipment lease costs. Generally, minimization of cost time is possible by flying at faster cruise speed [29]

The purpose of management of cost is to minimize the total flight cost (C_t) (DOC), the summation is given in Equation 3.16 where, (C_t) involves fixed costs (C_{fx}) plus variable costs (C_v). Fixed costs are those costs that are not related to the number of conducted flights, in other words, they are the cost must be paid even the whole fleet is grounded; those costs include aircraft and equipment depreciation, leases, insurance, and any others. Variable costs include fuel and oil, maintenance, and crew. Equation 3.15, shows the items included in calculating variable costs which is consist of the cost of fuel CF multiplied by the amount of fuel consumed (Δm), plus the cost of time CT, which is expressed in the form of [$/min] multiplied by the time (Δt) of the flight [22].

$$C_t = C_{fx} + C_v \quad (3.15)$$

$$C_t = C_{fx} + CF.\ \Delta m + CT\ .\ \Delta t \quad (3.16)$$

Equation 3.16is reformed into Equation 3.17 to be used as a ratio between the cost of time and cost of fuel ($\frac{CT}{CF}$).

$$C_t = C_{fx} + CF.\ (\ \Delta m + \Delta t.\ \frac{CT}{CF}) \quad (3.17)$$

Both C_{fx} and CF are not subjected to significant differences, it can be fixed in a specific flight, CF can be variable only if the there was a fuel remained from the preceding flight and another quantity of fuel must be added with different cost, in this case, the CF must include cost ratio of both fuel charges.

The relations between direct and indirect costs and the relation between fuel and time costs are very complex because of the system of airline operations is completely dynamic and nonlinear. The simplest way to simplify the complexity is to use the ration ($\frac{CT}{CF}$), by optimizing this ratio the total cost C_t for a specific flight is minimized as well. Reduced C_t can be achieved by flying an optimal economy speed that guarantees minimal fuel consumption and minimal flight time simultaneously.

The ratio between CT and CF ($\frac{CT}{CF}$), is defined as the Cost Index CI [kg/min]. The range of CI value differs based on the type of FMS used in the aircraft; the range starts from zero to 99, 200, 500, 999 or 9999 in some models [38].

When CI selected to be zero this implies that the cost of time considered to be zero, which can't be correct mathematically, but flying that way indicates that the airline wants just to save fuel regardless of the cost of time. On the other hand, by selecting CI 99, in this case, the aircraft is ordered to fly its maximum allowable speed, the operator claims that the cost of fuel is much concerned than the cost of time, in other words, the aircraft wanted to arrive at the destination in a specific time even if this costs it more fuel. The economical operational range for A320 is variable between 10 and 35, for example, if an airline selects CI 20 it means that the cost of 20 kilograms of fuel is equivalent to the cost of one minute of flying [39]. as expressed in Equation 3.18. For a better understanding of the cost index if an airline company found that for a specific aircraft the cost of 1 minute of operation is 10.8 $/min and the cost of jet fuel is 0.72 $/kg the CI will be 15. The effect of CI will be discussed earlier in the results chapter.

$$CI = \frac{CT}{CF} \qquad 3.18$$

The total cost can be minimized by minimizing the Economy Cruise Cost Function (ECCF), As interpreted from Equation 3.19, the minimization of the function can be achieved when flying at the highest possible ground speed (GS) with minimum fuel consumption FF and also minimum CI [22].

$$ECCF = \frac{CI+FF}{GS} \qquad 3.19$$

3.6 Cost Index Cruise Management

The cruise is managed by selecting the most correct cost index according to the flight conditions by optimizing cruise speed which is expressed in terms of Mach as Economic Mach number M_{ECON}, which results in a reduction of the total cost C_t of the cruising segment, aircraft weight (W), cruise geopotential pressure altitude H_p and atmospheric conditions expressed as ISA temperature deviation ΔT.

ECCF function is optimized for obtaining the minimum value by using APM of Airbus 320-214 equipped with CFM 56-5B4 turbofan engine. The minimization results in minimal fuel consumption and shortest flight time, so both cost of fuel and costs of time are minimized.

3.7 Selection of Optimization Technique

In general, Optimization is defined as the action of obtaining the best result under given specific conditions. In multi-criteria complex engineering systems, engineers have to take technical based decisions at several evaluation stages. The decisions are centric around either minimize the required effort or maximize the desired outcome.

In any practical conditions, the effort required or the desired outcome can be stated as a function of specific decision variables, optimization can be defined as the process of obtaining the situations that give the maximum or minimum value of the desired function that express the problem required to solve or evaluated.

Therefore a set of optimization techniques have been developed to solve different types of optimization problems, selecting the suitable optimization technique is quite related to the nature of the problem, in this work the selected SQP is found to be fit for the task for it accuracy and time of solution [40].

3.7.1 Statement of an Optimization Problem

An engineering optimization or a mathematical programming problem can be identified as in Equation 3.20:

$$\text{Find } X = \begin{Bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_n \end{Bmatrix} \quad \text{which minimizes } f(X) \qquad 3.20$$

Where, X is an n-dimensional vector (x_1, x_2,…x_n) called the design vector, f (X) is termed the objective function,

The function f(X) is subjected to the following constraints as shown in Equation 3.21 and 3.22 [40].

$$g_j \leq 0, \quad j = 1,2, \dots m \qquad 3.21$$

$$l_j = 0, \quad j = 1,2, \dots p \qquad 3.22$$

Where, g_j (X) and l_j (X) are known as inequality and equality constraints, respectively. The number of variables n and the number of constraints m and/or p need not be related in any way.

These types of problems, as presented in Equation 3.20 , are called constrained optimization problems. The real flight operation conditions are subjected to many constraints, those constraints can be due to ATC, weather, or are related directly to aircraft performance limitation, like the ones discussed in the background chapter.

The objective function is the APM model including the model of the atmosphere, which is forming the mathematical model of the problem to be solved to enhance the aircraft performance hence minimization of DOC for an airline.

In multi-criteria systems the design variables cannot be selected randomly; instead, they must satisfy a number of quantified functional requirements. The limitations that have to be satisfied to produce give acceptable designs are together called design constraints. Constraints that represent physical limitations on design variables, such as speed limits, maximum service ceiling, and maximum gross weight, etc. there are also operational constraints such as subjecting the flight to specific operational requirements such as arriving at the destination in a specific time as discussed in meet time of arrival criteria.

3.7.2 Sequential Quadratic Programming (SQP)

The Sequential Quadratic Programming SQP is selected to be used to perform the optimization of APM to minimize the DOC by using the best speed and altitude for every flight scenario. SQP is considered as one of the best and the most recently developed techniques of optimization. The technique is based on solving a set of nonlinear equations using Newton's method, and the derivation of simultaneous nonlinear equations using Kuhn–Tucker conditions to the Lagrangian of the constrained optimization. [40].

The problem of modeling of aircraft performance consists of multivariable parameters, so the equations constructing the APM are nonlinear equations. As with the most optimization techniques, SQP is not evolved from a single technique, but rather conceptual preceding algorithm. A reason to use SQP for nonlinear equations with a large scale of variables is to be able to solve a large number of quadratic programming sub-problems [41].

From the literature it has been found that SQP method is selected because it requires minimum iterations less number of gradient evaluations [42], this is suitable for APM condition as the algorithm will take a relatively very short time to converge the iteration to the desired solution within the required tolerance. Also, this nonlinear programming solving method provides accurate and fast solutions, and its flexibility allows for varying the performance index, model, and constraints with quite simple and fast reprogramming [43].

The algorithm is intended to be developed to a virtual tool to assist flight operators and planners to calculate the potential performance of a selected flight, based of flight condition and aircraft configuration, and to help in taking the best decision according to flight scenario, so the time taken to run the simulation is measured in few seconds which is suitable for urgent daily flight operation or even suitable to be used by the pilots during the flights.

CHAPTER 4

VALIDATION STUDY

This chapter discusses the outcomes of the APM simulations for different flight conditions for the purpose of the model validation. The validation shows how accurate the results are compared with reliable data sources. Without validation of the model, the outcomes cannot be used as evident to give answers to an operational problem.

The validation study is conducted for the aircraft itself and for the atmosphere model for different inputs at different flight conditions as explained in the following sections.

4.1 Validation of Atmosphere Model

The atmosphere model is built based on the relations provided by BADA which shows a perfect match with the International Standard Atmosphere ISA model is adopted by International Civil Aviation Organization (ICAO) to be used for aviation calculations. Making sure that the model is performing perfectly is of crucial importance, the effect of the atmosphere is very significant in the performance of the aircraft because of this it is handled with great care at the beginning of building the APM. The atmosphere model has been examined for different atmospheric parameters at different ISA conditions, the effect of ISA deviations are shown in

Table 4.1, for the main atmosphere parameters at a specific altitude (35,000 feet) and at Mach Number 0.78.

Table 4.1: Atmospheric parameters at different ISA conditions

	ISA+20	ISA	ISA-20
a [m/s]	309.79	296.54	282.66
ρ [kg/m3]	0.348	0.380	0.418
P [hpa]	23842.27	23842.27	23842.27
T [k]	238.81	218.81	198.81
TAS [m/s]	241.64	231.30	220.47
IAS [m/s]	136.03	136.03	136.03

4.2 Validation of APM

The APM model is validated based on the input and outputs compared with three different sources, which are data provided by BADA, A320 FCOM, and from real flight data. Inputs and outputs of the APM are shown in Figure 4.1

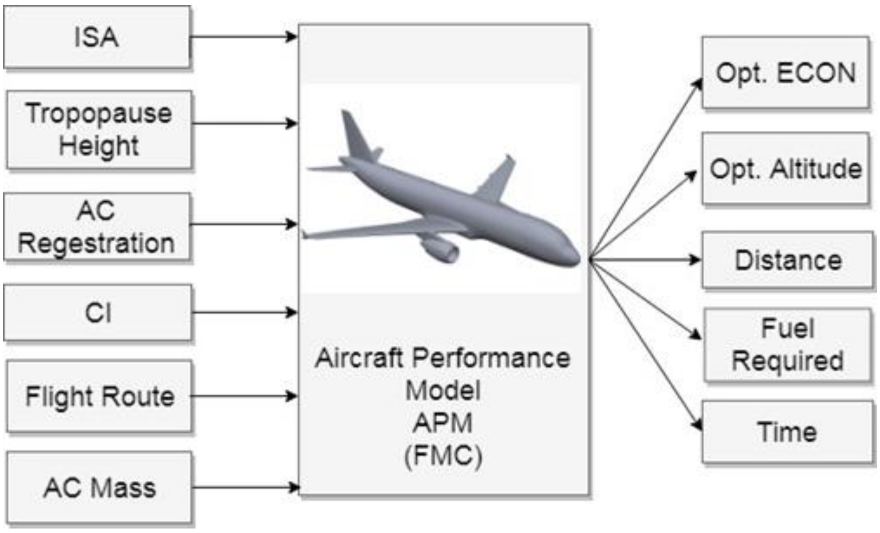


Figure 4.1: Scheme Diagram of Aircraft Performance Model

The Matlab algorithm for APM is using the same logic of A320 Flight Management Computer (FMC), which includes the performance database of the aircraft as well as the navigation database. The inputs are inserted before takeoff including initial position and destination along a specific route to calculate the distance, ISA conditions are given as ISA deviation, it is given from the weather report as ISA=0 if the deviation from ISA is zero hence the atmosphere is standard, or it can be for example +10, +20, -10, etc. according to the current temperature, then the troposphere height, the CI , the performance factor or it can be labeled degradation factor or drag factor based on type and version of the aircraft, this factor is a function of aircraft age and how much fuel consumed more due to increasing in aerodynamic drag of degradation of the engine performance, the values is given as a percentage number for example +5 means that the fuel consumption will be %5 more and the FMC will include it in calculations, the final main input is the aircraft gross weight. An example of FMC inputs is shown in Figure 4.2

Figure 4.2: FMC Initial Inputs Page

The validation of APM for A320-214 is conducted based on the methods of used by Airbus Company for cruise performance methods, mainly these methods compare the actual aircraft performance quality to the operating handbook values, there are three methods for the evaluation these are:

a. The fuel used method,
b. The fuel onboard method,
c. The specific range method.

The method used for this thesis is the fuel used method. As recommended by Airbus the inflight data recording must be conducted when the aircraft is stable at its cruising level after about 15 minutes from the top of climb (TOP) and with the engaged autopilot [12].

4.2.1 Fuel Used Method

The fuel used method is found to be the most suitable method for the study because it is based on the measure of the amount of fuel consumed in cruise over a significantly long time and then compare the results with the fuel consumption estimations of the Flight Crew Operating Manual FCOM.

Flight data was recorded based on the same manner recommended by the airbus flight data monitoring procedure. The flight was a trip between Masqat and Jeddah operated by Salam Air on Airbus A320-214 registration A40-OVB.

The main purpose of this simulation is to validate navigation functions and fuel consumption including the effect of wind and ISA deviations, the segments used for validation were straight legs where the wind speed and direction are almost constant.

The route of the flight consists of some legs according to the company's planned route; the same route is constructed in Sky Vector flight planner [44] based on the computerized flight plan of that flight as shown in Figure 4.3.

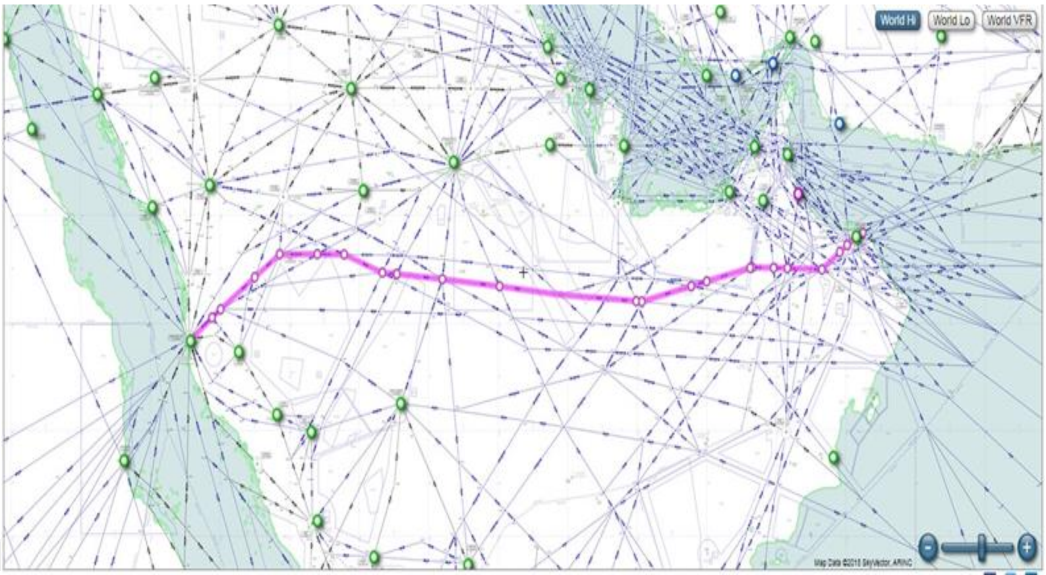


Figure 4.3: Muscat To Jeddah Flight Route

The evaluation of the APM starts with the calculations of the legs distance obtained from the coordinates of intersections and waypoints and compare it with the distance obtained from the algorithm, the results were in absolute perfect match with differences of few meters for in every few hundreds of nautical miles.

The sample of recorded inflight data used is A320 Cruise Performance Analysis - Flight Observation Form as seen shown in

The records include all operational parameters such as the performance factor (+5%), actual wind speed and direction, aircraft gross weight, magnetic heading, total air temperature, fuel flow for each engine, altitude, Mach number, and ground speed at each waypoint. The recorded flight data also include the statues of the air conditioner and the main input for such calculations which is the cost index CI.

Table 4.2: A320 Cruise Performance Analysis - Flight Observation Form

CRUISE PERFORMANCE ANALYSIS - FLIGHT OBSERVATION FORM													
Aircraft Type:	A 320-214												
Engine Type:	CFM 56 – 5B4												
Tail Number:	A40 - OBV												
Air Conditioning	NORM												
CG	30.2 %												
Performance Factor	+5.0												
CI	15												
#	Postion	Time	GW [kg]	M	GS [kt]	TAS [kt]	W/V	Mag Hdg	Alt [feet]	TAT [C]	FF1 [kg/h]	FF2 [kg/h]	FOB [kg]
1	DAVLU	11:14	64600	0.777	401	454	364/54	257	36000	-21	1260	1280	7880
2	DAVLU	11:24	64200	0.777	405	455	253/50	256	36000	-20	1240	1240	7440
3	LADBU	11:28	64000	0.780	408	457	254/51	270	36000	-20	1220	1220	7300
4	RAGBU	11:34	63700	0.780	406	457	253/54	269	36000	-20	1240	1260	7020
5	RAGBU	11:44	63400	0.779	400	456	261/57	269	36000	-20	1240	1260	6620
6	MEVDU	11:46	63300	0.781	401	357	259/58	269	36000	-20	1240	1240	6540
7	MEVDU	11:56	62800	0.778	396	456	260/61	271	36000	-20	1240	1240	6120
8	BOSOB	12:00	62700	0.780	395	456	260/62	270	36000	-20	1240	1240	5960
9	BOSOB	12:10	62200	0.780	396	456	257/62	270	36000	-20	1260	1220	5520

For this sample flight performance observation the evaluation is based on the fuel used at different flight segments as the method indicates the comparison is shown in Table 4.3. The quantity of fuel is presented as remaining Fuel on Board (FOB) in kilograms.

Table 4.3: Comparison of Actual and Calculated FOB

Position	Actual FOB [kg]	Calculated FOB [kg]	Error [%]
DAVLU	7880	-	-
LADBU	7300	7251	0.67
GARPO	7070	7032	0.54
MEVDO	6540	6501	0.60
BOSOB	5960	5927	0.55

This inflight data were recorded several times for different flight routes and aircraft configurations, and sometimes for the same segments of the same route in opposite direction, where the flight level and the effective wind id different. It can be noticed from the collected data, which is recorded manually at a different time interval, that the actual FOB reading resolution is 10 kg or 20 kg in some cases but the APM can give a resolution of a fraction of kg, also, the actual wind is slightly variable within the same time interval of recording, all of these factors give differences in fuel quantity of about 50 kg but the error is still below 1% which is quite good for reliable estimation of aircraft performance from the developed APM.

4.2.2 APM Validation by using SQP

The other reliable source to validate the APM is the performance files for A320 provided by BADA at specific flight conditions for specific aircraft configuration. In this validation study, BADA provides the optimum economy cruise speed M_{ECON} for maximum range cruise MRC in a file called MRC OPT file, which contains some computed results of the optimal M_{ECON} in ISA conditions.

BADA provides a single coefficient called Weight Coefficient (CW) that combining several input parameters, namely the pressure ratio δ and instantaneous aircraft mass, as expressed in Equation 4.1, where m_{mref} is the reference mass for A320 which equals to 77,000 kg. The pressure ratio δ and CI are combined in a single function called Cost Index Coefficient (CCI), as shown in 4.1 Figure 4.4. This approach is very efficient as it combines different flight parameters in weight and cost index coefficient.

$$CW = \frac{m}{\delta \, . \, m_{mref}} \qquad 4.1$$

$$CCI = \frac{CI \, . \, LHV}{60. \, \delta. \, a \, .W_{mref}} \qquad 4.2$$

However, it was necessary to fit the values presented in the MRC OPT file, so, the CI values those corresponding to CCI=0.1044 and CCI=1.4242 at an altitude of 36000 feet were computed. The CCI values presented here are just samples of the data provided by BADA [22].

The economic speed M_{ECON} is computed for small intervals in the cruising phase by using SQP algorithm. SQP technique is selected to be the optimization method because it requires the least number of gradient evaluations iterations. depicts the flowchart of the optimization process. Equation 4.3 , Equation 4.4 and Equation 4.5 are used for the optimization process.

$$\min \ ECCF \qquad 4.3$$

$$C_L \leq C_{Lmax} \qquad 4.4$$

$$0 \leq M \leq 0.82 \qquad 4.5$$

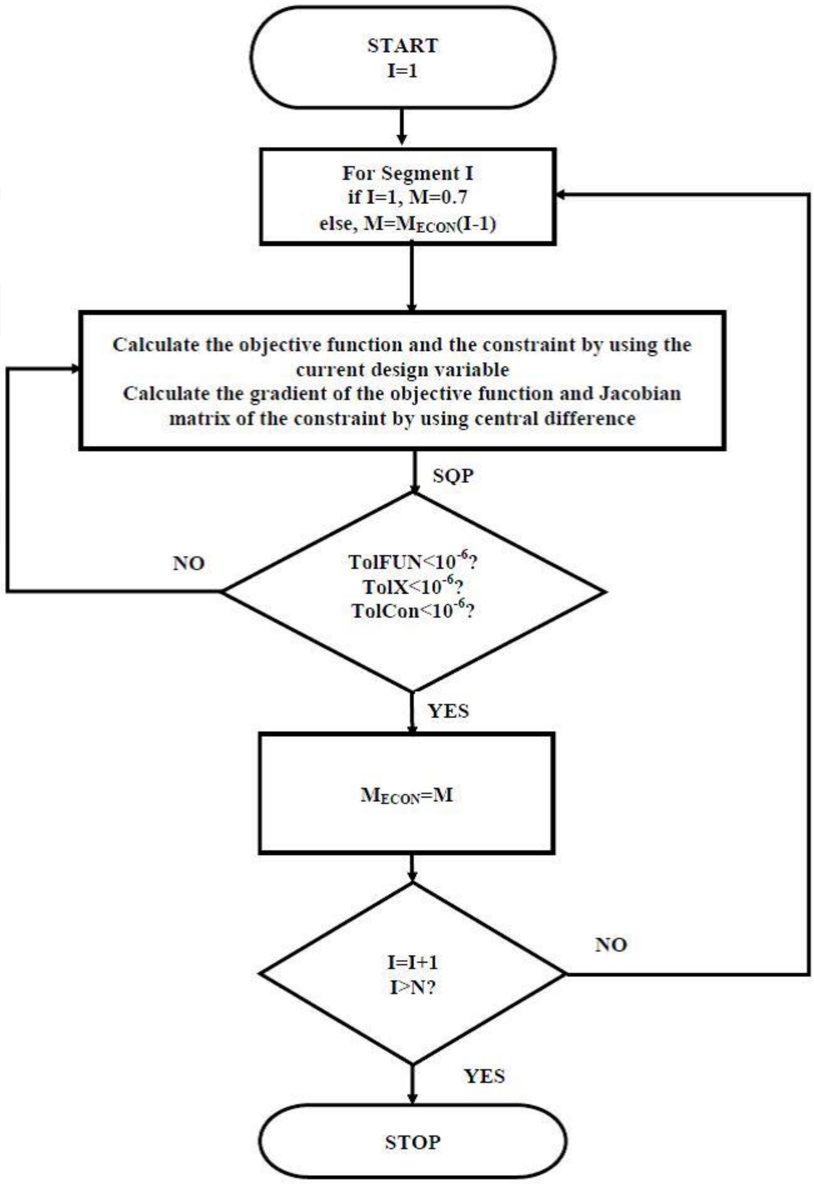


Figure 4.4: Algorithm flowchart of solving ECCF optimization problem

The previous optimization problem is applied to minimize ECCF function, so it is considered as the objective function for this system, the minimization is applied simultaneously for each small interval of the cruise as shown in Equation 4.3. As for any engineering problem some limitations must be considered, in this case the maximum lift coefficient C_{Lmax} limitation must be satisfied, is have to be greater than or equal the lift coefficient C_L under any flight condition, as shown Equation 4.4. The only design variable in this system is Mach number which is also subject to limitations, as shown in Equation 4.5, for A320 it is from zero to 0.82, for the optimization process the initial of Mach number for the first segment is selected to be 0.7 because it is expected to be close for the optimum value, as shown in Figure 4.5 Derivatives and constraints of the objective function are computed by central difference formula provided by the user. The optimizer terminates the iterations when the tolerance of the objective function (TolFun) and/or the variation in the design variables array (TolX) becomes smaller than 10^{-6} and the violation of the constraint (TolCon) becomes smaller than 10^{-6}. The indicated value of M in the flowchart satisfies the minimum value for ECCF which is M_{ECON}.

Once M_{ECON} of the first segment is obtained, the inputs of the next segment are defined. Then the new initial value of the next segment is M_{ECON} of the preceding segment. These techniques will significantly reduce the solution time.

The results show that, the maximum difference of M_{ECON} comparison of BADA and APM values for CCI is only around 0.5%.

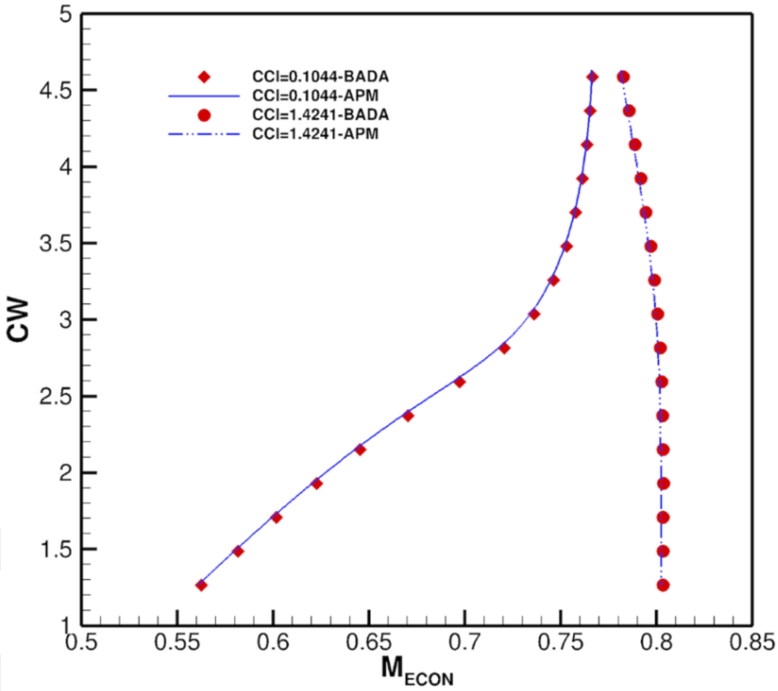


Figure 4.5: Comparison of CCI Values from APM and BADA

As shown in Figure 4.5 two values of CCI has been chosen, the first one is relatively low value 0.0144 at low CI in this MECON is very sensitive to variations of CW as presented in the FCOM, on the other hand at high CCI value of 1.4241 for high CI value M_{ECON} will be affected very little with changes of CW because at CI higher than 40 or 50 the change in M_{ECON} will be insignificant.

4.2.3 Validation by A320 FCOM

As an example for the model validation, the APM simulation is performed to compare the fuel consumption for a different aircraft weights at constant Mach number, M 0.78, ISA conditions, and cruising altitude of 35,000 feet (FL350), those flight parameters are chosen to be compared with published results from the FCOM of the same aircraft type [18] . As shown in Table 4.4 by comparing the amount of fuel flow per hour per one engine from FCOM and those obtained from the APM algorithm, it can be noticed that the maximum error is about 3% at light aircraft weights and it is about only 0.5% at heavy aircraft weights. This is good enough to give an accurate estimation of fuel consumption at different flight and weather conditions.

Table 4.4: Errors in Calculated Rate of Fuel Consumption at Different Aircraft Weights From FCOM and APM

Weight [1000 kg]	Fuel Flow [kg/hr/Engine]		Error %
	FCOM	APM	
54	1082	1049.752	3.07
56	1098	1067.115	2.81
58	1116	1086.965	2.60
60	1135	1108.390	2.34
62	1157	1131.570	2.20
64	1180	1156.725	1.97
66	1205	1184.125	1.73
68	1235	1214.075	1.69
70	1267	1246.940	1.58
72	1301	1283.175	1.37
74	1337	1323.310	1.02
76	1374	1368.005	0.44
78	1411	1418.065	0.50

CHAPTER 5

PARAMETRIC STUDY CASES

This chapter discusses the outcomes of the APM simulations for different flight conditions for the purpose of the model validation. The validation shows how accurate the results are compared with reliable data sources. Without validation of the model, the outcomes cannot be used as evident to give answers to an operational problem.

5.1 Study case 1: Effect of Temperature Variations on the Direct Operating Cost

The nominated parameter for evolution is the ambient temperature and its direct influence on the aircraft performance and hence the DOC. This study analyzes the direct effect of variable ambient temperature during the cruising for a relatively short domestic flight in Turley and how the results may affect the strategies and plans to perform optimal economic flights.

The flight scenario is a flight from Istanbul, Atatürk Airport (LTBA), to Hakkari, Yüksekova (LTCW). The total distance is 770 NM as shown in Figure 5.1 , [44] according to the route used by Turkish Airlines, including 600 NM for the cruising phase which is the phase considered in this study, the daily and seasonal average temperatures in both cities are shown in Table 5.1.

The average daily and seasonal variations in ISA deviations along the route are shown in

Table 5.2 [45].

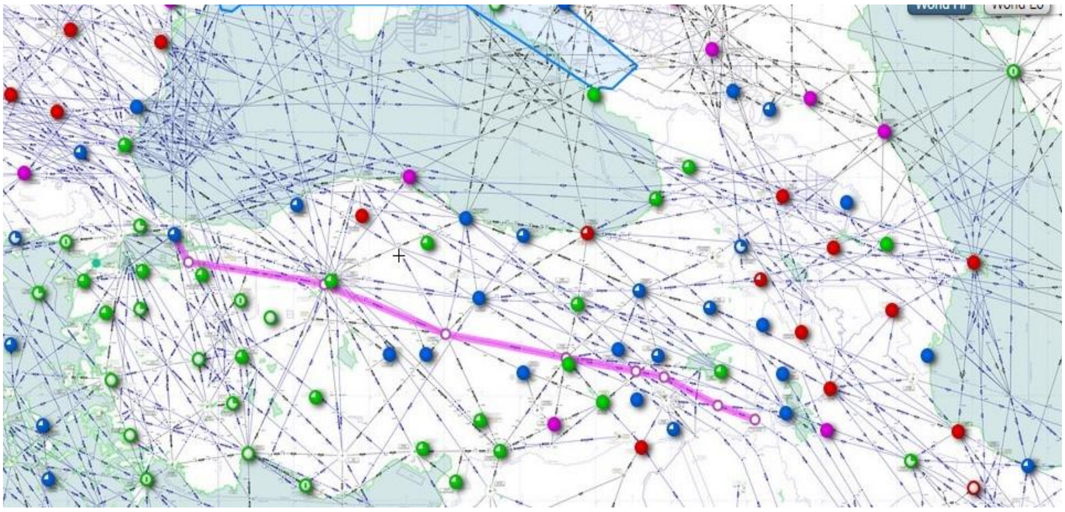


Figure 5.1: Route From Istanbul, Atatürk Airport (LTBA), to Hakkari, Yüksekova (LTCW).

Table 5.1: Daily and seasonal average temperatures at Istanbul and Hakkari

Airport	Elevation (feet)	Summer Temp (C°)		Winter Temp (C°)	
		Day	Night	Day	Night
LTBA	163	+26	+16.5	+8.4	+3.1
LTCW	6096	+38.8	+24.9	-0.4	-8.0

Table 5.2: Average ISA Deviations during the Flight

Enroute LTAB to LTCW	Summer Average ISA DEV (C°)		Winter Average ISA DEV (C°)	
	Day	Night	Day	Night
	+23.9	+11.9	-4.8	-11.3

The ISA deviations shown in

Table 5.2 Table 5.2 are used as a base of calculations for the daily changes in temperature, those values are used as an example for those deviations, any instantaneous values, if available, can be used as real changes occur on daily basis. The tropopause height is also considered in this case, at the tropopause the rate of decreasing temperature with increasing altitude is zero, hence laps rate LR is zero at that layer, which will result in constant ambient temperature.

An example of SWC is illustrated in Figure 5.2 [45]. The average values were used for this route are 29,000 feet in the winter and 35,000 feet in the summer.

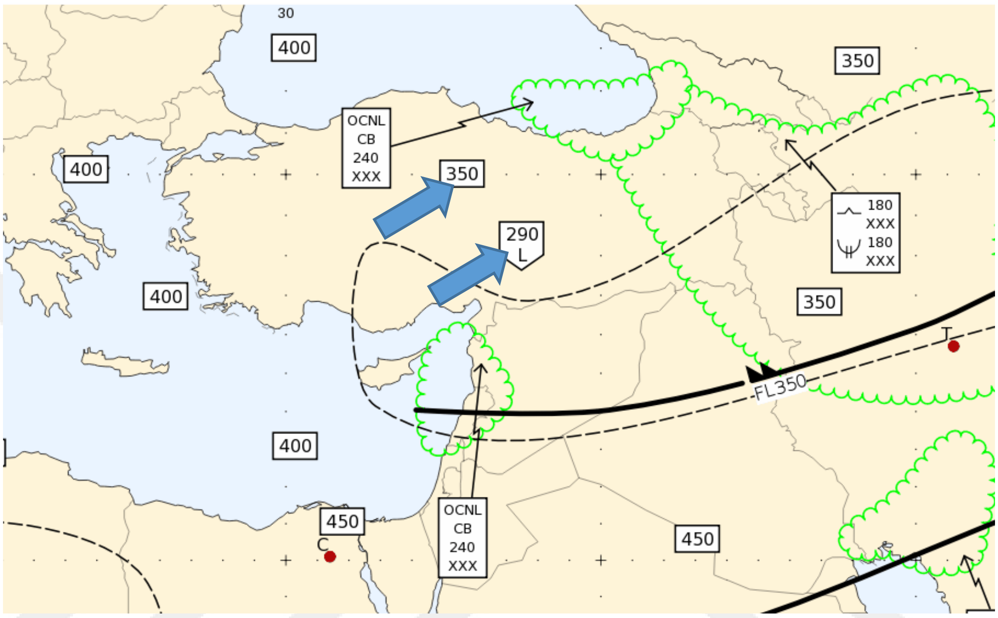


Figure 5.2: Weather Sectional Chart WSC

In this scenario, the aircraft gross weight at the top of the climb assumed to be 64 tons based on short route and 80% passengers capacity, the optimum altitude obtained from the APM is 37,000 feet and the cost index CI used is 15, which is the value recommended by Airbus for short and medium-range routes [15], [46], also it is the value used by THY for domestic flight during the time of conducting this study.

Airlines operating domestic flights in Turkey usually use cost index values between 15 and 20, which is estimated according to the airline estimation of its operating costs. By selecting 15 as a value for the cost index for this flight, the airline company declaring that the cost of one minute of operation is equivalent to the cost of 15 kg of fuel, in other words, 1 minute of flying costs the company about 10.5$, based on jet fuel price in December 2018 in Turkey, which is 0.7 $. It can be seen clearly that, the optimization of flight parameters, hence, M_{ECON} and optimum altitude are directly affected by the cost index used, which is estimated by the commercial department of the company by considering direct and indirect costs.

The effect of ISA deviations on the flight parameters such as the speed of sound, air temperature, and, air density are shown in Table 5.3. The pressure altitude H_P shown in the table is the optimum altitude for this flight scenario. The tropopause altitude is considered based on the average value in this region for both seasons, and as mentioned before it is obtained from the daily WSC reports.

Table 5.3: Effect of ISA Temperature Deviations on atmospheric parameters

ISA DEV [C]	Pressure Altitude [feet]	Tropopause Altitude [feet]	Air Temperature [C]	Air Density [kg/m3]	Speed of Sound [m/s]	Pressure [hPa]
23.9	37000	35000	-30.15	0.3137	312.50	218.84
11.9	37000	35000	-42.15	0.3286	304.69	217.87
0	37000	36000	-56.33	0.3480	295.19	216.64
-4.8	37000	29000	-47.26	0.3385	301.30	217.75
-11.3	37000	29000	-53.46	0.3420	297.14	215.49

The effect of ISA temperature deviations on the DOC of the flight can be expressed in terms of fuel saving in kilograms and time savings in minutes. For more comprehensive results the simulation is conducted for the daily changes in the summer and in the winter separately, as illustrated in Table 5.4.

Table 5.4: Cruise performance results in summer time

Summer	MECON	ISA DEV [C°]	Time [min]	Fuel [kg]
Day	0.7655	+23.9	77.42	2982.9
Night	0.7667	+11.9	79.27	2984.1
		Δ	+1.85	+1.2
		Total Δ cost = + 20.265 $		

In the case of the summer season, operating the flight at nighttime instead of the daytime, as seen in Table 6, will add 1.85 min to the flight time, and 1.2 kg of fuel even though the speed used is the economy speed ECON, which is calculated for every case separately, in total this will add 20.265 $ to the flight direct operating cost.

In the case of the winter season, as shown in Table 5.5, conducting the flight at nighttime where temperatures are lower, the flight time will be longer by 2.05 min and saving 4.0 kg of fuel, this will result in a total extra cost of 18.725 $.

Table 5.5: Cruise Performance Results in Winter Time

Winter	MECON	ISA [C]	Time [min]	Fuel [kg]
Day	0.7635	-4.8	80.50	2978.7
Night	0.7657	-11	82.55	2974.7
		Δ	+2.05	-4.0
		Total Δ cost = + 18.725 $		

It can be noticed from the results that, the effect of temperature variation on fuel consumption is very small due to flying at the optimum MECON at flight different conditions. However, the effect of changes in TAS plays a major role in changing the flight time for each case.

The algorithm calculates the total direct operating cost from the calculated cost of time and cost of fuel. According to this study case, the time cost is the dominant fraction of DOC, as it can be seen in Table 5.6 the total direct operating cost is calculated, showing clearly that the most affected fraction is the cost of time CT, while the cost of fuel CF is almost constant.

Table 5.6: Results of Total Direct Operating Costs

Season / Time		Time [min]	CT [$]	CF [$]	Total Cost [$]
Summer	Day	77.42	812.89	2088.1	2900.99
	Night	79.27	832.37	2088.8	2921.17
Winter	Day	80.50	845.32	2085.10	2930.42
	Night	82.55	866.77	2082.36	2949.13

For more clarification the differences in the cost of time CT at different daily and seasonally temperature variations are illustrated separately in Figure 5.3.

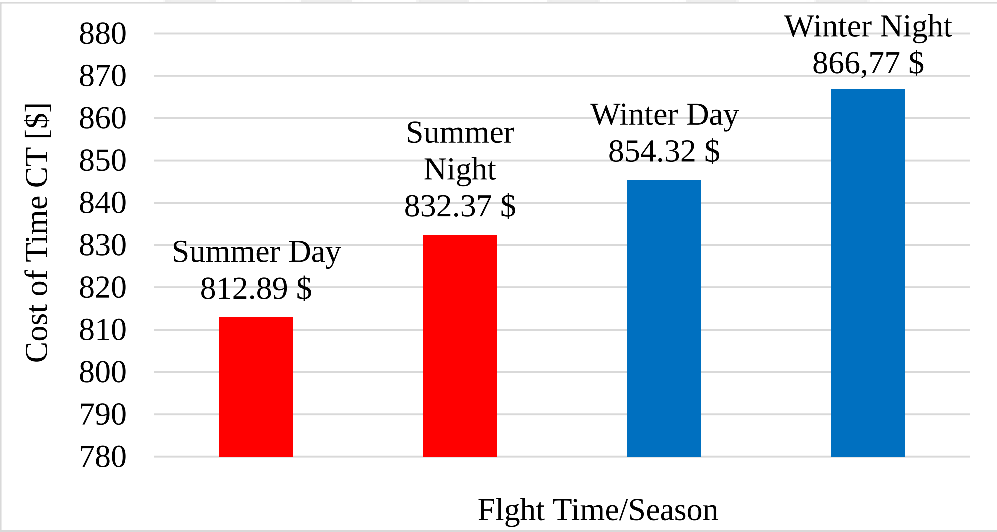


Figure 5.3: Cost of Time for Different Temperatures

To conclude this study case, it is found that, the estimations of flight cost is a complex process subjected to many parameters and variables. The most difficult factors to be estimated are those time-dependent factors that must be handled with great care and on daily and route bases.

This study case discusses the effect of one of the atmospheric dynamic parameters that play a major role in the airline's estimations of optimum flight performance and its impact on the strategic planning of flight scheduling and fleet management.

It can be observed from the results that, there is a significant effect of the temperature variations on aircraft cruise performance and consequently on the DOC of the flight. The main effect of temperature is on fuel consumption, calculations of the optimum speed, and the optimum altitude to be maintained. The other factor which is affected by the temperature is the endurance of the flight because of the direct effect of the temperature on the TAS at a constant Mach number, temperature deviation above ISA leads to higher TAS and consequently shorter flight time, and vice versa, in the case of temperatures lower than ISA.

From the flight scenario, it can be noticed that the effect of selecting the best time interval to operate the flight will have a direct effect on the DOC. In the summer season, for instance, flying during the daytime at the highest average temperature will save about 20$ per flight (one landing), than if the flight performed at night.

Assuming that an airline operating two daily flights on this route (four landings), this will be about 29,000 $ of savings per year.

In conclusion, the savings in this study case are in the cost of time but not in the cost of fuel, however, this is directly affected by the cost index chosen by the airline.

Finally, this study case aims to shed some light on the effect of temperature variations on the technical and economic performance of a flight. The results show significant variations on the direct operating costs, those can be used for better understating of the effect one of the atmospheric parameters on strategic flight planning for operating more efficient and optimum flights.

This study case is published in the Journal of Aeronautics and Space Technologies (JAST), under the title "Effect of Ambient Temperature Variations on the Direct Operating Cost of a Domestic Flight" [19].

5.2 Study Case 2: Effect of Weight Reduction on Minimization of Direct Operating Cost for an Airline

5.2.1 Background of Weight Reduction Strategies

This study case considers the minimization of the direct operating cost DOC of an airliner by applying small gross weight reduction techniques for an aircraft. This issue was motivated by the necessity to adopt new methods to reduce the operating costs by focusing on minor changes in the way of operating the aircraft; these minor changes could affect positively the overall annual evaluation of the costs due to its accumulative nature.

Airlines with large fleets or a large number of flights are continuously under pressure to reduce the cost which encourages imposing weight reduction strategies for cost-cuttings. Weight reduction strategies comprise for example design lighter and smaller seats, redesigning and reducing the number onboard lavatories, and reducing the weight of other equipment such as reducing the weight of its catering equipment, glassware kits, and trolley carts, etc., these measures can obviously reduce the gross weight of the aircraft.

One of the most famous stories (unconfirmed) is back to 1987, when American Airlines removed a single olive from each of its in-flight salads, resulting in reducing costs by about 40,000 $ a year, According to 1987 prices.

British Airways has assigned the task of weight reduction to the fuel efficiency team, which suggests reducing catering equipment weight and number and replace them with a lighter and smaller design, and choose to print in-flight magazine on a lighter type of papers.

United Airlines, the second largest airline in the US and the third in the world with 880 aircraft according to May 2019 figures, adopted the same approach to its in-flight magazine, saving only 28 grams per copy results in saving around 300,000$ a year

In order to provide an airline operating A320s with reliable figures about the potential savings from reducing few kilograms from aircraft weight the developed A320 APM is used to estimate fuel savings in terms of direct operating cost savings.

5.2.2 Weight Reduction Effect on DOC

The amounts of suggested weight reduction applied for this study case are from 1 to 50 kg with 5 kg step, in general, they are less than 0.07% of the gross weight of the aircraft. The effects of these tiny reductions are examined for Airbus A320-214 at different flight scenarios. The flight cases are classified into a short rage with 600 NM and long-range with 1800 NM.

The applied scenarios were resembled Pegasus Airlines to be used as an example to obtain more realistic results from the study case model. Pegasus use midsize jetliners fleet consists of Airbus 320 and Boeing 737 with a total of 81 aircraft and about 182,500 landing per year, which is about 500 landing per day, according to 2018 report [47]. The potential savings from those small amounts of gross weight reduction as calculated from A320 APM were assumed to be similar to those of the Boeing 737s fleet since both aircraft belonging to the same category and they are very similar in performance.

5.2.2.1 Effect of Weight Reduction on Short Route Flight Scenario

As mentioned earlier, The short route is assumed to be 600 NM for an aircraft maintaining 37,000 feet which are computed as the optimal altitude when the weight is 63 tons at the top of climb TOC (assuming 80% capacity), the optimum economy cruise is found to be M_{ECON} of 0.7673, and flight time is 81.89 minutes, all of the previous value was calculated by the APM code at standard ISA conditions.

The reduction in gross weight by infinitesimal fractions are presented in Table 5.7 the table shows the effect of weight reduction on DOC by amounts of 1, 5, 10 up to 50 kg.

Table 5.7: Effect of Small Weight Reductions on DOC in Short-range Cruise

ΔW [kg]	Fuel [kg]	Δ Fuel [kg]	DOC [$]	Δ DOC [$]	Annual Savings [$]
0	2997.95	-	3125.53	-	-
-1	2997.90	-0.05	3125.50	-0.03	-5471
-5	2997.74	-0.21	3125.37	-0.16	-29201
-10	2997.53	-0.37	3125.22	-0.28	-51101
-15	2997.32	-0.57	3125.06	-0.43	-78659
-20	2997.11	-0.78	3124.91	-0.58	-106946
-25	2996.90	-0.99	3124.76	-0.74	-135051
-30	2996.69	-1.20	3124.60	-0.89	-163154
-35	2996.48	-1.41	3124.45	-1.05	-191261
-40	2996.28	-1.61	3124.29	-1.20	-219364
-45	2996.07	-1.82	3124.14	-1.35	-247471
-50	2996.86	-2.03	3123.99	-1.51	-275576

The annual savings shown in Table 5.7 are based on the number of landing/year.

The results show clearly that the APM algorithm can compute the effect of a very small weight reduction of 1 kg from a total of 63 tons, which are accounted for less than 0.0016% of the total weight of the aircraft. It is also noticeable deducing few more kilograms from the aircraft weight results in more cost savings. From the results, reducing 50 kg from every flight may reduce the DOC by 275575 $ per year with the same rate of flights.

5.2.2.2 Effect of Weight Reduction on Long-Route Flight Scenario

In the case of the long-range cruise which is assumed to be 1800 NM with aircraft gross weight of 73 tons at the TOC (assuming 80% capacity), the computed optimum altitude is 35,000 feet, MECON 0.769. This study case assumes the fractions of weight reduction as of the short-range case. The results are presented in Table 5.8

Table 5.8: Effect of Small Weight Reductions on DOC in Long-Range Cruise

ΔW [kg]	Fuel [kg]	Δ Fuel [kg]	DOC [$]	Δ DOC [$]	Annual Savings [$]
0	10079.88	-	10198.31	-	-
-1	10079.76	-0.12	10198.21	-0.09	-16974
-5	10080.33	-0.62	10197.84	-0.47	-85046
-10	10079.71	-1.12	10197.37	-0.84	-153118
-15	10079.08	-1.75	10197.01	-1.31	-238346
-20	10078.46	-2.37	10196.44	-1.77	-323208
-25	10077.83	-2.99	10196.08	-2.23	-408253
-30	10077.21	-3.62	10195.51	-2.70	-493298
-35	10076.59	-4.24	10195.04	-3.17	-578343
-40	10075.96	-4.86	10194.58	-3.63	-663206
-45	10075.34	-5.49	10194.11	-4.10	-748251
-50	10074.70	6.11	10193.65	-4.56	-833113

It can be seen from a long-range cruise table of results, reducing just 1 kg from 73 tons aircraft can give savings of about 17,000 $/year, this is about triple the amount of savings form the short-range trip with the same amount of weight reduction.

The results show also the effect of different weight reductions, like in the short route trip, up to 50 kg. The annual savings are found to be 833,112 $/year, which is also about the triple of savings from short route conditions. It can be concluded from the results that long-range flights are affected by weight reduction than in short-range flights.

5.2.3 Conclusions of Airline Weight Reduction Strategies

From this study case, it can be obviously concluded that even with very small reductions in weight with a matter of few kilograms the effect on DOC is very significant.

This study introduces the significance of aircraft gross weight reduction. It is clearly found from the results that infinitesimally fraction of aircraft gross weight can affect the performance positively and reduce the cost on long term bases.

It can be observed from the results that longer-range flights are more sensitive to tiny weight reductions than from short-range flights due to the acquisitive nature of fuel savings, hence DOC, as a function of time and distance, even though the fraction of gross weight reduction is much smaller in a long route than in short routes.

It is highly recommended for future studies to suggest more practical methods for aircraft weight reduction and employing these methods with the help of APM and flight performance recorded data to minimize the DOC for more beneficial flights.

5.3 Effect of Cost Index on Optımizatıon of Economy Cruıse Speed for a Jet Airliner

5.3.1 Background of CI Effect on Optimal Flight Performance

In this study case, the effect of cost index on the optimization of economy cruising speed for a jet airliner is discussed. The motivation of the case came from a conflict in opinions in an airline about the permissibility of changing the CI during the long flights for time savings or based on the experience of some pilots from different airlines those adopting different policies. As expiated earlier the optimum speed and altitude are calculated instantaneously for the minimum value of economy cost index function ECCF as given in Equation 3.19. So the given value of the CI is the basic input for the FMC from which the Altitude and M_{ECON} are obtained. The given CI is of case-sensitive for economical flight operations because changing CI by the pilot before or during the flight will result in maintaining a speed different from the optimum value. The graphical optimization method is used and the data for the analysis was obtained by the APM, this method is found to suitable when there are one or two variables. Since the problem contains one variable the graphical optimization method is used for solving such optimization problems [48].

The suggested flight scenarios assumed at ISA conditions, no wind, given aircraft weight and cruising distance, to inspect the direct effect of different cost indices on selecting the optimum economy speed to minimize the trip DOC. The APM algorithm determines the optimum economy speed by computing the minimum value of the economy cruise cost function ECCF, which represents the minimal costs and fuel-burn. The results discuss also the penalties of using uncertain estimations of cost indices or violating them on the direct operating costs.

5.3.2 Effect of CI on Aircraft Performance

The APM algorithm is performed for different Airbus A320 flight scenarios to inspect the effect of CI on obtaining the optimum ECON speeds.

These optimum speeds were obtained based on different selected values of cost indices, starting with the minimum value for cost index, CI 0, which is equivalent to zero cost of time that can be achieved by flying at MRC speed, also the maximum value of cost index CI 99 is used, which is equivalent to LRC. The other cost indices used were CI 10, 15, 25 respectively; those values are laying in the most operational range for most of the A320s operators. For maximum accuracy of the results the algorithm calculates the change in aircraft weight at 10 NM segments, this is found to be the best value for the segments of calculations along the cruising phase, below which the resolution of the results are unaffected and the simulation will take a longer time for execution.

The effect of CIs is examined for two different scenarios based on the distance of the trip, 600 NM for a short distance, and 1800 NM for long distance.

5.3.2.1 Effect of Cost Index Selection on Short Route Flight Scenario

The considered short route selected for this scenario is 600 NM. This flight scenario is similar to a flight from Rome to Istanbul with about 600 NM of cruise distance with a gross weight of 64 tons (80% capacity) the optimum altitude is found to be 37000 feet at the top of climb TOC and at standard ISA conditions. As it can be seen from Figure 5.4 economy Mach number M_{ECON} is decreasing with progressing of cruise distance because of the reduction in aircraft gross weight because of fuel consumption.

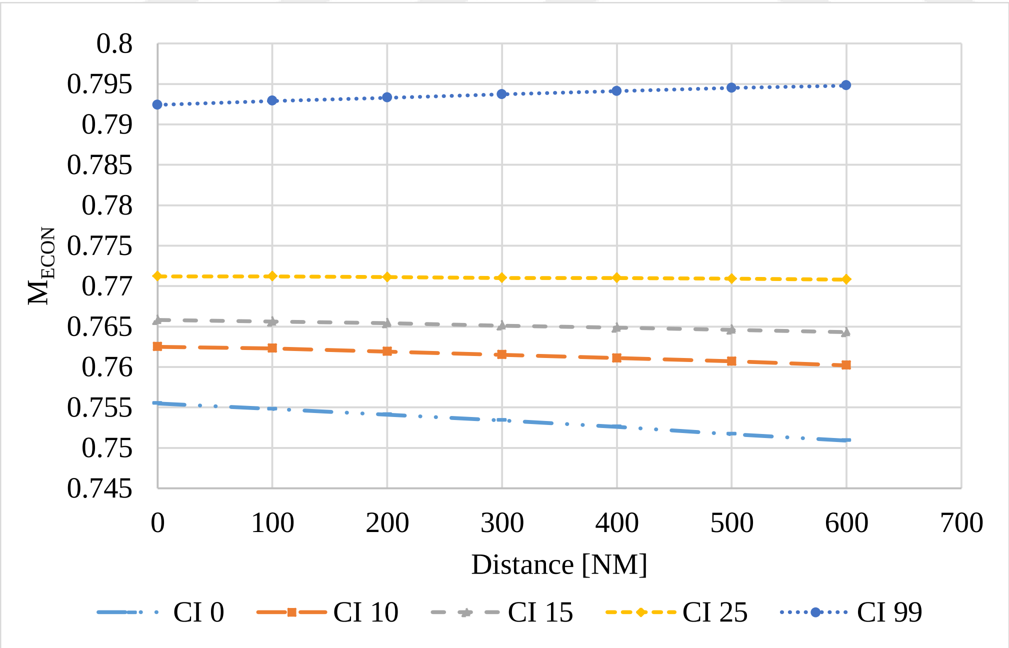


Figure 5.4: Short Cruise - Effect of CI on MECON vs Travelled Cruise Distance

It can be seen from the MECON trend at CI 0 that the speed is noticeably decreasing from 0.7545 at TOC to 0.7496 at TOD with an amount of 0.049 of Mach, this amount of speed reduction results from the tendency of the algorithm to seek for the minimum speed at minimum fuel consumption regardless the time cost which is considered to be zero in this case.

For the next three values of the operational cost indices 10, 15, and 25, the MECON at TOC is increasing with increasing CI value, however, the rate of decreasing MECON with the reduction in the aircraft gross weight is less, which is obtained to be only 0.0004 of Mach, that is because the time factor becomes more effective when selecting higher cost indices. In the last value for cost index which is CI 99 the maximum value that represents considering the value of time not the value of fuel, hence flying with the maximum possible speed, in this case, the MECON in increasing with the reduction of aircraft weight because the lighter the aircraft the faster it can fly.

5.3.2.2 Effect of Cost Index Selection on Long Route Flight Scenario

The suggested second scenario is the long-range cruise which is considered similar to a flight from Masqat to Istanbul at which the cruising distance is about 1800 NM, aircraft weight is 75 tons at the TOC, at different cost indices, initial altitude 34,000 feet, one step climb at mid-route, and final altitude 36,000 ft.

As shown in Figure 5.5, the optimum M_{ECON} at CI 0 is noticeably decreasing while the optimization is seeking for the minimum fuel consumption rates, then at the step climb, the MECON will jump to a higher value which is the optimum at the new altitude. In the case of the long-range cruise which is three times greater than the short distance the speed reduction is more noticeable as the fuel consumption for each segment of the cruise is more for long-distance.

Likewise, for the short route case, the effect of operational cost indices is checked where the MECOM rate of decreasing will be smaller as the CI value increase. The effect of using different CI's will be discussed in the following sections.

When the maximum CI is used (CI 99), the starting MECOM at the TOC is 0.7891 and at the TOD the speed will accelerate to 0.7964, the difference is 0.0073 of the Mach. According to Airbus [39], the speed of LRC which can be achieved by inserting CI 99 is maximum operating speed MMO-0.02, for the A320 family it is equal to M 0.80, according to the algorithm results the error in MECON is less than 1%.

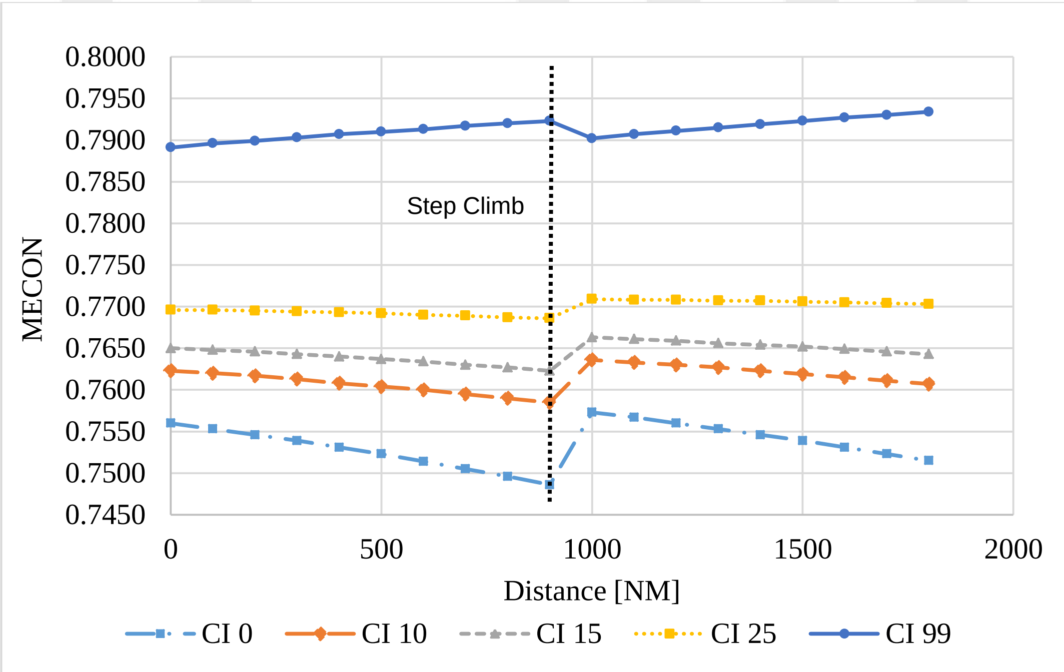


Figure 5.5: Long Cruise - Effect of CI on MECON vs Travelled Cruise Distance

5.3.3 Effect of Cost index on the Direct Operating Cost DOC

In this section, the effect of operational CI on the direct operating cost is examined for the short-range and long-range cruise. For a specific airline company, the adopted cost index is CI 15, the average cost of fuel is 0.75 $/kg (according to August 2019 prices in Turkey). Table 5.9 shows the DOC of using minimum and maximum CI where time is traded with fuel, based on the cost of time equals to 11.25 $/min.

The difference between extreme CI values shows that flying at Maximum LRC speed will results in 63.83 $ extra cost. The main focus here is when the pilot changes the CI to a lower or higher value than that adopted by the company, which is the case for many pilots where the CI is used as for speed control!

Reducing CI to 10 instead of 15 will result in saving 8 kg of fuel but adding 1 minute to the flight time with almost no change in the DOC while using CI 25 instead of CI 15 will result in losing 2.40 $, even those value are small values for a short-range flight, however, for a company operating hundreds of short flight daily the cost differences will be effective at the end of the year.

Table 5.9: Effect of CI on DOC in Short-range Cruise

CI	M_{ECON} @ TOC	M_{ECON} @ TOD	Fuel Consumed [kg]	Time [min]	DOC [$]
0	0.7545	0.7496	2967.0	83.09	3160.11
10	0.7625	0.7605	2969.6	82.12	3151.08
15	0.7658	0.7643	2975.0	81.62	3149.48
25	0.7712	0.7708	2987.0	81.01	3151.61
99	0.7924	0.7956	3133.0	78.50	3232.88

The graphical representation of the effect of CI on DOC in short route cruise is shown in Table 5.9, more points are shown in the graph than those presented in Figure 5.6, and those values are around CI 15 the value selected in this study case. The flat portion of the curve represents the operational values of CI which is used by most of airline companies.

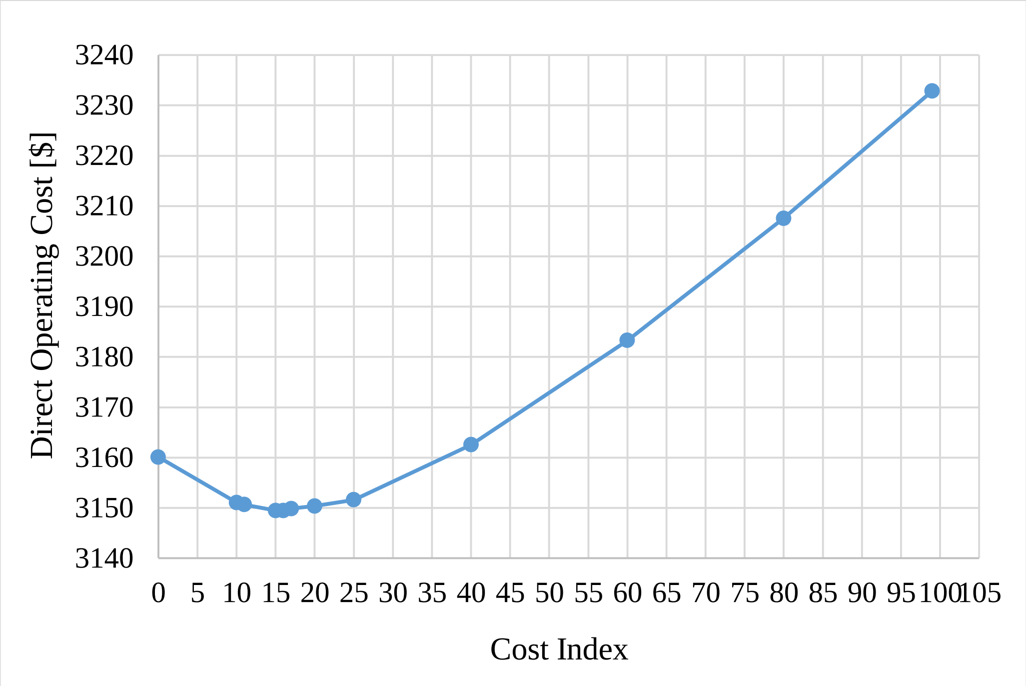


Figure 5.6: Effect of CI on DOC in Short-Range

In the case of long-range cruise the effect of CI is more significant, as shown in Table 5.10, the difference between extreme CI values is interestingly shows that flying with minimum speed will results in 236.8 $ extra cost. Reducing CI to 10 instead of 15 will result in saving 2.66 $ while using CI 25 will result in saving about 2 minutes but consuming 19 more kilograms of fuel as a result losing 2.51 $, those values are small values for long-range flights, however, for a company operating hundreds of long-range flights daily, the cost differences will be effective at the end of the year.

Table 5.10: Effect of CI on DOC in Long-range Cruise

CI	MECON @ TOC	MECON @ TOD	Fuel Consumed [kg]	Time [min]	DOC [$]
0	0.7559	0.7510	9957.6	249.48	10274.91
10	0.7623	0.7616	9967.5	246.01	10243.28
15	0.7650	0.7656	9983.4	244.72	10240.65
25	0.7696	0.7720	10027.0	242.69	10250.62
99	0.7891	0.7964	10517.0	235.26	10534.46

The graphical representation of effect of CI on DOC in long route cruise is shown in Figure 5.7, as for the short-range cruise case more points are shown in the graph than those presented in Table 5.10, and those values are around CI 15 the value selected in this study case the flat portion of the curve represent the operational values of CI which is used by most of the airline companies.

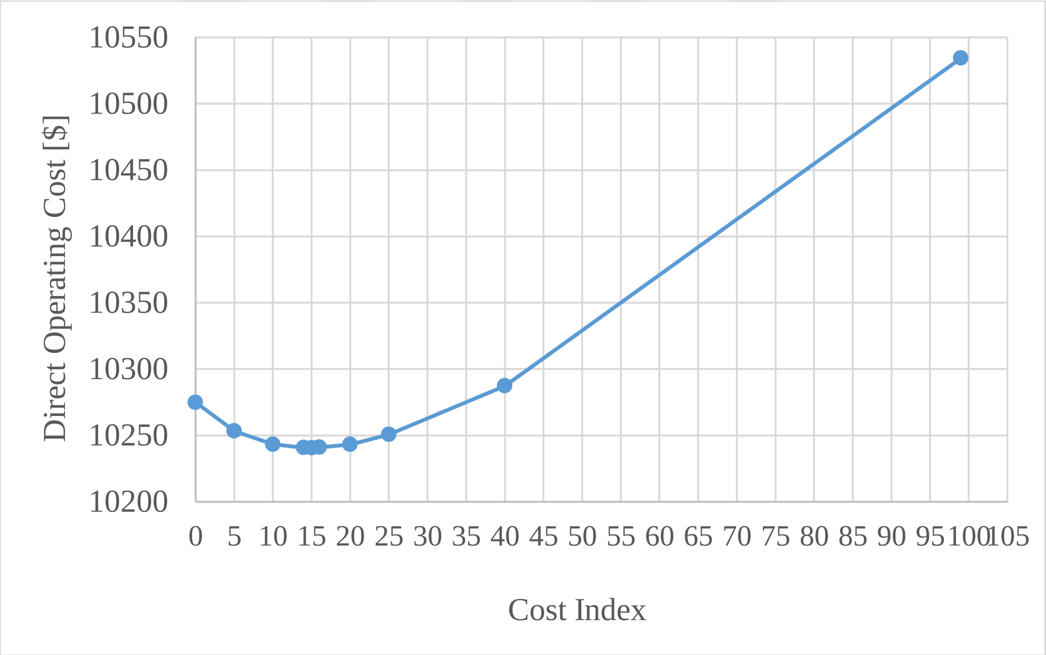


Figure 5.7: Effect of CI on DOC in Long-range

5.3.4 Conclusions of CI Effect on DOC

It can be concluded from this study case that the selection of cost index efficiently provides a flexible tool to manage flight time and fuel burn. Accurate calculations of the airline cost structure and operational priorities are essential for cost optimization to decide when to trade fuel with time or vice-versa.

The cost index and initial flight conditions such as the aircraft gross weight and weather conditions are the bases of aircraft performance calculations. The optimum performance of the aircraft gives minimum DOC by flying maximum economy speed M_{ECON} with less amount of fuel consumption in the shortest possible time. The optimum flight is that can maintain optimum altitude and optimum varying M_{ECON} along the route, those elements are not possible to be kept all the time due to ATC constraints, however, the flight crew is responsible to keep as close as possible to those values.

This study case aims to illustrate the importance of optimizing the cruising speed to perform the most economic performance of the trip. It is obvious that using different cost index to control the speed is absolutely misconception approach to control the speed of the aircraft, because of this is strictly not recommended by the manufacturer, especially when moving to higher CI values. the scenarios presented in this paper were real cases where there is a tendency from some pilots to increase the cost index attempting to save some time especially in long routes, the results were presented to some operator to figure out the penalties of increasing the cost index as a manner of time-saving which gives negative results which lead to strong recommendations to respect cost index values adopted by the company.

It is recommended for future studies to take into consideration applying more variables and constraints where more advanced optimization methods like the gradient-based method or evolutionary optimization methods can be considered.

5.4 Minimization of Aircraft Fuel Consumption Subjected to Arrival Time Constraint

This study case is considered as a complex operational case in which a flight is assumed to be under time constraints. In airline operations time is a very critical parameter to guarantee optimal and efficient outcomes, flights are required to arrive at their destinations at a specific time, this is called meet-time of arrival, which is one of the biggest challenges in daily issues for airline operation that have a direct impact on the direct operating cost DOC of airlines [49]. The operations department is responsible for the preparation of flight plans for each flight according to its conditions, the main task for the flight plane is to be economically efficient, however, in most of the time, the flight plan parameters are hard to be fulfilled accurately because of many reasons, such as weather conditions which cause the flight to be delayed because of diversions to avoid bad weather or in-ground delay due to slowing the traffic down for some technical considerations such as poor visibility or downgrading of approach assisting systems. Another cause of delay could be ATC operational constraints which force the traffic to use nonoptimal altitude or in some cases the speed because the priority is given for faster heavy aircraft. The delay can be also caused by restricting some airspace for some security reasons or due to airport congestion. In any of the previous probable cases and more, the flight crew will be urged to fly faster by the increasing speed which is higher than the managed optimal calculated speed.

Airlines consider arriving in time as not just to satisfy the passengers or the schedule, it is mainly meant to avoid the additional extra cost of delay consequences that could result from reasons such as the necessity to reconnect passengers who could miss their connection to other flights or accommodate them or missing the slot time of arrival which is already booked for the airline, etc. Delays might also interrupt traffic sequencing and scheduling in airports and make it much more costly and complex to be handled. [50].

As in the previous study cases, the same A320-214 APM is used and implemented into the SQP algorithm of MATLAB optimization toolbox as a function evaluator.

This study case discussed the effect of increasing the speed of aircraft to meet-time of arrival and to give an answer to the flight operators, about if the penalty of the delay is less or more the extra cost of fuel paid due to flying faster.

The management of time and fuel is the basic task of the APM, performance calculation depends on flight parameters like weight, range, cost index, and the altitude. The APM optimization algorithm is performed to compute changes in DOC with meet-time of arrival conditions. This will give great support for flight planning under time constraints conditions where the proper speed and altitude is supplied from the APM.

5.4.1 Applying SQP for Fuel Consumption

The SQP optimization algorithm is applied for different aircraft configurations in the cruise phase. The flight parameters are chosen to be similar to specific flight scenarios.

The suggested flight scenarios are dealt with as an optimization problem that is subjected to the minimization of fuel consumption in the case of constrained meet-time of arrival. The minimization of fuel quantity FQ is related to fuel flow FF expressed ECCF, Equation 3.19) which is minimized as well.

The objective function for minimizing fuel consumption is given in Equation 5.1. The required meet-time of arrival constraint (E_{dem}) is implemented in the optimization problem from Equation 5.2. The C_{Lmax} limitations are given in Equation 5.3. Equation 5.4 represents the limits of the operational altitude that is considered constant during the cruise. Equation 5.5 shows the limits of altitude and M, respectively.

$$\min \ FQ \tag{5.1}$$

$$E \leq E_{dem} \tag{5.2}$$

$$C_{Li} \leq C_{Lmaxi} \tag{5.3}$$

$$0 \leq h \leq 39600 \text{ ft} \tag{5.4}$$

$$0 \leq M_i \leq 0.82 \tag{5.5}$$

One should notice that Equation 5.3and Equation 5.5 the i index represents the number of the individual segments for recalculation. The dimension of the optimization process depends on the number of i index. The optimization problem has i+1 number of inequality constraints and i+1 number of design variables.

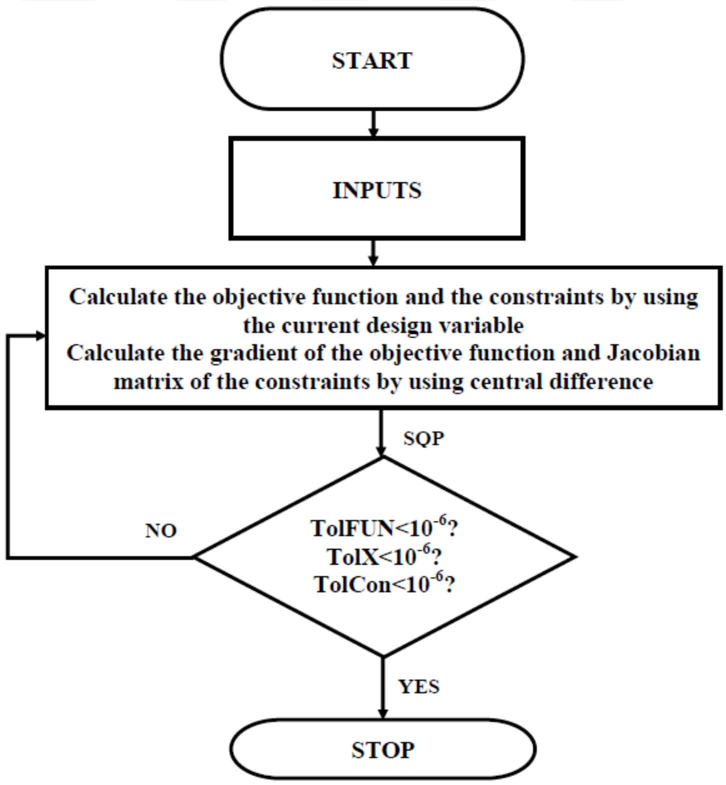


Figure 5.8: Flowchart for Minimum Fuel Quantity Optimization.

The SQP algorithm flowchart of minimal fuel quantity optimization is presented in Figure 5.8. The optimizer considers the same termination criteria of the validation optimization problem. The initial value for M is 0.7 and the initial altitude value is 36000 feet are chosen based on the expected values for such flight conditions.

The SQP algorithm optimal results are present the initial population for the genetic algorithm and the optimization problem illustrated in Equations Equation 5.1 and 5.5 are solved and satisfied.

The results show no changes in the objective because of this it have been found that SQP method is well satisfied analysis of the results.

5.4.2 Optimization of Speed and Altitude

The study cases are categorized based on the length of the cruise phase distance. The selected distances are 500 NM for short-range and 1250 NM for long-range. For these cases, three different gross weights have been selected, which are 64000 kg, 67000 kg, and 70000 kg respectively, CI 20 is selected for all cases (Airbus, 1998). The study cases are tested for no time-constraints operations and time-constraints operations to evaluate the effect of time constraints of the DOC.

5.4.2.1 No-time Constrained Condition

In no time-constraint case Equation 5.3 is omitted, the operating condition considers flying with minimum fuel consumption only for maximum range cruise MRC condition. The speed and the altitude were optimized for each segment for minimal fuel consumption. The results in Figure 5.9 (a) shows that the fuel consumption decreases is directly proportional with the weight reduction. Also from Figure 5.9 (b) as illustrated the optimum altitude increases with the weight reduction due to the reduction in fuel weight. It should be taken into consideration the obtained optimum altitudes the operational altitudes are not the same. The operational altitude is known as the recommended altitude and calculated the aircraft flight management system (FMS), which is assigned according to ATC flight rules, which is rounded to the nearest 1000 feet.

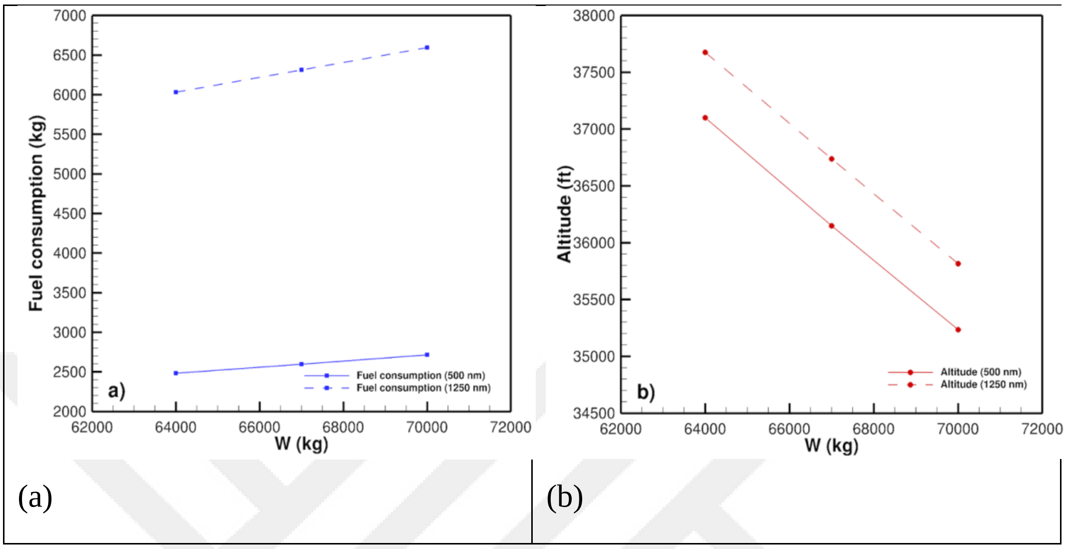


Figure 5.9: a) Effect of Weight and distance on Fuel Consumption, b) Effect of Distance, and weight on the Optimum Altitude.

The cruising phase endurances are calculated 500 NM and 1250 NM at three different gross weights 64, 67, and 70 tons respectively, shown in Table 5.11 It can be seen from the results the differences in the cruising endurance is very small because the time is calculated for each case at its corresponding optimum altitude as shown in the table.

Table 5.11: Calculation of Endurance and Optimum Altitude at Different Gross Weights and Ranges

Range [NM]	Gross Weight [kg]	Optimum Altitude [feet]	Endurance [second]
500	70000	35233.8	4152.0
	67000	36152.0	4167.8
	64000	37103.1	4166.8
1250	70000	35817.6	10412.6
	67000	36727.3	10424.9
	64000	37677.9	10425.2

5.4.2.2 Short-range Time Constrained Condition

In the short-range case of 500 NM, The results from the time-constrained condition are plotted in Figure 5.10 in this case the fuel consumption is calculated based on a specific optimum speed for the suggested weights. The obtained optimum altitude is less than the altitude for no time constraints case because the true airspeed is higher regardless of the amount consumed fuel. The time constrained condition is plotted in Figure 5.10 (a), in this, case the fuel consumption is increased because of flying at a higher speed. Figure 5.10 (b) shows the optimal altitude for 64000 kg weight is almost identical in constraint and non-constrained time because the optimal altitude is above 37000 feet so it is in the tropopause layer which is assumed to be 36,000 feet according to the algorithm because any increase in Mach number will be accompanied with an increase in true airspeed.

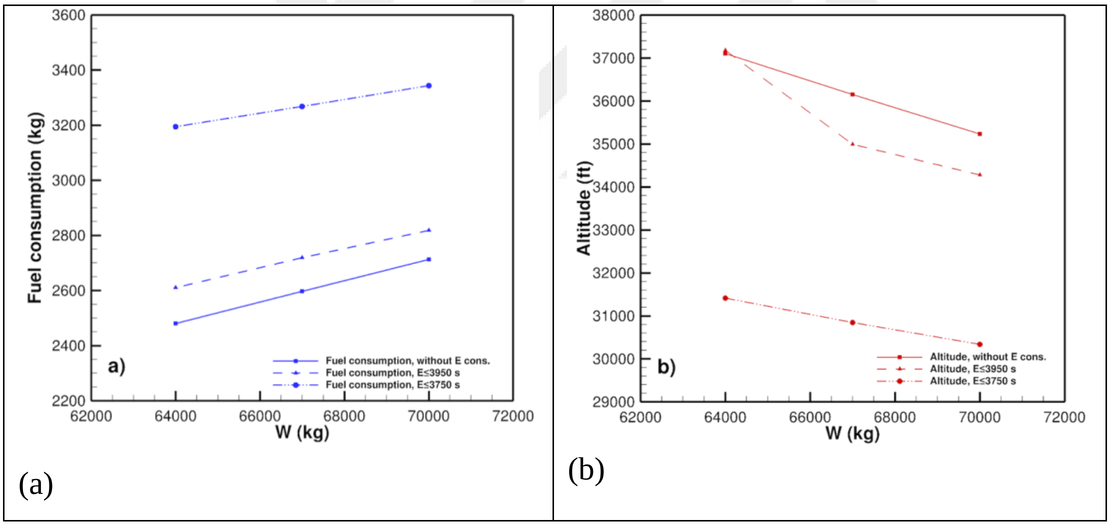


Figure 5.10: a) Effect of Endurance and Weight on Fuel Consumption in 500 NM Range, b) Effect of Endurance and weight on Optimum Altitude in 500 NM range

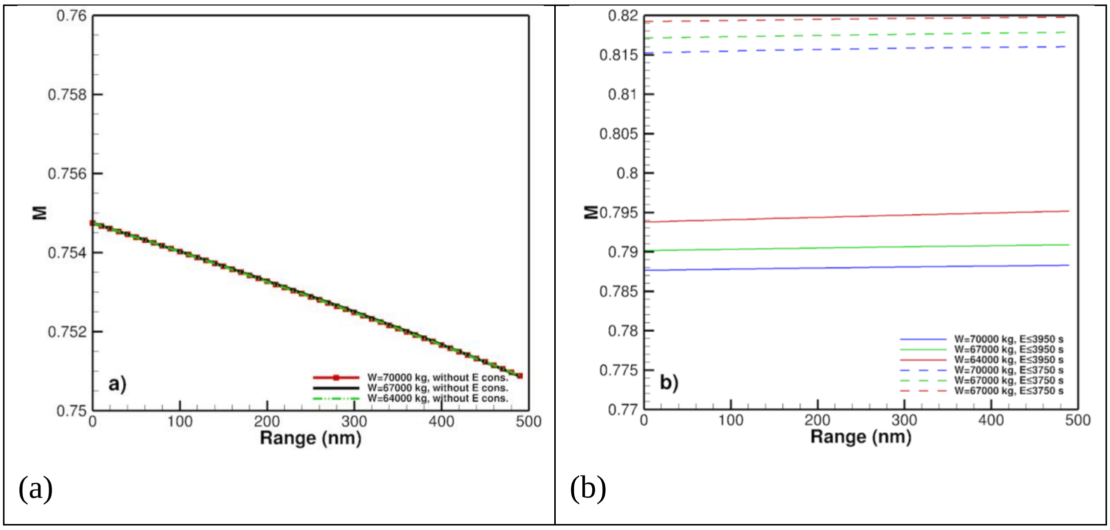


Figure 5.11: a) Effect of Range, Endurance, and Weight on Optimal Mach Number for no Time Constraints in 500 NM cruise b) Effect of Range, Endurance, and Weight on Optimal Mach Number With Time Constraints in 500 NM cruise

In the condition of normal flight operations without any time constraints, the optimum Mach number is, as expected, noticed to be slightly decreasing as the aircraft weight gets lighter with time because fuel consumption, as illustrated in Figure 5.11 (a). Contrary, the Mach number is slightly increased when the time is constrained, as shown in Figure 5.11 (b). The reason for a noticeable increase in Mach number is due to flying at a lower altitude that the optimum at which a higher true airspeed can be achieved. In 3750 seconds case at 64000 kg weight, the Mach number is close to the maximum limit which is M 0.82 at the end of the cruise range. On the other hand, the true airspeed TAS will be almost constant but with less fuel consumption.

5.4.2.3 Long-range Time Constrained Condition

In the long-range case of 1250 NM with constrained time higher variations in the amount of fuel consumption are noticed. The inspection of the effect of flying under time constraints conditions is performed at two constrained endurances which are assumed to be met, which are 10000 seconds and 9500 seconds respectively. The results are illustrated in Figure 5.12, the optimum altitude for meet-time of arrival case has shown a similar tendency of the short-range case but with a significant decrease in the optimal altitude as a result of higher speed, the rate of reduction in altitude increases with higher gross weight to achieve the required speed of the given meet-time of arrival case. As a result, the fuel consumption increases in higher gross weight and reducing altitude.

The effect of increasing cruise speed in long-range cruise of 1250 NM is plotted in Figure 5.13. In no time constraints case, the optimum Mach number is slightly decreasing with gross weight as a result of fuel consumption as expected, however, when the arrival time is constraints it is slightly increasing, because at lower altitudes a higher true airspeed can be achieved for the same value of Mach number.

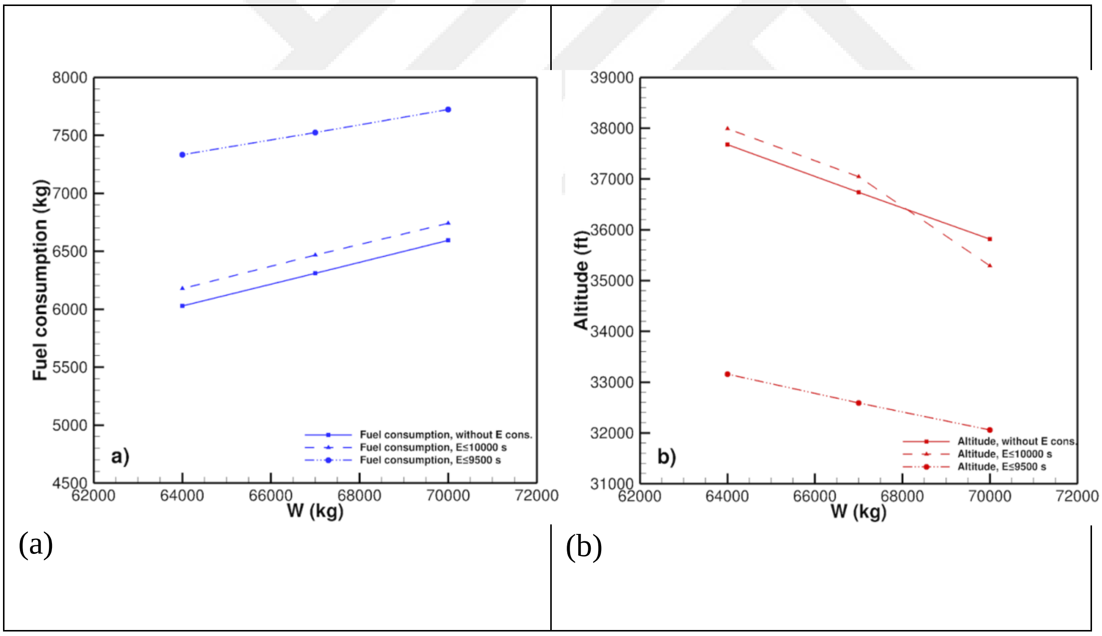
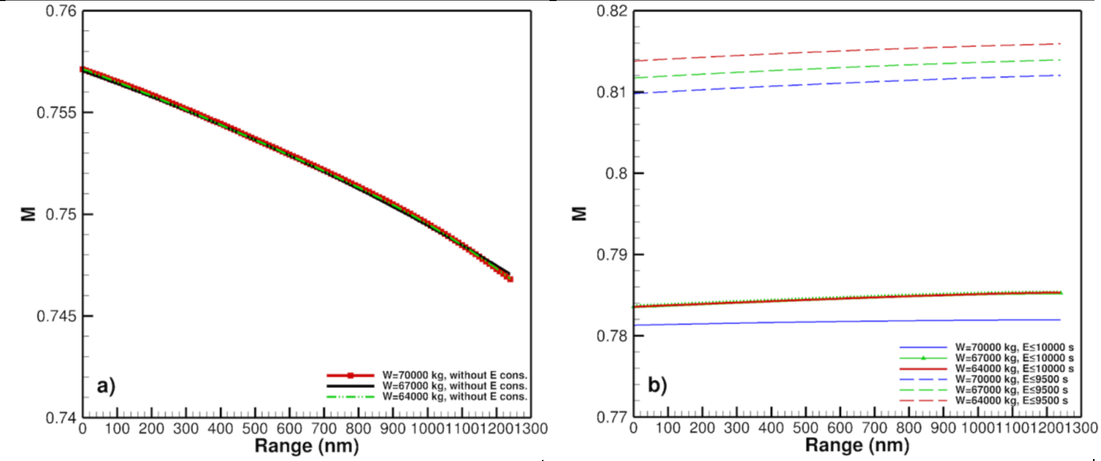


Figure 5.12: a) Effect of Endurance and Weight on Fuel Consumption in 1250 NM Range, b) Effect of Endurance and weight on Optimum Altitude in 1250 NM range



(a) (b)

Figure 5.13: a) Effect of Range, Endurance, and Weight on Optimal Mach Number for no Time Constraints in 1250 NM cruise b) Effect of Range, Endurance, and Weight on Optimal Mach Number for With Time Constraints in 1250 NM cruise

5.4.3 Optimization of Direct Operating Cost

The economic management of an airline that deals with daily flight operations is directly connected to the direct operating cost DOC. In the case of the restricted meet time of arrival, the cost of time is under focus as it could cause more losses than the extra fuel burnt, because of this, the DOC is minimized by the optimizer and then expressed in terms currency, if the minimal DOC value is found to be less than the potential cost penalty the aircraft must fly the speed that satisfies the meet time of arrival, on the other hand, if DOC is found to be greater than the potential additional cost from the delay, in other words, the additional fuel cost is greater than the cost of time delay then it is better not to consider the meet time of arrival time. As it can be interpreted the optimization algorithm is a very supportive tool for decision making for such flight operations.

5.4.3.1 Effect of Time Constraints on DOC for Short-range Flight

The costs of short-range condition of are illustrated in Figure 5.14, the cost of fuel is presented in Figure 5.14 (a) for the two time-constrained cases and for non-constrained cases, as expected the cost of fuel is increasing with higher aircraft gross weight and those higher weight force the aircraft to maintain lower altitudes where the fuel consumption is higher. It can be noticed also that the value of no time constraints and the values for 3950 seconds constrained time are closer in values because the difference in endurance is about 200 seconds for different weight configurations, which gives very close values in fuel consumption cost.

In Figure 5.14 (b), the DOC cost is presented as a function of aircraft weight for the same previous cases which shows clearly the cost of flying at any of the potential cases and which one can be beneficial for the airline.

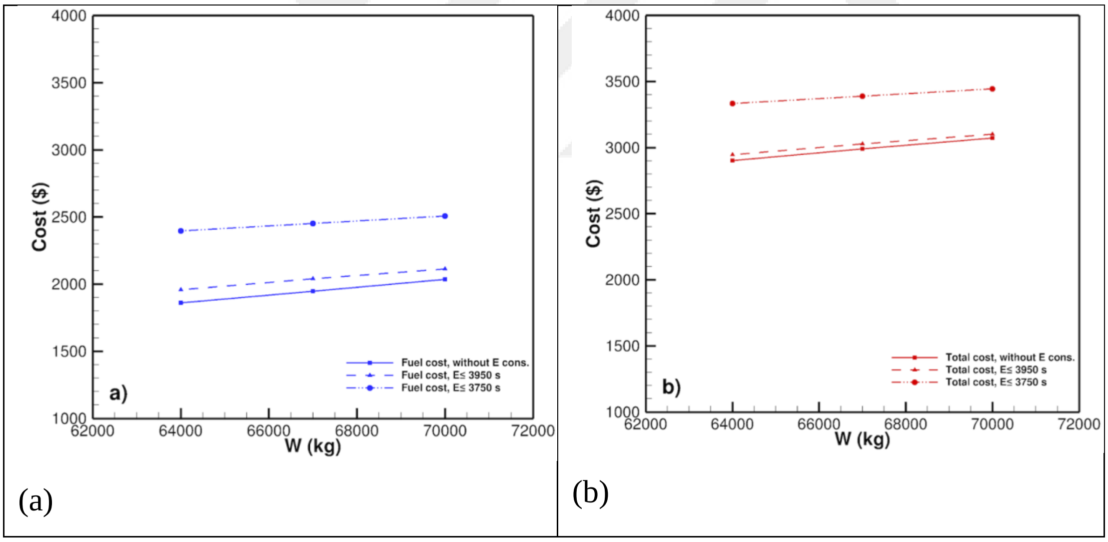


Figure 5.14: a) Effect of Weight and Endurance on Cost of Fuel in 500 NM Case, b) Effect of Weight and Endurance on Direct Operating Cost in 500 NM Case

The tabulated values in Table 5.12 show the variations in DOC between normal flight without any time constraints and another flight subjected to time constraints of 3950 seconds. The table presents details in the form of differences in the fuel consumed, cost of fuel, endurance, cost of time, and the DOC. The DOC values are related to the gross weight. The major portion of added cost is found to be 43.52 $ at the lowest tested weight of 64000 kg because the aircraft is flying lower altitude that the optimum so the fuel consumption and cost were slight.

Table 5.12: Effect of Constraint (E≤ 3950s) on DOC for 500 NM Range

Range [NM]	Weight [kg]	Δ Fuel [kg]	Δ CF [$]	Δ E [second]	Δ CT [$]	Δ DOC [$]
500	70000	105.002	78.75	-202.0	-50.5	28.24
	67000	122.110	91.58	-217.8	-54.4	37.12
	64000	130.314	97.73	-216.8	-54.2	43.52

In the case of 3750 seconds time-constrained, the difference between normal flight and the constrained flight is about 400 seconds for the different gross weights conditions, the shorter time force the aircraft to fly faster results in higher fuel consumptions and cost, contrary saving in the cost of time, however, it is not beneficial to trade it for higher fuel costs. The results show added value to DOC with about 431.24$ in 64000 kg weight condition, as presented in Table 5.13

Table 5.13: Effect of Constraint (E≤ 3750s) on DOC for 500 NM Range

Range [NM]	Weight [kg]	Δ Fuel [kg]	Δ CF [$]	Δ E [second]	Δ CT [$]	Δ DOC [$]
500	70000	629.95	+472.46	-402.0	-100.50	+371.95
	67000	670.61	+502.96	-417.8	-104.45	+398.50
	64000	713.93	+535.44	-416.8	-104.20	+431.24

5.4.3.2 Effect of Time Constraints on DOC for Long-range Flight

In the 1250 NM distance case, the effect of increasing speed on the DOC is more significant because the added cost is accumulated as a function of endurance because it takes longer cruise time and it is also a function of the assumed fight configuration and the criteria of time constraints. Table 5.15 (a) illustrates the fuel cost as a function of gross weight, the trend is almost the same for short-range cruise case. Table 5.15 (b) presents the DOC values for 9500 seconds and 10,000 seconds time constraints and for the normal flight case without time constraint. In both cases of constrained time, the cost tends to increase because the fuel consumption is also increased as the speed getting higher to cope with the time of arrival.

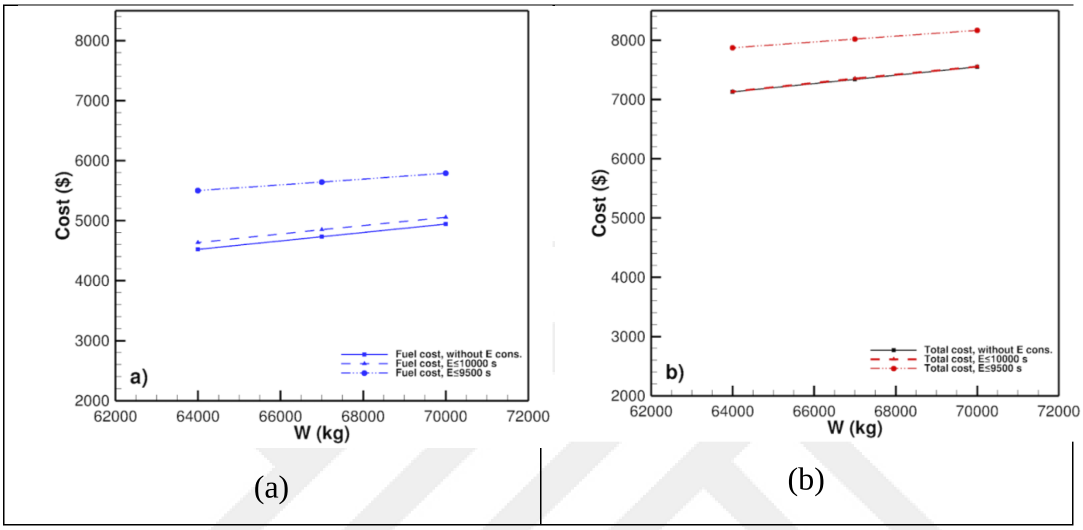


Figure 5.15: a) Effect of Weight and Endurance on Cost of Fuel in 1250 NM Case, b) Effect of Weight and Endurance on Direct Operating Cost in 1250 NM Case

In the long-range cruise case the numerical values of differences between no time constraint cases and 10000 seconds cases are presented in Table 5.14. The saving of about 400 seconds from the flight time gives a small increase in the DOC (from 6 to 12 $ based on the weight), in this case, the cost of fuel is increased bot the cost of time is reduced, the results of DOC as seen from the table is positive, it means there is an extra cost added. Now the company can decide if it is worthy to fly faster with those additional costs compared with the cost that can result from the delay.

Table 5.14: Comparison of DOC at Time Constraint (E≤ 10000 s) and Normal flight at Different Weights in Longe Cruise Case.

Range [NM]	Weight [kg]	Δ Fuel [kg]	Δ CF [$]	Δ E [second]	Δ CT [$]	Δ DOC [$]
1250	70000	+147.81	+110.86	-412.64	-103.16	+7.69
	67000	+157.40	+118.05	-424.93	-106.23	+11.81
	64000	+150.35	+112.76	-425.21	-106.30	+6.46

In the case of 9,500 seconds, time constraints condition the aircraft must flu faster to cope with the programmed time of arrival. This case is tested as the previous ones at different aircraft gross weights, as presented in Table 5.15, the results show higher fuel consumptions, in this case, it is not worthy to trade 747 $ of fuel cost for 231$ of time cost, the fuel cost is much higher than the value of time. However, it is not clear how much penalties could be paid because of this delay, if the airline using an active system to know about those potential costs in real-time then the decision will be much easier.

Table 5.15: Comparison of DOC at Time Constraint (E≤ 9500 s) and Normal flight at Different Weights in Longe Cruise Case.

Range [NM]	Weight [kg]	Δ Fuel [kg]	Δ CF [$]	Δ E [second]	Δ CT [$]	Δ DOC [$]
1250	70000	1129.41	847.06	-912.64	-228.16	618.90
	67000	1214.33	910.75	-924.93	-231.23	679.52
	64000	1304.48	978.36	-925.21	-231.30	747.06

In all previous scenarios the best decision to be considered based mainly on the amount of added value to the DOC when attempting to arrive at the destination at a predetermined time to avoid or minimize the delays penalties.

5.4.4 Flight Operations with Time and Altitude Constraints

From an airline operations perspective, the optimal altitude is hard to be maintained most of the times due to air traffic control regulations. The suggested scenario is very usual in real flight operations, in this case, the aircraft is obliged by ATC to maintain 36000 feet along the 1250 NM of cruise range, the suggested gross weight at the beginning of cruise hence, at top of climb is assumed to be 67000 kg. The algorithm computes the optimal speed that minimizes the fuel consumption at the given altitude. To compare the differences the optimal altitude is also computed for the case of ATC rule are not applied or they are very flexible, the optimum altitude obtained is 36727.4 feet.

The differences in DOC for flying off-optimal altitude are presented in Table 5.16. The difference in altitude of only 727 feet can increase DOC by 23.10 $, assuming the airline making 1500 flight per day it will cost it more than 30,700 $ per day.

Table 5.16: Effect of Optimum Altitude on Direct Operating Cost

Altitude [feet]	Fuel Consumed [kg]	Endurance [second]	CF [$]	CT [$]	DOC [$]
36000	6321.15	10477.5	4740.70	2619.37	7360.07
36731.1	6310.04	10423.2	4731.17	2605.80	7336.97
Δ= -731.1	Δ= +11.01	Δ= +54.3	Δ= +7.57	Δ= +13.57	Δ= +23.10

The importance of maintaining the optimum altitude is introduced in the results in the form of a direct effect on the DOC. The results are analyzed for a flight operated under a time-constrained case of 10,000 seconds. As shown in Table 5.17, the given altitude is constrained at 36,000 feet which must be kept unchanged during the cruise, and the optimum altitude according to case inputs is 37040 feet which are higher lower than the constrained altitude by about 1040 feet. The results show flying at an altitude 1000 feet below the calculated optimal altitude adds about 17.23$ to DOC for this flight.

Table 5.17: Effect of Optimum Altitude on Direct Operating Cost for 10000 Second Time Constraints

Altitude [feet]	Fuel Consumed [kg]	Endurance [second]	CF [$]	CT [$]	DOC [$]
36000	6489.98	10000	4867.43	2500	7368.41
37040.5	6468.04	10000	4851.28	2500	7351.18
Δ= -1040.5	Δ=+ 22.04	Δ = 0.00	Δ= +17.23	Δ = 0.00	Δ= +17.23

In the third case, the constrained time of arrival is assumed to be 9500 seconds at 36000 feet, as shown in Table 5.18, the computed optimum speed is increased to conform to the specified constrained arrival time. The algorithm gives a warning for violating of A320 maximum operating speed (MMO) which is Mach 0.82 however the algorithm will allow MMO speed but not beyond it, as a result, the flight time required cannot be satisfied, as seen from the results the minimum time can be achieved in 9563.9 seconds instead of 9500 seconds, but for the optimum altitude which is obtained according to this time constraint, the endurance is less than 9500 seconds. The results can be summarized as, flying 3407 feet above the optimum altitude adds 120 kg of fuel consumption and about one minute to the flight those results in an extra 120.59$ added to the DOC which accounts for about 1.5% more cost than flying the optimum parameters.

Table 5.18: Effect of Optimum Altitude on Direct Operating Cost for 9500 Seconds Time Constraints

Altitude [feet]	Fuel Consumed [kg]	Endurance [sec]	CF [$]	CT [$]	DOC [$]
36000	7665.66	9564.7	5749.29	2390.95	8139.49
32592.7	7525.17	9500.0	5643.85	2376.00	8019.87
Δ= +3407.3	Δ=+140.49	Δ= +64.7	Δ= +105.44	Δ= +16.95	Δ= +119.62

It can be concluded from previous cases that the differences in DOC value are very much affected by the margin of optimal values for speed and altitude, and how close can be are the aircraft to those values. In general, each flight scenario must be analyzed according to the available inputs and according to the expected outcomes so that the results can be useful to help for conducting more economically efficient flights.

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Concluding Remarks

This research focuses on the strategies adopted by airlines to reduce direct operating costs via developing an aircraft performance mathematical model to simulate the effect of different flight conditions of A320 on general performance and minimizing direct operating costs by optimizing cruise speed and altitude.

The estimation of flight cost is found to be a complex process subjected to many parameters and variables. The most difficult factors to be estimated are those time-dependent factors that must be handled with great care and on daily and route bases.

In the first study case this research analyses the effect of one of the atmospheric dynamic factors that play a major role in the airline's estimations of optimum flight performance and its impact on the strategic planning of flight scheduling and fleet management.

It can be observed from the results that, there is a significant effect of the temperature variations on aircraft cruise performance and consequently on the direct operating costs of an airline. The most significant effect of temperature is on fuel consumption, calculations of the optimum speed, and the optimum cruising altitude. The other factor which is affected by the temperature is the endurance of the flight because of the direct effect of the temperature on the TAS at a constant Mach number, temperature deviation above ISA leads to higher TAS and consequently shorter flight time, and vice versa, in the case of temperatures lower than ISA.

From the flight scenario, it can be noticed that, during the summer season, flying during the daytime at the highest average temperature will save about 20$ per flight (one landing), than if the flight performed at night. Assuming that an airline operating two daily flights on this route (four landings), this will be about 29,000 $ of savings per year.

Surprisingly, it has been found that the cost of time was the dominant factor not the cost of fuel, however, this is directly affected by the cost index chosen to be the airline.

It can be interpreted from the results that, accurate calculations of airline operational costs and operating priorities is crucial when aiming to optimize cost by trading trip fuel for trip time.

The optimum performance of the aircraft achieved by minimizing DOC by flying maximum economy speed with less amount of fuel consumption in the shortest possible time. The optimum flight is that can maintain optimum altitude and optimum varying M_{ECON} along the route, those elements is not possible to be maintained all the time due to ATC constraints, however, the flight crew are responsible to keep as close as possible to those values.

It is obvious that the selection of CI is very sensitive to the DOC, as it is determined from the real flight scenarios. The results were supplied to some operators to figure out the penalties of increasing the cost index as a manner of time-saving which gives negative results which lead to strong recommendations to respect CI values provided by the operator.

The effect of aircraft gross weight on aircraft performance was also examined and it is found to be one of the most effective factors in flight operations analysis. The gross weight of an aircraft has a direct effect on aircraft fuel consumption, optimum speed, and optimum altitude. Minimizing gross weight affecting directly the costs of flight, the lighter the better, however, the heavier is the better only if the weight is considered as useful load, so it is the load that is paid for.

The APM algorithm developed for this research shows very interesting results. The capability of the algorithm is proven by the ability to compute the effect of relatively very small amounts of weight reduction. The effect is expressed in terms of variation is cruise speed, fuel consumption, and the direct operating cost. The small reductions were as small as one kilogram, which is less than 0.0016% of the gross weight of the aircraft, but still, we can see some benefits in a matter of thousands of dollars per year from cutting such small weights.

The research also studied the relationship between weight reduction and the cruising distance and it is found that the longer ranges are much sensitive to weight reduction because it affects directly the fuel consumption as a function of cruise time, so longer means more fuel reduced due to weight cut, this is interestingly beneficial even with a lower fraction of weight reduction in longer flight because it is heavier because more fuel is needed. The fraction in this case is less than 0.0014%.

This study case recommends the airlines and researchers to conduct more studies and develop new methods and adopt new strategies to control and minimize the flight weight aiming for millions of dollars of savings in DOC.

The APM was also implemented in more complex cases such as flying under the pressure of time constraints better known as meet-time of arrival issue. The aircraft performance is intended to be improved by optimizing cruise speed and altitude to minimize fuel consumption.

The optimization was conducted by selecting the most suitable optimization technique for such a case. The method selected was the sequential quadratic programming SQP, which give very accurate results with a very short time of conversions

In airline operation when the flight is behind the schedule means it cost the carrier extra fees, to solve this problem, and to reduce cost the penalties from the delay simply the aircraft must fly faster. How fast the aircraft have to fly depends on the given time of arrival, so the flight time is constrained accordingly. To simplify the complexity of this problem, the study cases are divided according to the suggested range and weight and different time constraints. The optimizer computes all of these cases fastly and accurately. From the real flight scenarios applied for time constraints conditions is obviously seen that the amount and cost of fuel are increased with the need for a higher speed to save the time, however, the saving in cost of time must be compared with the extra consumed fuel cost, the decision of which option will save more is the one to be applied. The APM algorithm proves its capability to solve such complex issues by implementing the SQP method which optimizes the relationship between time and fuel for minimum DOC.

6.2 Recommendations and Further Work

- It is recommended for future research to pay more attention to the effect of other atmospheric parameters on aircraft performance and how to employ them to reduce the DOC.
- Develop new techniques to minimize the gross weight of aircraft and monitor the small unconsidered items used on-board.
- Investigate the impact of the intended modern air traffic management system such as continuous climb operations CCO and the potential benefits from such techniques.
- Develop the current APM to be valid for other flight phases such as climb and descent and from different elevations.
- Develop the APM to be used for different types of A320 family or for any other aircraft type if there is enough data provided by BADA.
- Study the impact of the amount of fuel consumption on the environment by measuring the emissions resulted from the fuel burnt and the impact of this on the DOC.

- It is highly recommended for the researchers to focus on the issues that arise from real flight operations and avoid generalized solutions because the operational environments are very different from an airline to another.

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