ISTANBUL TECHNICAL UNIVERSITY ★ FACULTY OF AERONAUTICS AND ASTRONAUTICS

PERFORMANCE CALCULATION: MIDDLE-CLASS AIRCRAFT

GRADUATION PROJECT

Mehmet Emin Yıldırım

Department of Aeronautical Engineering

Thesis Advisor: Dr. Öğr. Üyesi Hayri Acar

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Mehmet Emin Yıldırım, student of ITU Faculty of Aeronautics and Astronautics student ID **11015008**, successfully defended the **graduation** entitled **"PERFORMANCE CALCULATION: MIDDLE-CLASS AIRCRAFT"**, which he prepared after fulfilling the requirements specified in the associated legislations, before the jury whose signatures are below.

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Date of Submission : 13 July 2020

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1. Introduction

Increasing an aircraft's performance is an import problem for aircraft's operator. Many studies by airlines and researchers to decrease flight cost. The performance improvement studies have becoming more important since The Gulf War. Also, global warming issues makes consuming less fuel very important.

For this manner, in this project study Boeing 777-300ER's Istanbul-Houston flight will be worked in the performance and cost view. After studies and calculations, some suggestions for improving cost and fuel performance will be made.

In Chapter 2, Flight Route Methods are stated after literature review. After that chapter, the software that are used for route planning by airlines and operators are mentioned.

In Chapter 4, the literature data for performance calculated are searched. The next chapter includes Flight Operation Cost Calculation Methods.

Flight route for determined aircraft and airport are planned by using software named Professional Flight Planner X in Chapter 6. Different approaches are used in planning of flight routes. After the route plan is obtained, performance calculations are made in Chapter 7, with using same software.

Flight operation cost are calculated in the way that mentioned earlier parts, in Chapter 8. In Chapter 9, performance improvement methods are applied to routes.

2. Flight Route Planning Methods

In the earlier year of aviation, navigation and flight route planning methods were very hard. Since navigation equipment in plane was not sufficient, pilots had to fly with visual data and experience. With further developments in technology, navigation and flight planning methods had become a science and many studies were done about this topic.

Flight Planning can be described as representation of special information of an aircraft's planned flight and its rules are stated in ICAO Annex 2, Chapter 3.3 [1]

At present time, airlines collect all data about flight to determine the optimum flight route. These operational data include many different parameters. Even though it changes in time, cost calculations target the nearest result.

These are some main parameters that are used in a flight planning:

-Flight Beginning Point / Take-Off Runway

-Flight Ending Place / Landing Point

-Flight Heading

-Flight Distance

-Aircraft's Speed

-Aircraft's Fuel Capacity

-Aircraft's Weight and Balance/Structural Limits

Flight planning includes information about initial weather conditions on the flight route, predicted air temperature at different altitudes, wind directions and forces, performance parameters taken by constructor of aircraft, number of passengers, and payload weight. [2]

With this manner, a flight plane presents detailed data of direction of flight, flight altitude, fuel weight, flight speed, performance parameters, to pilot. Moreover, it has NOTAM information of departure field, landing field, and alternate aerodrome. NOTAM stands for Notice to Airmen and is described as notice containing information essential to personnel concerned with flight operations but not known far enough in advance to be publicized by other means. [3]

Flight plan also includes safety and legal requirements such as contingency fuel, route and altitude necessities, weight limits, airworthiness of aircraft. According to safety and legal requirements, following methods should be considered:

-Choosing the most economic route with air control units which will be over-passed and meteorological conditions.

-Determining optimum time of flight.

-Deciding of departure and arrival time to avoid deviation in flight route and arrival aerodrome.

-Combining these data to obtain the highest profit with increasing payload weight.

Combining all these data and analyzing them in short period causes mistakes made by dispatcher and planner. As a result of mistakes, cost of flight increases. To prevent or minimize these negative outcomes, different flight programming systems such as Lido OC (Lufthansa), f:Wz, Jepp (Jeppesen Flight Planning), Professional Flight Planner X, EDS, Sabre are developed and used by almost every airline. These software aim saving flight cost with optimizing route, speed, altitude, overpass cost, maintenance cost, crew cost, fuel values and payload weight.

Flight plan optimization primarily targets decreasing fuel consumption and total cost to minimum possible value. For this reason, many parameters are counted in optimization studies. Planning methods varies in this manner. As seen in Fig 2.1, there are 4 main factors that affect fuel consumption: Take-off weight, landing weight, fuel weight and flight altitude. With using this knowledge, considering the other parameters that affect these 4 main factors, decreasing fuel consumption and maximizing the profit of a long-range flight are decided as project’s aim. In further studies, optimum routes will be researched. Also, effects of fuel weight, flight speed, payload weight and aircraft’s weight on total cost of flight will be investigated.

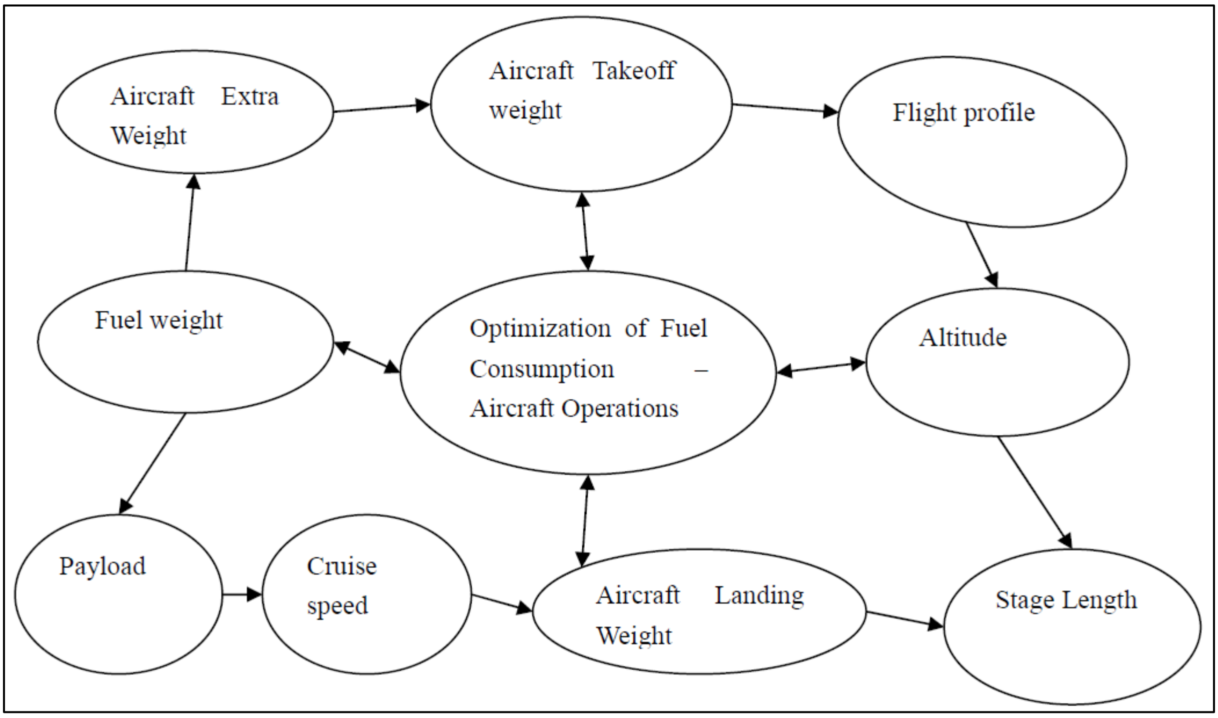


Fig. 2.1: Fuel Consumption Optimization Model [4]

In this project, 3 main flight planning methods will be used: Great-Circle Distance, Cost Index Method and Redispatch Method. Great-Circle Distance is a method of calculating the minimum distance between two points on the Earth. Cost Index Method is a method that aims optimizing average fuel consumption. Fuel consumption respect to aircraft weight will be studied with Redispatch Method.

2.1 Great-Circle Distance

Calculating the minimum distance from two points on the Earth is the first step of creating a flight route. This distance is calculated using Great-Circle Distance.

lat_1 ve $long_1$ latitude and longitude of first point (departure aerodrome)

lat_2 ve $long_2$ latitude and longitude of second point (landing aerodrome)

D Great-Circle Distance

$$D = 60 \times cos^{-1}[\sin(lat_1) \times \sin(lat_2) + \cos(lat_1) \times \cos(lat_2) \times \cos(long_2 - long_1)]$$

(1.1) [4]

In this formula, latitude at the Northern Hemisphere and longitude at the Western Hemisphere have positive, latitude at the Southern Hemisphere and longitude at the Eastern Hemisphere have negative values.

According to Great-Circle Distance information, required fuel weight is calculated at standard atmospheric conditions with considering take-off, climb, cruise, loiter, descending and landing phases of flight. Obtained flue weight value is optimized with payload and after the optimization, it has the standard values of planning phase. However, for the planning flight, route must be changed and optimized because of some dynamic reasons such as daily meteorological conditions, over-pass costs, NOTAM's, extra fuel consumption due to delay, crew cost. Moreover, temperature, wind direction and wind speed and critically affect flight route and distance, especially in transoceanic flights.

PC WINDTEMP 3.4
Equivalent HeadWinds and Standard Deviations for Air Routes 3/6/2003
Units of Measure: Nautical Miles, Knots Analysis: GreatCircle
FileName: fund_example.wtp

IDENTIFICATION					SEASON			DIRECT		RETURN	
Orig	Dest	Range	Alt	Air Speed	Month	St.Dev.	% Rel.	Winds	Equiv. Range	Winds	Equiv. Range
KSEA	EGLL	4,157	35,000	484	Jan (WI)	17	50	+13	4,051	-17	4,306
							75	+1	4,145	-28	4,412
							85	-5	4,198	-34	4,472
KSEA	EGLL	4,157			Apr (SP)	15	50	+16	4,024	-18	4,320
							75	+6	4,109	-29	4,418
							85	+0	4,156	-34	4,472
KSEA	EGLL	4,157			Jul (SU)	14	50	+15	4,036	-17	4,304
							75	+5	4,116	-26	4,396
							85	0	4,161	-32	4,447
KSEA	EGLL	4,157			Oct (AU)	17	50	+17	4,016	-20	4,340
							75	+5	4,111	-32	4,451
							85	-1	4,164	-38	4,513

Fig. 2.2: Effect of wind on distance [5]

In Fig. 2.2, effect of wind at 35000 ft flight from Seattle (KSEA) to London (EGGL) at constant speed (0.84 Mach) is stated.

In this connection, it can be stated that the most important factor of determining flight route is wind. Live wind data are obtained by weather forecast and target to shorten flight distance as possible, with considering predictions. After all required data is calculated and route is specified, Take-off weight (TOW) of aircraft is determined. Take-off Weight is the most important parameter in cost and profit rate calculations made by airlines.

As stated in reference [6], flight made on route has longer distance than Great-Circle Distance might be more sufficient in some specific conditions of environmental factors.

2.2 Cost Index Method

Cost Index is another method that affects positively. This method includes following studies: Flight speeds are optimized according to dynamic meteorological conditions and weight (cost index). Many aircraft's route is organized in heavy-air traffic areas (RVSM, reduced vertical separation minima).

$$\mathrm{CI} = \frac{\text{Cost depend on time} \sim \$/\text{sa}}{\text{Fuel Cost} \sim \text{cent/lb}} \qquad \mathbf{(2.2)}$$

Cost Index is described as time dependent costs to fuel cost ratio. Time dependent costs are crew cost, aircraft's maintenance cost, lease cost (if aircraft is leased), delay caused costs, etc. However, some of these costs change very quickly and have a minority respect to others, they are ignored during the calculations. For this manner, crew and maintenance costs are taken account. According to time dependent costs, increase of flight speed also increases profit of flight. Because higher flight speed means that more distance in same time and decrease in the maintenance cost. In addition to this, if aircraft exceed the optimum speed, fuel consumption will sharply increase and profit decrease. So, the flight speed must be determined carefully considering fuel consumption and time parameters [7].

Cost Index Value is figured as an index between aircraft's maximum range cruise (MRC) fuel consumption speed and long-range cruise speed. [8]

During a flight planning, determining optimal flight speed and altitude of cruise flight is one of the most important parts of the planning. Constant speed at optimum altitude method has been used for many years. It is proofed theoretically and practically that plans made by Cost Index Method have significant cost saving.

FLEET	CURRENT COST INDEX	OPTIMUM COST INDEX	TIME IMPACT MINUTES	ANNUAL COST SAVINGS ($000's)
737-400	30	12	+1	US$754 – $771
737-700	45	12	+3	US$1,790 – $1,971
MD-80	40	22	+2	US$319 – $431

Fig. 2.4: Cost Index effect on 1000 miles flight [6]

Flight plans made by Cost Index Method has 2-3% fuel saving compared to LRC or constant speed. Moreover, this advantage might increase up to 10% in the case of unexpected wind conditions at lower altitudes. [5]

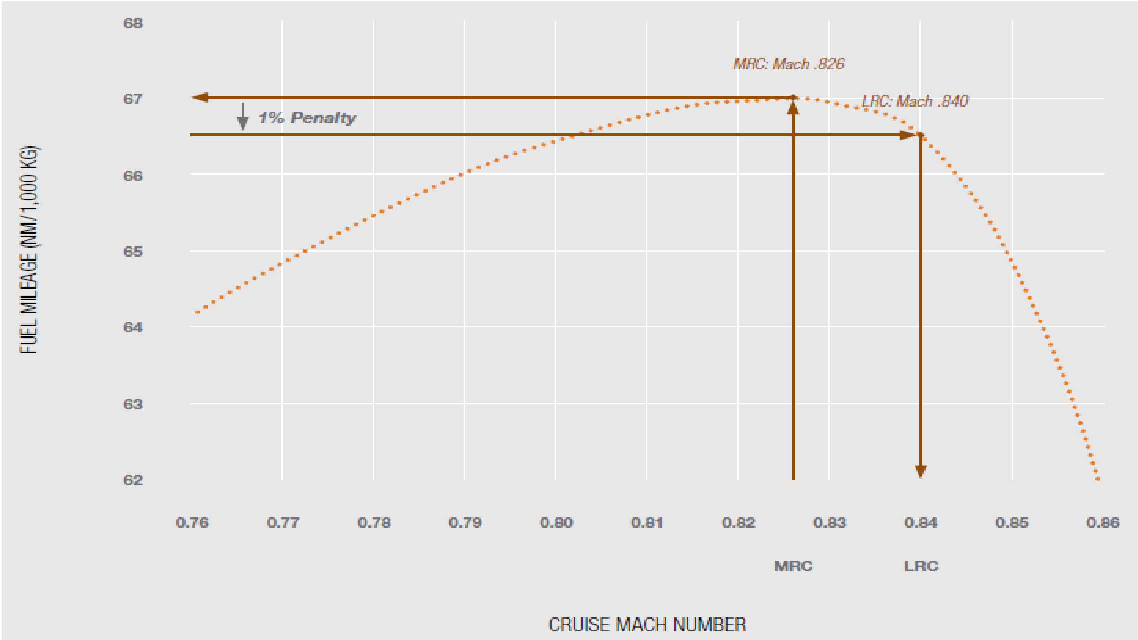


Fig. 2.4: MRC and LRC speeds [8]

Lovergen and Hansman have concluded their study with a statement that Cost Index Method with optimum flight speed has 2.4% fuel saving [9]

The two-legged flight method that used by some airlines in long-range flights is studied in a master thesis by Frank Bos. He stated in his thesis that this method has 5-10% fuel saving compared to direct, non-stop flight. After the cost index approximation, this savings might increase more than this value. [10]

In Fig. 2.5, Fuel requirement and total cost of a Houston-London flight made by Continental Airlines' Boeing 777 according to Cost Index speed and constant speed is stated.

Method	Trip Fuel	Fuel Cost (cents/lb.)	Fuel Cost ($)	Flight Time (hrs)	Flight Cost ($/hr)	Cost of Time	Total Cost	
CI 100	147200	41.1	60469	9.75	1500	14625	75094	
CI 50	146100	41.1	60017	9.96	1500	14940	74957	Best
CI 30	145900	41.1	59935	10.07	1500	15105	75040	
CI 20	145900	41.1	59935	10.12	1500	15180	75115	
CI 10	145900	41.1	59935	10.18	1500	15270	75205	
CI 0	146000	41.1	59976	10.25	1500	15375	75351	
.85 Mach	152300	41.1	62564	9.4	1500	14100	76664	Worst
.84 Mach	149600	41.1	61455	9.52	1500	14280	75735	
.83 Mach	148300	41.1	60921	9.63	1500	14445	75366	
	Price ($/Gal)	Price (cents / lb.)		CI Computed				
	2.74	41.1		37				

Fig 2.5: Cost Calculations with constant speed and Cost Index [8]

After the analyzing Fig. 2.5, following statements can be argued: Compared to lower CI values, Higher CI values causes aircraft to flight lower altitude and higher TAS value, and this causes fuel consumption negative. However, lower CI values increase time dependent costs. So, CI optimization must be done very carefully.

CI values of different aircrafts can be seen in Fig. 2.6.

Entered Cost Index (CI)

AIRPLANE MODEL	MRC	TYPICAL AIRLINE CI VALUES	APPROXIMATE LRC EQUIVALENT
717	0	40 to 60	70
737-3/4/500	0	5 to 25	25
737-6/7/800	0	10 to 30	35
757	0	15 to 50	85
767	0	15 to 55	70
777	0	90 to 150	180
MD-11	0	80 to 120	200
747-400	0	25 to 80	230

Fig. 2.7: Cost Index Values for different aircraft types [6]

2.3 Redispatch Technique

Fuel consumption of an aircraft is primarily affected by aircraft's weight, flight speed and wind conditions. With the light of this knowledge, decreasing aircraft's weight is the most sufficient method because of causing decrease in propulsion requirements.

Approximate % Block Fuel Savings Per 1000 Lb (454 Kg) ZFW Reduction

717-200	737-3/4/500	737-6/7/8/900	757-200/300	767-2/3/400	777-200/300	747-400
.9%	.7%	.6%	.5%	.3%	.2%	.2%

Fig. 2.7: Fuel savings per mass [5]

According to Fig. 2.7, it can be stated that decreasing the weight of aircraft might provide huge amount of fuel savings. This decrease of weight might cause by using lightweight components or loading less fuel on airplane. However, to operate the flight in safety standards, the certain amount of fuel must be on aircraft.

This certain amount of fuel is named as Contingency Fuel and determined as 5% of the burnoff fuel weight. This fuel can be decreased to 3% in terms that if there is a backup aerodrome enroute [7].

Taxi and APU Fuel	The fuel that is used before take-off for taxi and Axulary Power Unit.
Trip Fuel	The fuel that is planned to burn from take-off to landing.
Contingency Fuel	Additional fuel for unexpected situations such as routing changes, weather changes etc..
Alternate Fuel	The fuel for using to land the alternate aerodrome in case of not being able to land to destination aerodrome.
Final Reserve Fuel	The fuel that required for holding at 1500 feet altitude for 30 minutes time. It must be on the aircraft according to regulations and if fuel drops below this value crew declares emergency situation.
Extra Fuel	The fuel added by captain or dispatcher with the view of NOTAM’s and other possible effects to flight route.

Redispatch Technique aims keeping the amount of fuel loaded on aircraft at minimum value in the limits of ICAO Safety Regulations. In this technique, another aerodrome enroute is specified as intermediate airport [8]. At the time when the aircraft comes to Re-dispatch Point, NOTAM’s, weather conditions, operational conditions in the intermediate airport are told to cockpit crew. If all conditions are suitable to land to main destination aerodrome, flight is completed at main destination. Otherwise, the aircraft lands on intermediate airport. After refueling, it takes-off for main destination airport.

In this technique, contingency fuel is calculated with the fuel weight that consumed from decision point to main destination airport, instead of all trip fuel weight. So, the weight of contingency fuel decreases and fuel is saved.

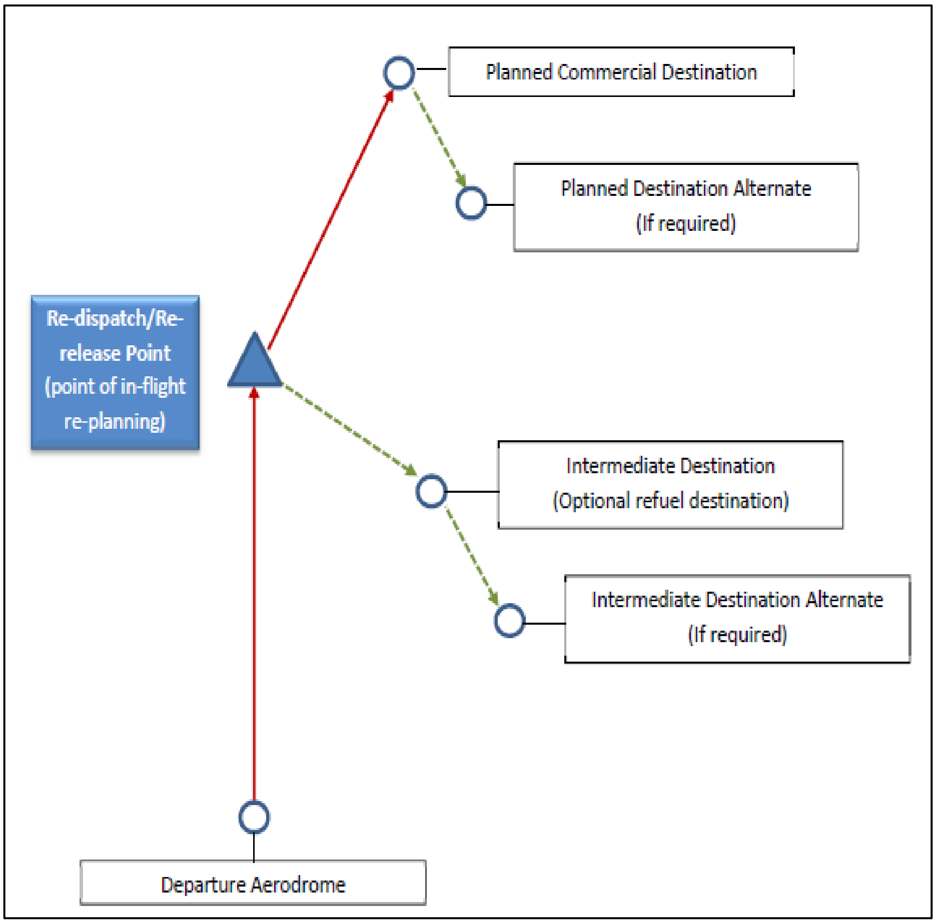


Fig. 2.8: Redispatch Technique Diagram [7]

Redispatch Technique is used in two different ways. Both two ways do not change taxi, alternate, final, and extra fuel weight. The first way states that contingency fuel is calculated as taking 10% value of fuel consumed from redispatch point and main destination airport [7]. In the second way, the contingency fuel is the 10% of the fuel consumed between departure and intermediate airport. The first way is safer than second way, but the second way might have more fuel saving.

3. Flight Route Planning Software

Many airlines including Turkish Airlines use a software to planning flight routes. This software processes many data in very short time and determines the optimum route for operation. So, dispatcher and flight planner's mistakes are minimized and improvements on cost and aircraft performance occurs.

In market, more than one software is used by airlines, on airlines' demand. Two of the most common software are Sabre and PFPX.

3.1 Sabre Software

SABRE Software presents a simple interface to plan flight with using the parameters that cost index value, passenger weight and number, payload, ZFW of the aircraft, and fuel weight. Moreover, this software considers weather conditions, crew and maintenance costs, overflight costs and NOTAM information.

Sabre Software makes the optimization with using Sub-routes, Airways and Freeflight. Sub-routes are routes that used by airlines in previous flights. Freeflight is the route that planned only by using coordinates, ignoring airways. The criteria in this optimization are as follows:

- Altitude

  Minimum and maximum altitude value according to aircraft's performance parameters.

- Wind and Temperature

  In the case that wind is activated, route is optimized with wind data. When this is inactivated, software chooses the shortest route.

- Overflight Cost

  Overflight Cost is generally calculated by distance taken in horizontal. The software does not calculate the certain cost, but it plans two routes: One of them ignores all overflight costs, and the other is the route that avoids high overflight cost.

- Cost Index

  The software optimizes cost index value and uses the optimum Cost Index Value for operation.

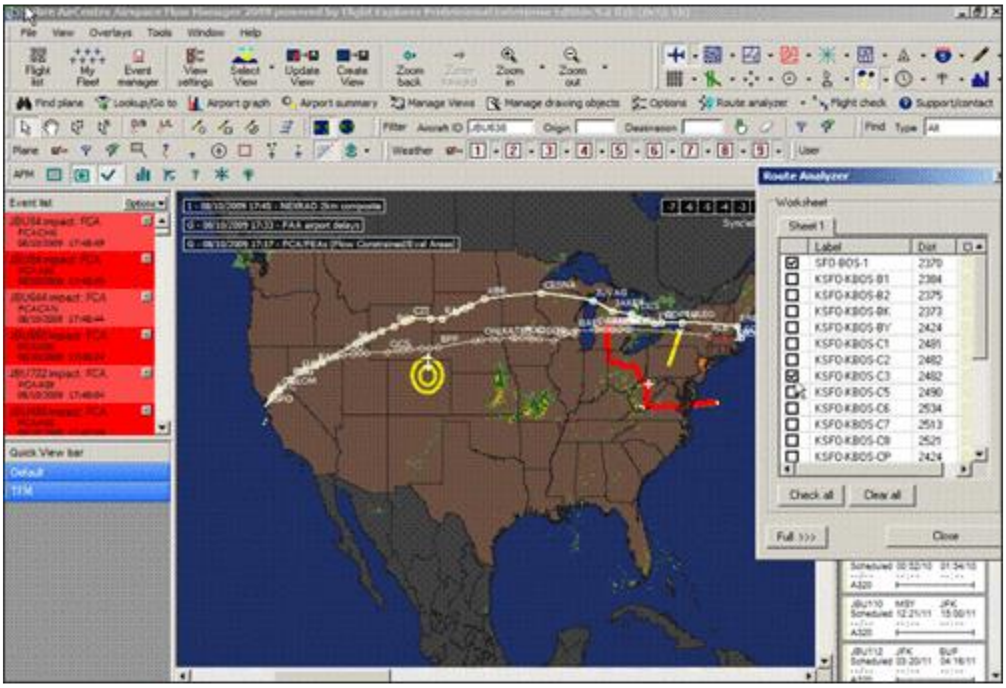


Fig. 3.1: Planning Interface of SABRE Software [9]

3.2 Professional Flight Planner X (PFPX)

Accessing to commercial software such as SABRE is not reachable. So, in this project study, Professional Flight Planner X software by Aerosoft is used.

PFPX Flight Planning Software includes many data upload option, so it is suitable use in many applications such as dispatcher training. This software gives the nearest results to common commercial software in market, so it is decided to use it in this project study.

The important inputs and parameters used in PFPX Software are stated and explained as follows:

- Flight

  The flight information such as flight code, departure airport, runway, destination airport, landing runway, flight type, planned departure time etc..

- Aircraft

  Software has many aircrafts in its default database. In flight planning part, user can specify the aircraft of flight. Flight speed, Cost Index Value, flight altitude and step size of cruise can be determined by the user.

- Payload

The weight of payload is determined by user of the software. Either a specific amount of payload or maximum payload can be chosen. Also, zero fuel weight (ZFW) of aircraft can be rearranged.

- Fuel

Fuel weight will be loaded on aircraft that includes contingency fuel, trip fuel, alternate fuel, extra fuel is determined. It can be optimized according to user’s demands.

- Costs

Fuel cost, constant flight costs, time dependent cost and delay cost are determined by user.

- Route

The part that route of flight is determined. The determination can be either completely done by software itself, or with using user’s inputs.

- Alternates

In this part, the alternate airport is chosen and added to flight plan.

- Redispatch

The part that determined the choices of redispatch methods.

- Weather

Weather can be uploaded from the internet live. Also, the user can determine certain weather conditions for planning.

- Map

Flight plan is showed on a map includes weather conditions, other airports worldwide, enroute NOTAM’s etc.

4. Performance Parameters

While creating a flight plan, some conditions are taken account. These conditions can be classified in two parts, first one is dynamic environment factors such as wind direction, speed of wind, temperature, and regional atmospheric levels. Second part is aircraft's performance parameters. It is important that determining best plan with using aircraft's performance parameters and dynamic conditions for flight operation costs. For this manner, performance parameters taken from aircraft's constructor are used.

With using determined parameter, climbing, cruising, and descending phases of flight are discussed. Required equations are mentioned in equation part. During the project study, a package software will be used, and software's performance parameters are used. The software parameter values are assumed as equal to constructor's parameter values. Also, software make calculations with using climbing, cruising, and descending equations.

4.1 Selecting Aircraft Model

In this project, aircraft model is chosen taking account of some specifications of aircrafts, such as maintenance cost, payload capacity, range, and flight performance. After discussions, Boeing 777-300ER is chosen. This type of aircraft is used by many airlines in the world, as well as the Turkish Airlines. In 2016, more than 600 Boeing 777-300ER were used. [10]

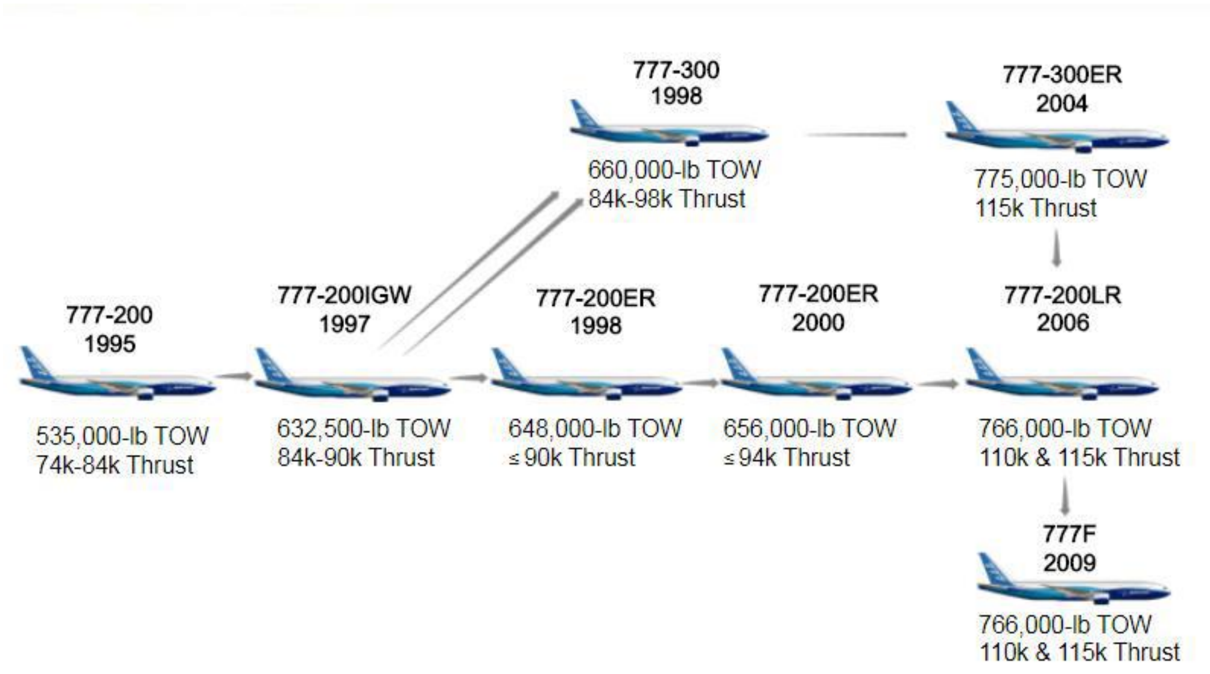


Fig.1.1: Boeing 777 Family [11]

4.2 Determining Aircraft's Performance Parameters

An aircraft's performance parameters are discussed in three main parts: Aerodynamics, Structure, and Powerplant.

Zero-lift drag coefficient Lift-dependent drag factor Maximum aerodynamic efficiency Maximum lift coefficient Wing planform area	Aerodynamics
Total weight of aircraft Maximum weight of fuel Maximum load factor	Structure
Maximum net thrust or power for engine Specific fuel consumption (thrust or power) Propeller efficiency	Powerplant

Fig 4.2: Aircraft's Performance Parameters Classification [12]

4.2.1 Aerodynamic Performance Parameters

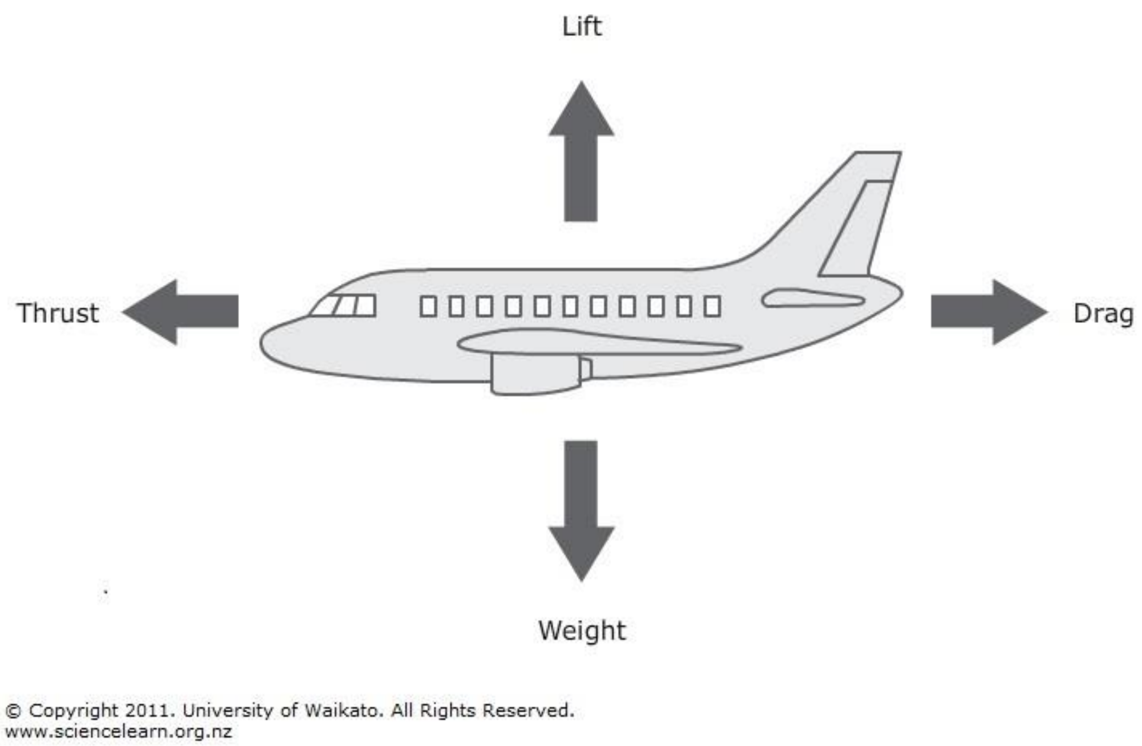


Fig 4.3: 4 Main Forces of Flight [13]

4 main forces are affected on airplane in flight. These are thrust, gravitational, lift, and drag forces. Lift and drag forces are aerodynamic forces. These aerodynamic forces can be expressed as follows: [13]

$$L = qSC_L = \frac{1}{2}\rho V^2 SC_L \quad \mathbf{(4.1)}$$

$$D = qSC_D = \frac{1}{2}\rho V^2 SC_D \quad \mathbf{(4.2)}$$

Where

L is Lift Force, N

q is Dynamic Pressure, kg/m*s^2

V is Speed of Aircraft, m/s

ρ is Density of Air, kg/m^3

S is Wing Area of Aircraft, m^2

C_L is Lift Coefficient

C_D is Lift Coefficient

Drag Coefficient is calculated with addition of two components: Zero Lift Drag Coefficient (C_{D0}) and Induced Drag (C_{Di}). [14]

$$C_D = C_{D0} + C_{Di} \quad \mathbf{(4.3)}$$

$$C_{Di} = KC_L^x \quad \mathbf{(4.4)}$$

$$C_{Di} = \frac{C_L^2}{\pi AR\epsilon} \quad \mathbf{(4.5)}$$

AR is Aspect Ratio

ϵ is Oswald Span Efficiency Factor

C_{D0} is named as Zero-Lift Drag Coefficient, and a coefficient which changes with speed and altitude of flight. According to Torenbeek, C_{D0} value is between 0.014 and 0.020 for aircrafts in civil aviation [6]. K, and x are functions of wing shape, Mach, and Reynold Numbers. So, the functional relationship between Lift Coefficient, Drag Coefficient, and aerodynamic numbers can be expressed as follows: [14]

$$C_L = C_L(\alpha, M, Re, shape)$$

$$C_D = C_D(\alpha, M, Re, shape)$$

Where α is angle of attack, M is Mach Number, and Re is Reynolds Number. For our study, since aircraft and its shape already determined, $\alpha, M, and\ Re$ can be used to optimizing the route.

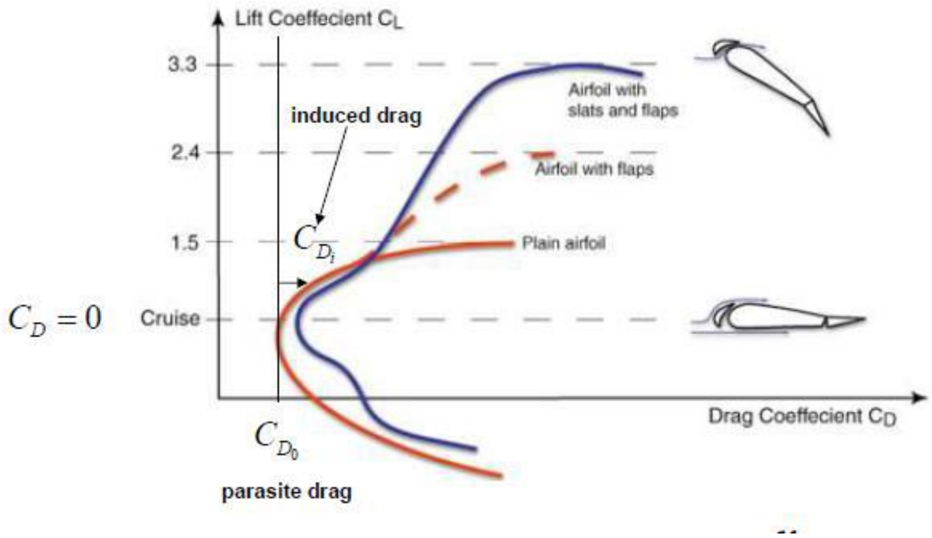


Fig 4.4: C_L and C_D Chart [12]

4.2.1.1 Performance Calculations for Climbing

In the climbing phase of flight, four main forces on aircraft are calculated with using the relationship of angle of climb. Angle of climb (γ) is the angle between a horizontal plane representing the Earth's surface and the actual flight path followed by the aircraft during its ascent and determined by the excess thrust per unit weight. [14]

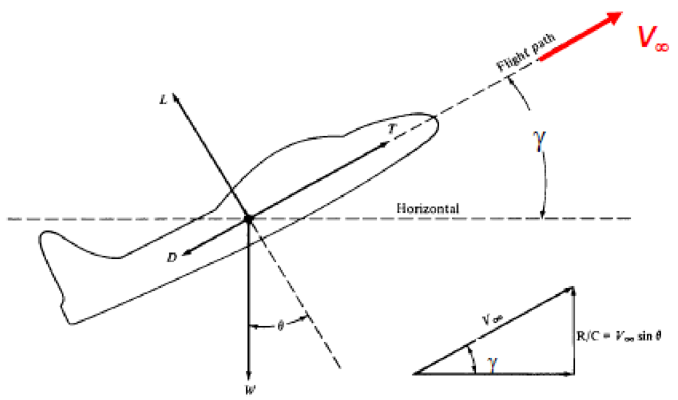


Fig 4.5: Angle of Climb and Acting Forces in Climbing

These are some parameters that is used in climbing performance calculations:

γ Angle of Climb

T Thrust Force (N)

D Drag Force (N)

W Weight (N)

R/C Rate of Climb

q Dynamic Pressure (kg/ms$^{2)}$

Δt Time Spent in Climbing (s)

c Thrust Specific Fuel Consumption (N/hour/N)

W_f Fuel Weight (N)

X Distance Taken in Horizontal Respect to Ground

C_{D0} Zero Lift Drag Coefficient

Angle of climb equation can be expressed as follows, mentioned Fig. 4.5:

$$\sin\gamma = \frac{T}{W} - \frac{D}{W} \quad \textbf{(4.6)}$$

$$\frac{D}{W} = \frac{qC_{D0}}{(W/S)} - \frac{k(W/S)}{q} \quad \textbf{(4.7)}$$

$$T = \sigma T_{SL} \quad \textbf{(4.8)}$$

Mathematical expression of Rate of Climb can be written as:

$$(R/C)_{ortalama} = V_{avg}\sin\gamma \quad \textbf{(4.9)}$$

- Distance Taken During Climb

Distance Taken During Climb is calculated with using horizontal component of velocity and time spent in climb.

$$\frac{dX}{dt} = V\cos\gamma \implies \Delta X = \frac{V_{avg}\cos\gamma_{avg}\Delta t}{1000} \quad \textbf{(4.10)}$$

- Climbing Time

Climbing Time can be calculated with altitude difference between before and after climbing and Rate of Climb.

$$\frac{\Delta h}{\Delta t} \rightarrow \Delta t = \frac{\Delta h}{(R/C)_{ortalama}} \quad \mathbf{(4.11)}$$

- Fuel Consumption During Climb

Weight difference between beginning and end of climb is equal to weight of fuel burnt. It can be expressed in mathematical form as follows:

$$\frac{dW_f}{dt} = cT \rightarrow \frac{\Delta W_f}{\Delta t} = cT \rightarrow \frac{\Delta W_f}{W} = \frac{c(T/W)_{avg}\,\Delta t}{3600} \quad \mathbf{(4.12)}$$

4.2.1.2 Performance Calculations for Cruise

In cruise flight, velocity and altitude of aircraft are constant, so there is an equilibrium situation. This situation can be written in mathematical form as equations of equilibrium: [14]

$$T - D = 0 \quad \mathbf{(4.13)}$$

$$L - W = 0 \quad \mathbf{(4.14)}$$

$$\frac{dX}{dt} = V \quad \mathbf{(4.15)}$$

$$\frac{dh}{dt} = 0 \quad \mathbf{(4.16)}$$

$$-\frac{dW}{dt} = cT \quad \mathbf{(4.17)}$$

If these equations are combined:

$$-\frac{dX}{dW} = \frac{VE}{cW} \quad \mathbf{(4.18)}$$

E is named as aerodynamic efficiency and described as lift to drag ratio.

$$E = \frac{L}{D} = \frac{C_L}{C_d} \qquad (\mathbf{4.19})$$

Weight of aircraft changes in time, because of fuel consumption. This change can be expressed as follows:

W_1 is the weight at start of cruise

W_2 is the weight at finish of cruise

W_{fuel} is the weight of fuel burnt during cruise

ω mass ratio (assumed as 1.5 for long range flights [12].)

ξ weight expression of mass ratio

$$W_1 = W_2 + W_{fuel}, \qquad \omega = \frac{W_2 + W_{fuel}}{W_2}\ , \qquad \xi = 1 - \frac{1}{\omega} \quad (\mathbf{4.20})$$

For best range equations for cruise flight can be written as follows: [14]

$$q_{BR} = \left(\frac{W}{S}\right)\left(\frac{3k}{C_{D0}}\right)^{1/2} \ V_{BR} = \left(\frac{2(W/S)}{\rho_{SL}\sigma}\right)^{1/2}\left(\frac{3k}{C_{D0}}\right)^{1/4} \quad \textbf{(4.21)}$$

$$D_{BR} = T_{BR}\left(\frac{1.115W}{E_m}\right) \qquad \textbf{(4.22)}$$

$$E_{BR} = 0.866E_m(Constant) \quad \textbf{(4.23)}$$

$$c_{L_{BR}} = 0.577c_{L_{E_m}}(constant) \ \textbf{(4.24)}$$

Cruise flight conditions are investigated in 3 main parts.

- Assuming velocity and lift coefficient are constant

$$X = -\int_1^2 \frac{VE}{cW}dW\ , \quad V = \sqrt{\frac{2W}{\sigma S C_L}}\ , \qquad E = \frac{L}{D} = \frac{C_L}{C_d + kC_L^2}\ (constant) \qquad (\mathbf{4.25})$$

With using the assumptions made in this part, the equation turns into:

$$X_{V,C_L} = \frac{VE}{c}\left[\ln 1 - \frac{1}{\xi}\right] \quad \textbf{(4.26)}$$

For best range:

$$E_m = \frac{1}{2\sqrt{kC_{D0}}} \quad \textbf{(4.27)}$$

$$X_{BR;\,V,C_L} = \frac{0.086 E_m V_{BR}}{E}\left[\ln 1 - \frac{1}{\xi}\right] \quad \textbf{(4.28)}$$

- Assuming density of air and lift coefficient are constant

As weight decreases, velocity will decrease to equal the lift force to weight. The velocity in this expression is made by using W_1.

$$X_{h,C_L} = \frac{2EV}{c}\left[1 - (1-\xi)^{1/2}\right] \quad \textbf{(4.29)}$$

For best range:

$$X_{BR;\,h,C_L} = \frac{1.732 E_m V_{BR}}{c}\left[1 - (1-\xi)^{1/2}\right] \quad \textbf{(4.30)}$$

- Assuming density of air and velocity are constant

In these conditions, as weight decreases, C_L will decrease. In cruise part, all parameters are taken in the start of cruise phase of flight. So, the last equation for cruise flight as follows:

$$X_{BE;\,h,V} = \frac{2E_m V_{BR}}{c} arctan\left[\frac{0.433\xi}{1-0.25\xi}\right] \quad \textbf{(4.31)}$$

4.2.1.3 Performance Calculation Methods for Descend

In descend phase of flight, acting forces on aircraft are studied with respect to horizontal line and flight path.

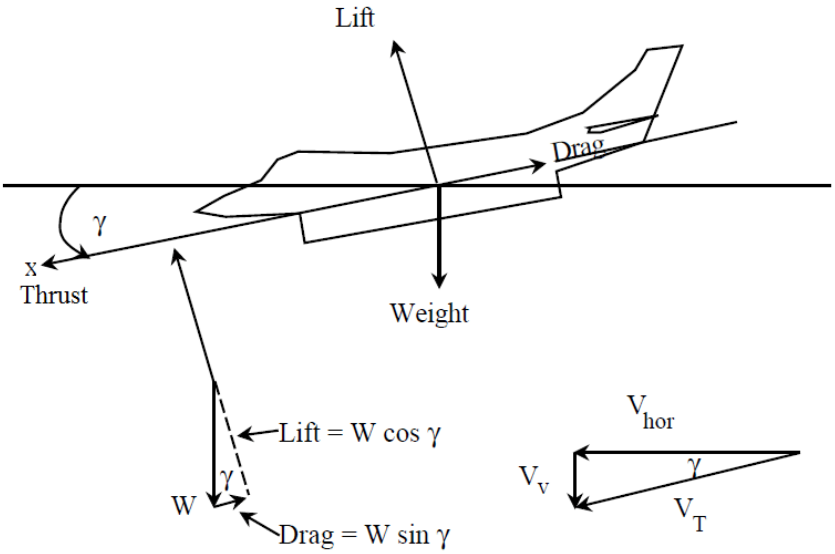


Fig. 4.6: Forces acting on aircraft in descend [16]

For calculations of time of descending, velocity that aircraft has best hover and fines value are important.

$X_{BR;\,h,C_L} = E_m(h_1 - h_2)$ **(4.32)**

$t_{br} = \frac{14508 E_m}{V_{br}}\left(e^{-h_1/14508} - e^{-h_2/14508}\right)$ **(4.33)**

Boeing 777-300ER's aerodynamic performance parameters at 35000 feet altitude and 0.84 Mach (494 kts TAS) are shown in Fig. 4.7.

Aircraft	787-8	A350-900	A350-1000N	777-300ER
Wingspan	60,1	64,8	64,8	64,8
Wing area m2 trapezodial	325	400	416	428
Wing area m2 Airbus	370	443	461	454
Wing area m2 Wimpress	360	431,48	449,01	442,20
Wing area m2 exposed	301	362	376	372
Aspect ratio	10,78	11,26	10,82	9,51
Wing loading Trapez. kg/m2	701	670	740	821
Wingloading Airbus kg/m2	616	605	668	774
Wingloading Exposed kg/m2	757	740	819	945
OEW/MTOW	0,510	0,504	0,434	0,477
MTOW kg	227.930	268.000	308.000	351.534
MTOW lb	502.500	590.839	679.024	775.000
MLW kg	172.365	205.000	233.000	251.290
MLW lb	380.000	451.948	513.677	554.000
MZFW kg	161.025	192.000	220.000	237.682
MZFW lb	355.000	423.288	485.017	523.999
MSP kg	45.025	57.000	68.000	69.853
MSP lb	99.264	125.663	149.914	153.999
OEW kg	116.000	135.000	152.000	167.829
OEW lb	255.736	297.619	335.103	370.000
maxPaxnoCargo 3class kg	23.814	29.830	33.250	34.768
Cruise CI FL350	0,50	0,48	0,53	0,60
Weight % FL350	83%	83%	83%	83%
Weight FL350	189.182	222.440	255.640	291.773
Cruise L/D FL350	20,8	21,4	21,3	20,1
Cruise FF kg/hr FL350	4.811	5.374	6.206	7.996
Cruise drag lbf FL350	20.088	22.896	26.444	32.052
Cruise drag N FL350	89.357	101.845	117.627	142.573
Cruise Dp N FL350	52.934	62.441	65.835	67.282
Cruise Di N FL350	36.423	39.403	51.792	75.291
Cruise Cdp FL350	0,0136	0,0130	0,0132	0,0135
Cruise Cdi FL350	0,0094	0,0082	0,0104	0,0151
Spec range Breguet	**7.672**	**8.054**	**8.411**	**7.906**
Range maxPaxnoCargo nm	**7650**	**8100**	**8400**	**7930**

Fig. 4.7 Boeing 777-300ER Performance Parameters

4.2.2 Structural Performance Parameters

Maximum taxi weight, maximum take-off weight, maximum landing weight, maximum zero fuel weight and maximum inflight weight are structural performance parameters that will be used in this project. Moreover, fuel capacity of aircraft is needed for calculations.

	Pounds	Kilograms
Maximum Taxi Weight (MTW)	777,000	352,441
Maximum Takeoff Weight (MTOW)	775,000	351,534
Maximum Landing Weight (MLW)	554,000	251,290
Maximum Zero Fuel Weight (MZFW)	524,000	237,682
Minimum Inflight Weight (MIW)	305,500	138,573

Fig 4.8: Structural Performance Parameters of Boeing 777-300ER [17]

	Volume	Maximum Weight	
	U.S. Gallons	LB	KG
Main L or R	10,300	73,130	33,171
Center	27,290	193,759	87,887

Fig. 4.9: Fuel Capacity of Boeing 777-300ER [17]

Condition	Minimum Loading Limit	Maximum Loading Limit
Flaps are closed	-1.0g	+2.5g
Flaps are open	0.0g	+2.0g

Fig. 4.10: Structural Loading Limits of 777-300ER [17]

If flaps are open at 25 and 30 degrees, maximum limits change to +2.0g for MLW, and +1.5g for MTOW [17].

4.2.3 Thrust Systems Performance Parameters

Boeing 777-300ER has two high-bypass ratio turbofan engines, GE90-115BL. Each engine produces 115,540 pounds take-off thrust, which is equal to 110,000 HP [17].

Equations used in calculations of thrust system performance parameters are as follows:

$$c = \frac{dW_{fuel}/dt}{T}, \qquad T = \sigma T_{SL} \qquad \textbf{(4.34)}$$

4.3 Aircraft's Performance Limitations

In this part of study, Boeing 777-300ER's performance limitations are investigated in Flight Envelope, Load Factor, Stall Speed and Critical Mach Number titles.

4.3.1 Flight Envelope

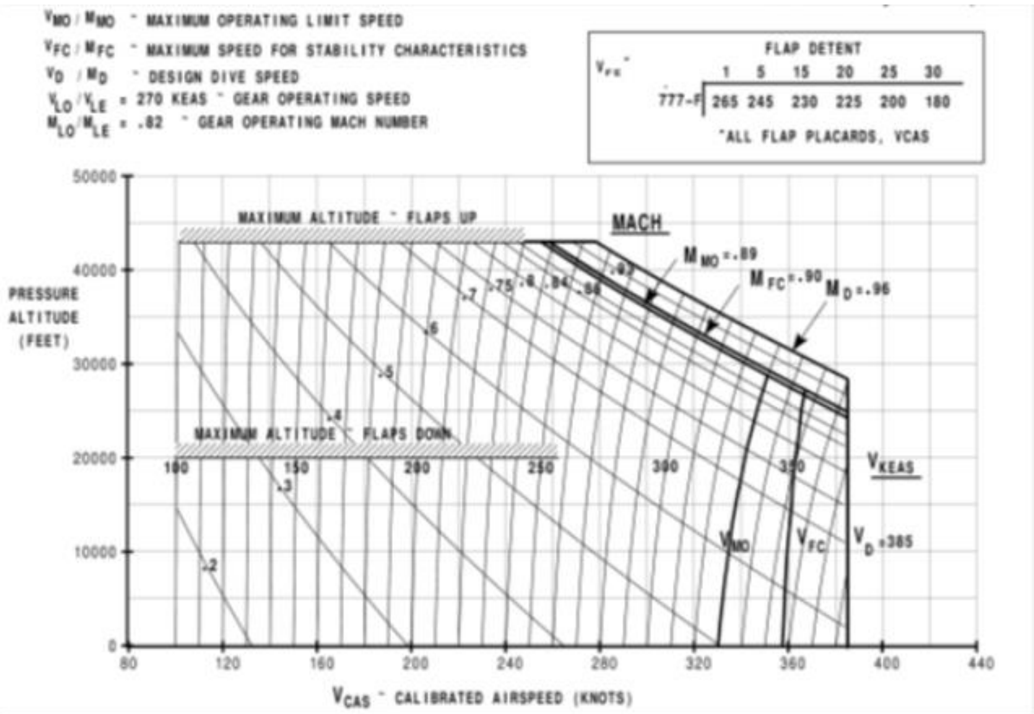


Fig. 4.12: B777F Operational Speed Chart [11]

In Fig. 4.12, Flight Envelope of Boeing 777F is shown. Since, Flight Envelope for B777-300ER could not be found, the nearest found data is used. Switching to Mach Number from airspeed point is taken as 30100 feet altitude. At lower altitudes than 30100 feet, airspeeds determine the limits. At higher altitudes than 30100 feet, Mach Number determines the limits.

According to these limitations, the aircraft's maximum operational speed V_{MO} is between 320-340 kts, related to altitude. M_{MO} is constant and 0.89 Mach. For stability characteristics, maximum speed V_{FC} is between 355-360 kts, M_{FC} is constant and 0.90 Mach, maximum diving speed V_D 385 kts, M_D is 0.96 Mach. Furthermore, maximum flap altitude is 20000 feet, and maximum operation speed V_{LE}/V_{Lo} 270 kts, M_{LE}/M_{Lo} 0.82 Mach for opening and closing landing gear.

4.3.2 Maneuvering Envelope

An aircraft's structural performance values and operational limitations are determined by maneuvering envelope of speed and load factors. [19] In Fig. 4.13, load factor and structural performance characteristics related to air speed and flap position can be seen.

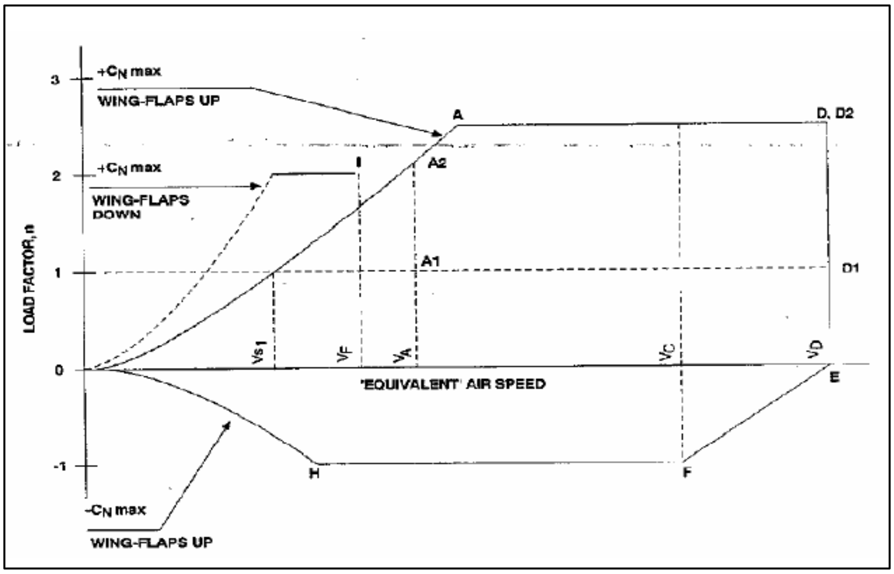


Fig. 4.13: V-n diagram of wide-body aircrafts [19]

4.3.3 Stall Speed

Stall speed can be defined as slowest speed a plane can fly to maintain level flight. Stall speed depends on $C_{L,\,max.}$ So, airfoil and aerodynamics characteristics of aircraft determines the stall speed.

$$L = W = \frac{1}{2}\rho V^2 S C_L \qquad \textbf{(4.35)}$$

$$C_{Lmax} \;\rightarrow\; V_{stall} \qquad V_{stall} = \left[\frac{2(\frac{W}{S})}{\rho_{SL}\sigma C_{Lmax}}\right]^{1/2} \quad \textbf{(4.36)}$$

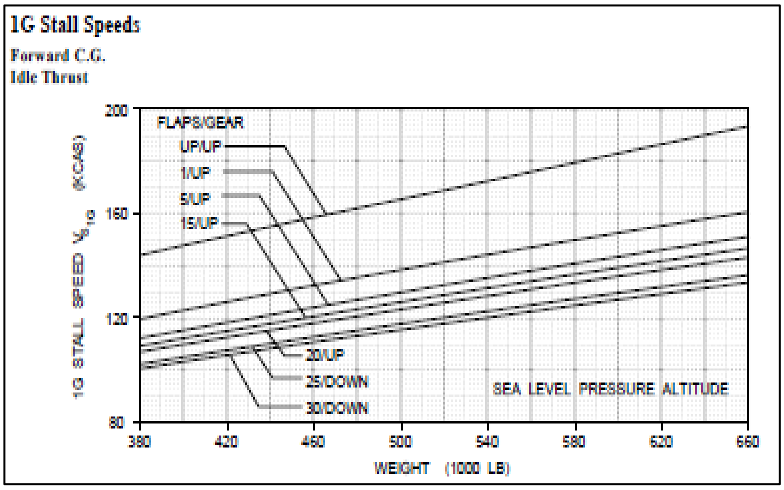


Fig 4.14: B777 Stall Speeds [20]

4.3.4 Critical Mach Number

During the flight, speed values of air on different parts of plane are different. Especially, on top parts of airfoil, air reaches higher speed. The Mach Number that creates 1 Mach Number some part on aircraft flow is defined as Critical Mach Number. This situation may cause shock waves and increase C_D, decrease Lift force.

In Fig. 4.15 change in C_D respect to Mach Number is shown.

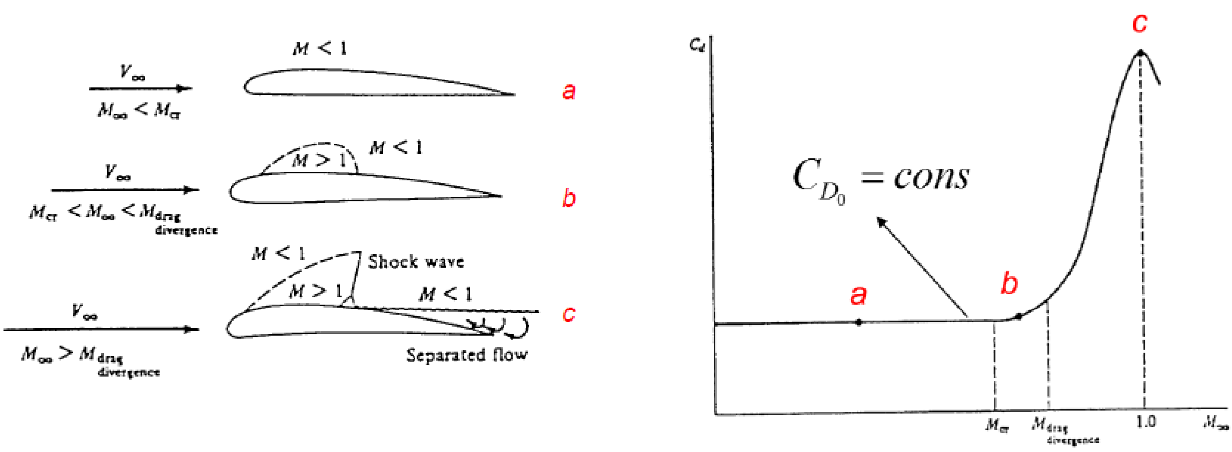


Fig. 4.15: Critical Mach Number and C_D [12]

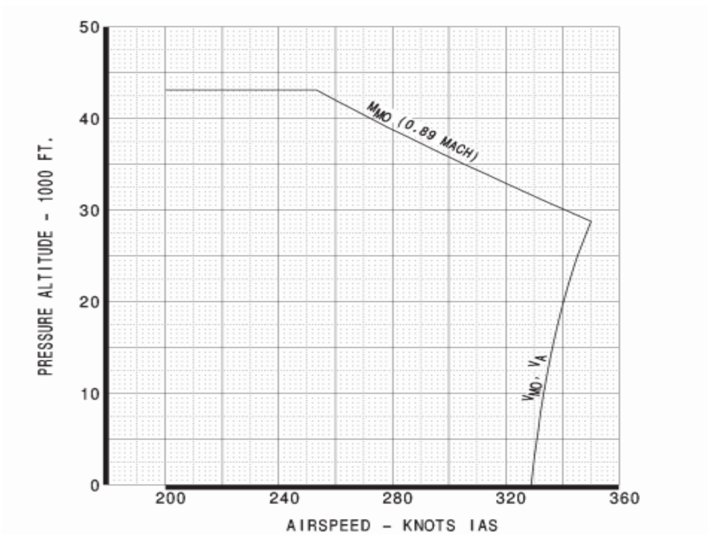


Fig. 4.16: B777 Speed Envelope [20]

As seen in Fig. 4.16, at the sea level, M_{Cr} is shown as indicated air speed, which is 330 kts. Above the limit of 29500 feet, M_{Cr} is 0.89 Mach.

5. Flight Operation Cost Calculation Methods

Flight Operation Cost (FOC) is all costs of flight operated by an aircraft operator. This cost is consisting of variable and constant costs. Variable costs are fuel and oil, maintenance, and crew costs. Fixed costs are depreciation, rentals, insurance, and other costs. [21]

FOC can be formed in two different type: Cost per block hour and total cost. Total cost is the sum of all expenses of flight. Cost per block hour is the cost of operating an aircraft in flight for one-hour time and it is calculated dividing total cost by total flight time. These two types of FOC enables to compare cost of flight more accurately.

Aircraft Category	Cost per Block Hour										Col. 11
	Col. 1 Fuel and Oil	Col. 2 Maintenance	Col. 3 Crew	Col. 4 Total Variable	Col. 5 Depreciation	Col. 6 Rentals	Col. 7 Insurance	Col. 8 Other	Col. 9 Total Fixed	Col. 10 Total	Block Hours
Wide-body more than 300 seats	$10,275	$1,687	$1,538	$13,500	$761	$318	$9	$5	$1,093	$14,592	191,834
Wide-body 300 seats and below	$5,719	$1,343	$1,174	$8,236	$522	$328	$10	$6	$867	$9,103	2,006,089
Narrow-body more than 160 seats	$3,102	$964	$777	$4,843	$352	$199	$6	$1	$558	$5,400	2,260,009
Narrow-body 160 seats and below	$2,394	$715	$724	$3,833	$221	$325	$9	$3	$558	$4,390	8,959,309
RJ more than 60 seats	$287	$444	$349	$1,080	$144	$188	$6	$5	$344	$1,424	2,156,423
RJ 60 seats and below	$145	$468	$379	$993	$59	$179	$6	$3	$248	$1,240	2,596,269
Turboprop more than 60 seats	NR	$654	$323	$1,020	$264	$155	$3	$2	$423	$1,443	210,338
Turboprop 20-60 seats	$310	$250	$258	$818	$265	$107	$0	$9	$382	$1,200	112,295
Turboprop under 20 seats (Part 23)	$1,050	$175	$850	$2,075	$0	$479	$241	$167	$888	$2,962	4,605
All Aircraft	**$2,322**	**$754**	**$688**	**$3,764**	**$244**	**$270**	**$8**	**$4**	**$526**	**$4,289**	**18,497,171**

Fig. 5.1: Operation and Fixed Costs per Block Hour [21]

The selected aircraft for this study is Boeing 777-300ER and classified as Wide-body more than 300 seats. So, the first row of Fig. 6.1 represents Boeing 777-300ER's cost per block hour values.

Moreover, there is another form of cost named as total cost per seat mile. It can be described as a common unit of measurement used to compare the efficiency of various airlines. It is obtained by dividing total operation cost by available seat mile. Cost per available seat mile can be written as CASM in short form. [22]

Estimated Operating Cost Comparison	6,000 nm mission		
	B777-300ER	A350-1000	B777-9X
Fuel Cost	$107,250	$85,313	$98,638
Maintenance Cost	$16,900	$13,200	$14,872
Crew Cost	$20,800	$20,800	$22,085
Navigation and Landing Fees	$11,500	$10,900	$11,400
Total Operating Cost	$156,450	$130,213	$146,995
Total Cost per Aircraft Mile	$26.08	$21.70	$24.50
Number of Seats- 3 Class	350	350	407
Total Cost per Seat Mile	0.0745	0.0620	0.0602

Fig. 5.2: Comparison of 3 different aircraft's operation costs in 6000 nm mission [23]

- **Fuel Cost**

Fuel cost is calculated by multiplying total fuel burnt by unit fuel price.

$$Total\ Fuel\ Cost\ (\$) = Total\ Fuel\ Burnt\ (kg)\ x\ Unit\ Fuel\ Price\ (\frac{\$}{kg})$$

26 June 2020	Share in World Index	cts/gal	$/bbl	$/mt	Index Value 2000 = 100	vs. 1 week ago	vs. 1 month ago	vs.1 yr ago
Jet Fuel Price	100%	99.58	41.82	330.16	114.33	-8.1%	18.3%	-48.1%
Asia & Oceania	22%	100.69	42.29	334.10	120.83	-5.8%	23.6%	-46.3%
Europe & CIS	28%	97.18	40.82	321.63	109.97	-9.9%	20.6%	-49.8%
Middle East & Africa	7%	93.58	39.30	310.11	117.37	-8.0%	25.2%	-49.6%
North America	39%	101.65	42.69	337.27	113.50	-8.1%	13.6%	-47.5%
Latin & Central America	4%	101.33	42.56	336.20	117.89	-7.7%	12.2%	-48.3%

Fig. 5.3: Jet Fuel Prices in different operating areas [24]

$/mt is the sign of US dollars per metric ton.

- **Maintenance Cost**

Maintenance cost is the price of labor and components to keep the aircraft in reliability limits. According to IATA [5], this cost consists of 4 main parts: Base, line, engines, and components.

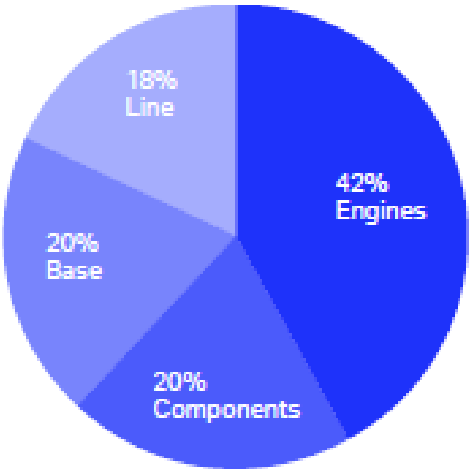


Fig. 5.4: Distribution of maintenance cost [25]

Moreover, there is another approach to maintenance cost which is preferred by Boeing. This approach states that airframe labor, airframe material, engine labor, and engine material are the 4 main parts that consist total maintenance cost of aircraft.

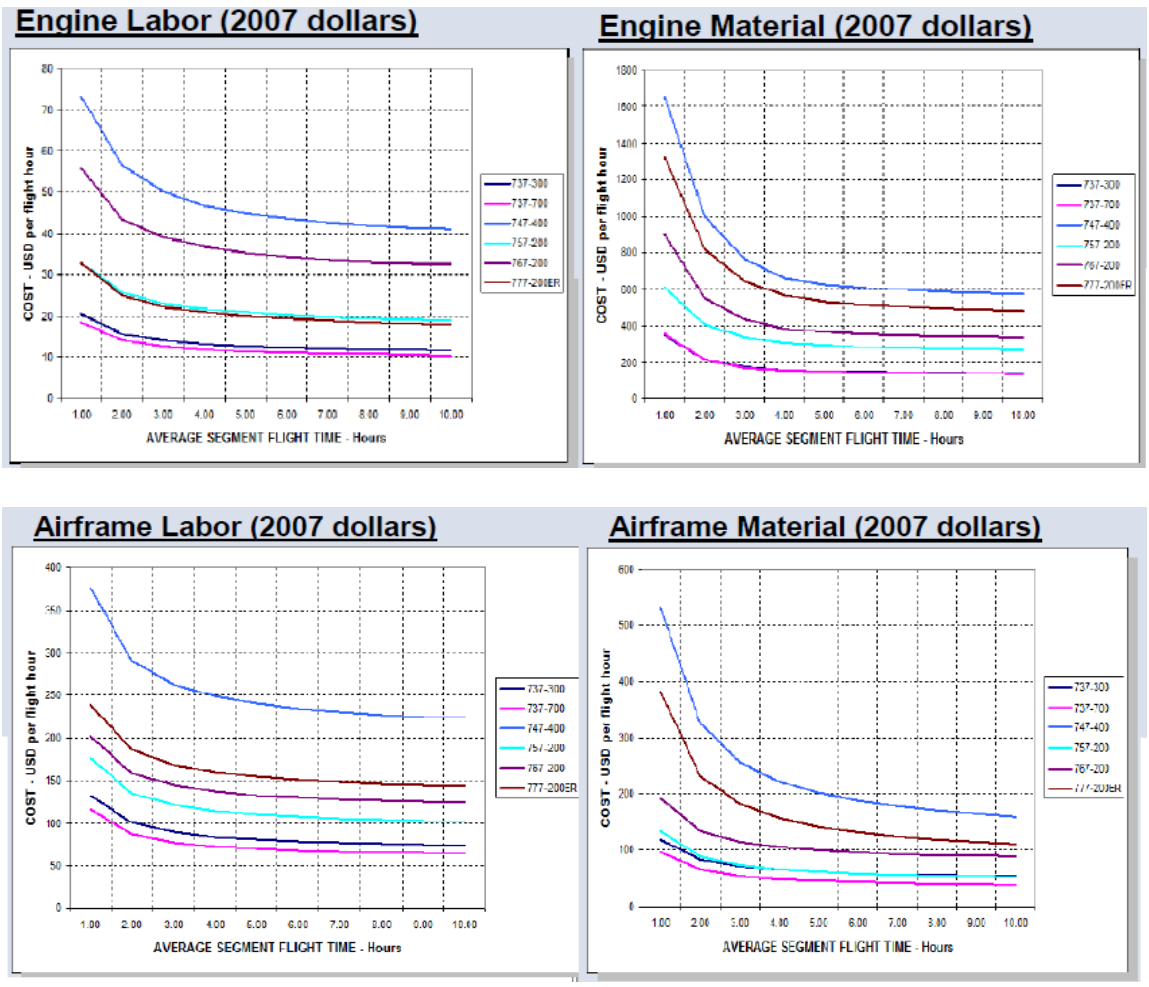


Fig. 5.5: Boeing Aircrafts' Maintenance Costs [26]

- **Crew Cost**

Crew cost is calculated by summing cockpit crew cost (CPC) and cabin crew cost (CAC). The following equation stated in reference [27] can be used in calculations.

$$Total\ Crew\ Cost = CPC + CAC$$

$$CPC = Unit\ Cost\ of\ Cockpit\ Crew\ x\ t_{block}$$

$$CPC = Unit\ Cost\ of\ Cabin\ Crew\ x\ n_{can}\ x\ t_{block}$$

- **Overflight Cost**

Overflight Cost is the cost that aircraft operator must pay to countries which their airspace is enroute of flight. This cost is dependent on aircraft's maximum take-off weight, the distance aircraft takes in the airspace and the country's standards. For Europe Airspace, Eurocontrol provides to consumers a software named *RSO (Route Per State Flown) Distance Tool*. This software is free of charge, and fees are updated by Eurocontrol monthly.

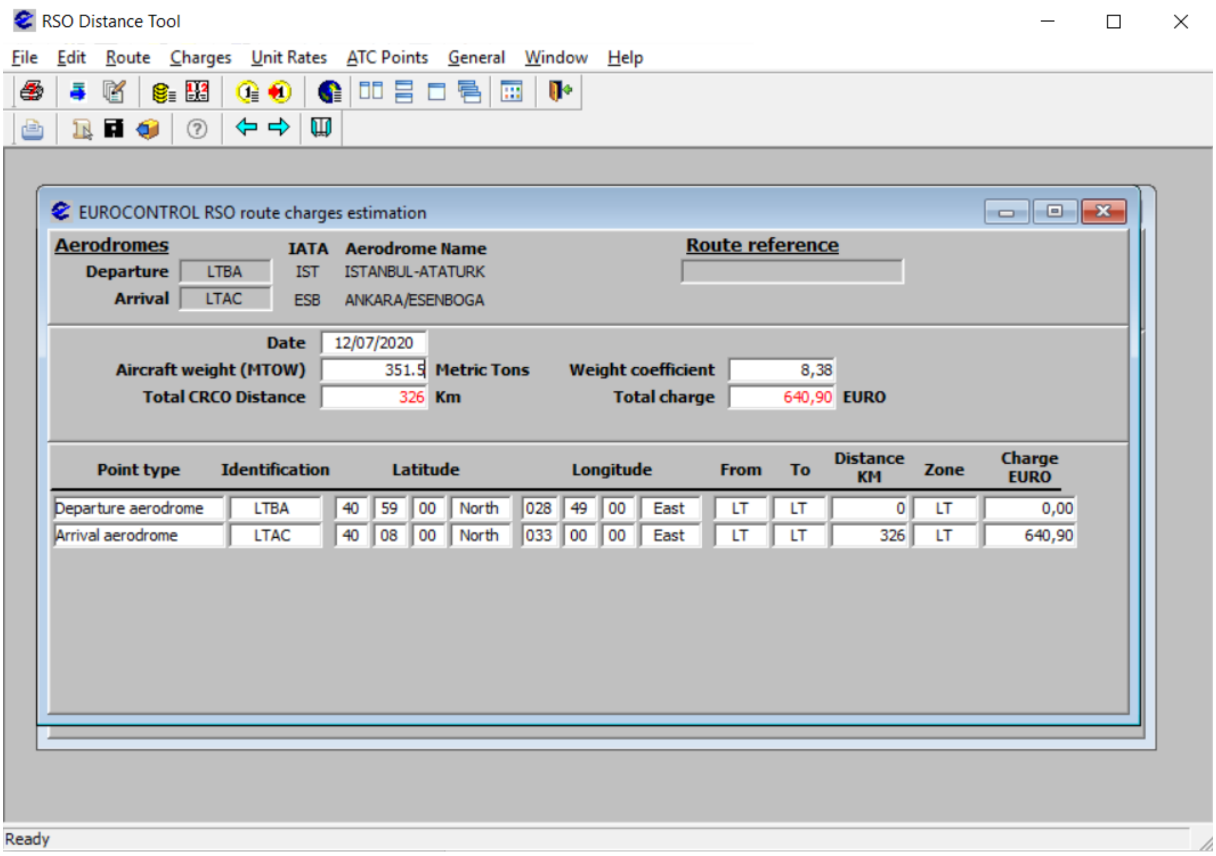


Fig. 5.6: Cost calculation interface of RSO Distance Tool

The overflight cost over Atlantic Ocean is calculated with using average overflight costs taken from Turkish Airlines Database. For Canada, overflight cost can be calculated on the website of NAV Canada, which is the Canada’s civil air navigation services provider [8]. The last part of overflight cost is for United States. Airlines do not have to pay for using airspace of United States if departure or arrival airport is a United States’ Airport. In this case, the cost is only paid to airport operator.

- **Delay Cost**

Delays on flight operation causes unexpected costs. Calculation methods of these costs are complicated and affected by many different data. In flight cost calculation software, coefficients obtained by real delay costs are used. Moreover, delay costs are simplified by Eurocontrol and published in reference [28]. For further information, it can be searched.

6. **Istanbul-Houston Route Planning**

In this part, the route for studying in thesis will be selected. Boeing 777-300ER is widely used by many airlines, as well as Turkish Airlines. There are 33 Boeing 777-300ER in Turkish Airlines' fleet. This type of aircraft is used in both short-range flights such as domestic flights and long-range flights. In shorter flights, the aircraft is not efficient to use. However, for fleet programming issues, they must be used. Also, in long-range flights, performance improvements are much more than short-range flights. For this reason, it is decided that the route will be selected to investigate in calculations.

For this manner, after long-range flights made by Turkish Airlines are searched, Istanbul-Houston flight is chosen. This flight departs from Istanbul Airport (IATA: IST, ICAO: LTFM) and arrives to Houston George Bush International Airport (IATA: IAH, ICAO: KIAH). This flight which was operating with 7 frequency per week before the Covid-19 effects on aviation. According to latest update, flights will be started with 3 frequency per week in June 2020. It has a callsign as TK33.

IST-IAH flight route will be created with using Great Circle Distance and OPT route. While creating the route of flight, average weather forecasts, Great Circle Distance, Overhead Costs, and routes that preferred by Turkish Airlines will be taken in account.

According to reference [30], Istanbul Airport and Houston George Bush Airport have coordinates as follows:

Airport	Latitude	Longitude
LTFM/ Istanbul Airport	41° 15' 41.47" N	28° 44' 33.79" E
KIAH/ Houston Airport	29° 58' 55.01" N	95° 20' 26.21" W

Table 6.1: Coordinates of Departure and Arrival Airports

The formula of Great Circle Distance mentioned in Chapter 2. It is used to calculate the Great Circle Distance between Istanbul Airport and Houston George Bush Airport. The result is 10,253 km which is equal to 5,536 nautical miles.

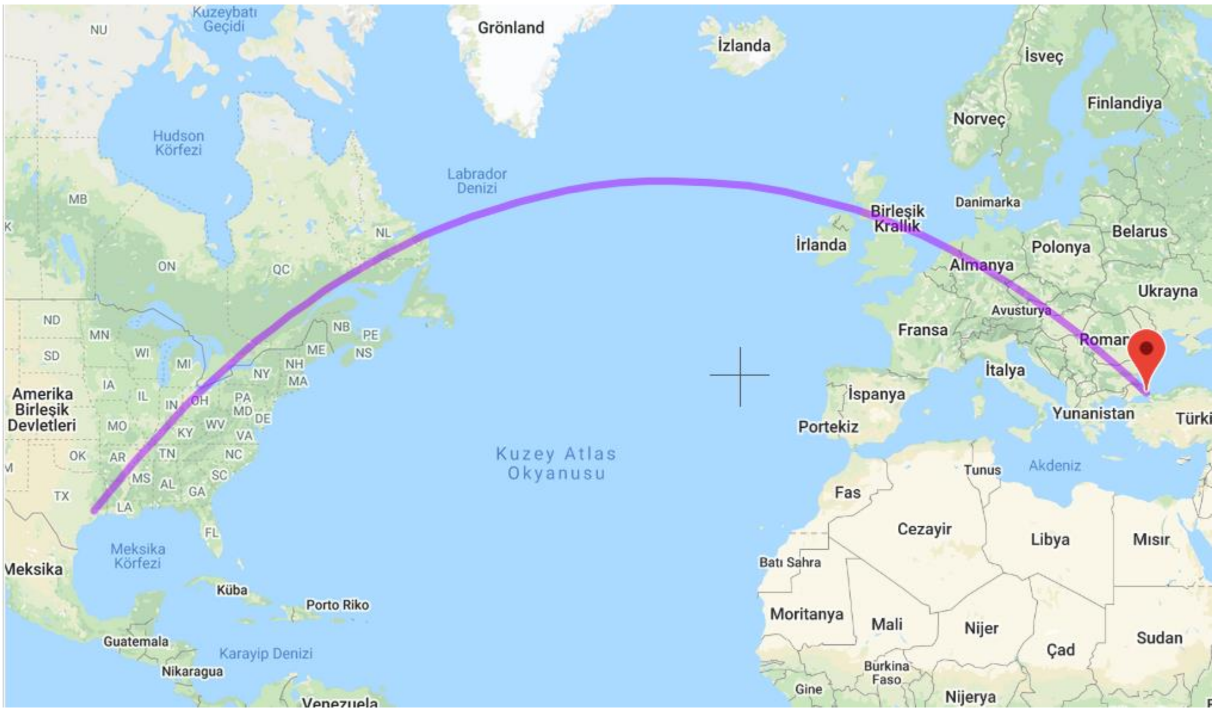


Fig. 6.1: Great Circle Distance of IST-IAH Route on Map [31]

Great Circle Route has entrance waypoints to Atlantic named MIMKU, to Canadian Airspace named JANJO, and to USA Airspace named DORET.

Studies on Flightradar24 [3] and Flight Plan Database [39] states that the distance of IST-KIH route differs from 5620 nautical miles to 5660 nautical miles (10,412 km to 10,481 km).

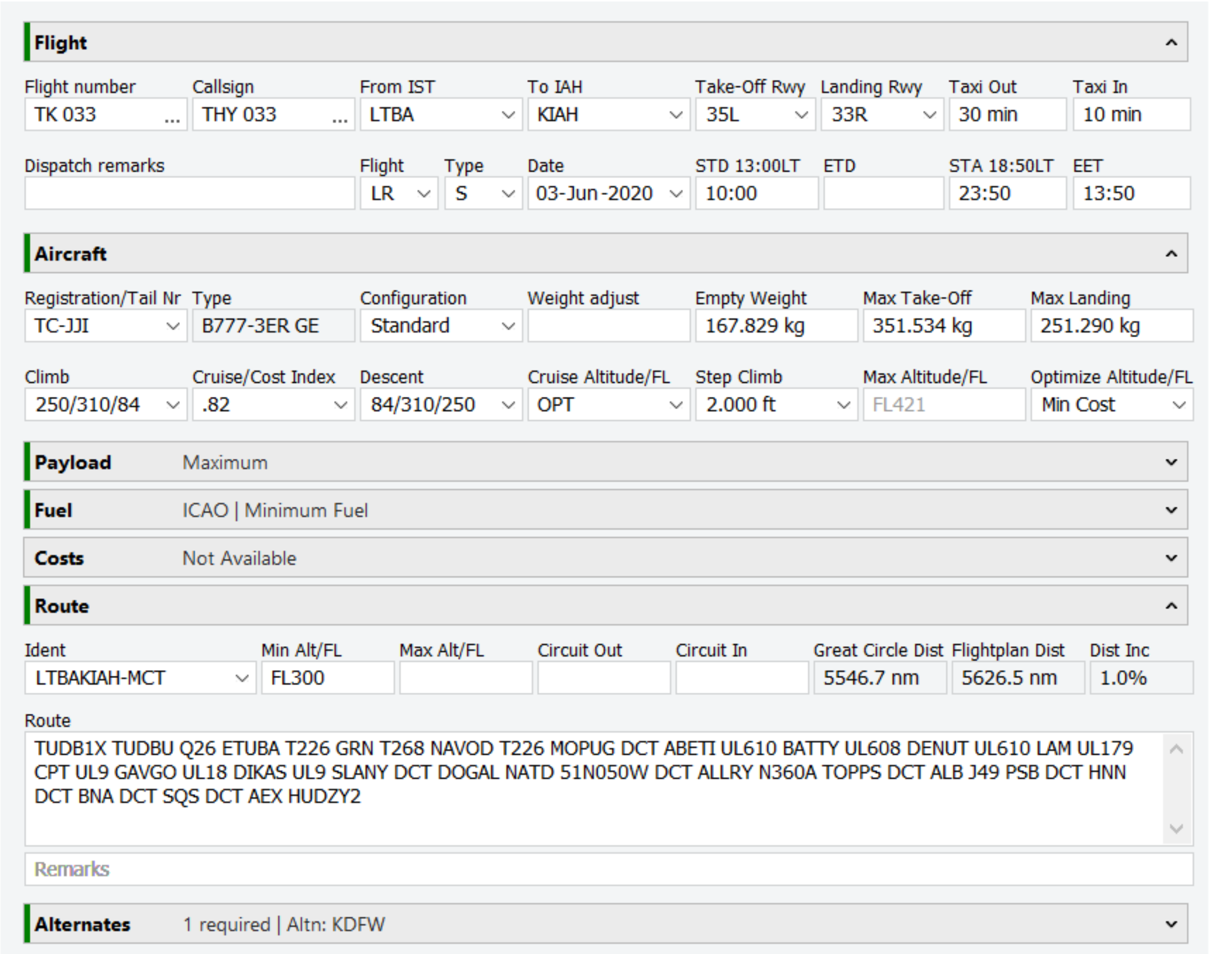


Fig. 6.2: PFPX Route Planning

In PFPX program, Istanbul Airport has not included. So, route is planned from Ataturk Airport. Backup aerodrome at arrival is chosen as Dallas Fort Worth Airport (KDFW) which is 208 nm away from Houston Airport.

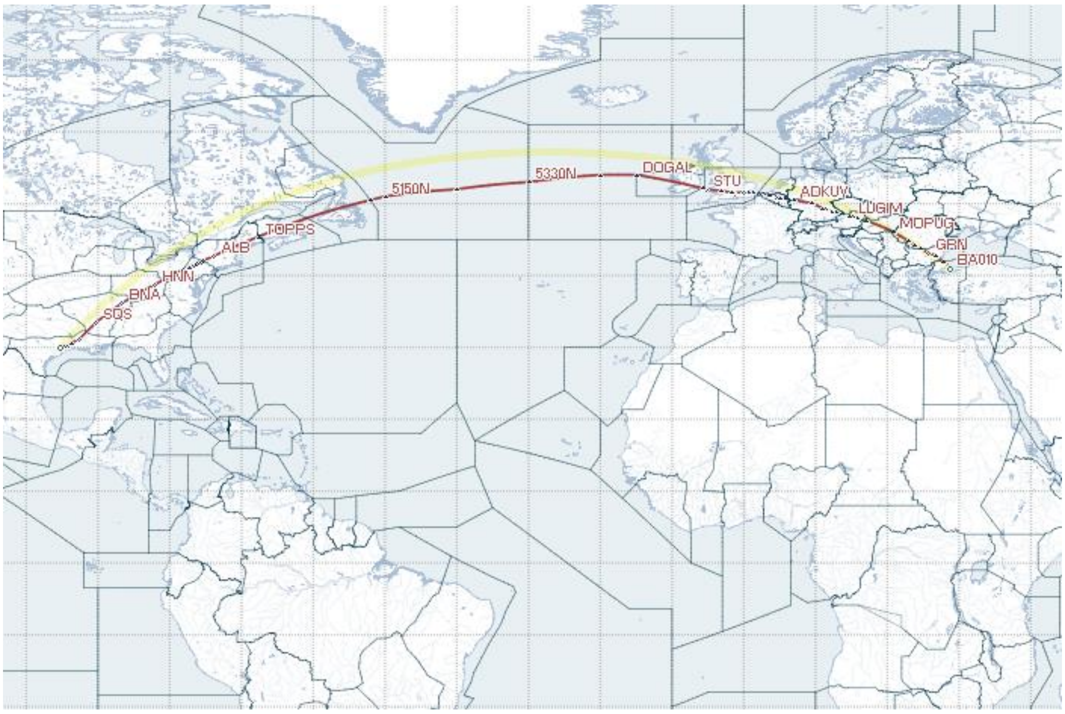


Fig. 6.5: OPT Route and Great Circle Distance

Fuel Planning (kg)	ICAO	Fuel	Time
TRIP		98.786	11:56
CONT 5%		4.939	00:42
HOLD	KIAH	3.513	00:30
ALTN	KDFW	5.066	00:37
FINAL RESV		3.506	00:30
MIN T/O		115.810	14:15
TAXI		1.020	00:30
RELEASE	LTBA	116.830	14:45
ARR FUEL	KIAH	16.684	02:09
Load Planning (kg)	**TC-JJI**	**Plan**	**Limit**
Empty Weight		167.829	
Payload		66.437	
Zero Fuel Weight		234.266	237.682
Fuel		116.830	147.850
Ramp Weight		351.096	351.534
Take-Off Weight LTBA		350.076	351.534
Landing Weight KIAH	Limit	251.290	251.290
Underload		0	Lim LDW

Fig. 6.3: Required Fuel Calculated by PFPX

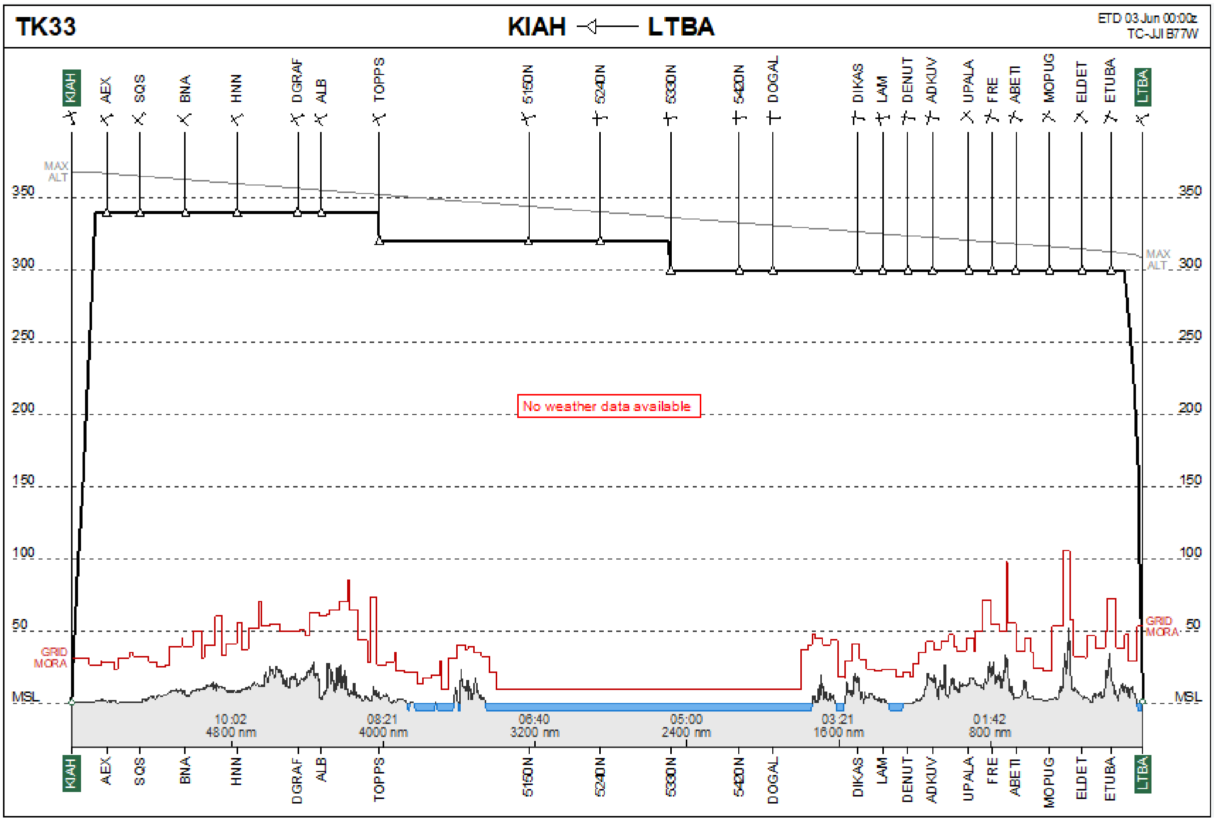


Fig. 6.4: OPT Flight Chart

7. Performance Calculations

Performance calculation methods, aircraft's performance parameters, and other needed information are mentioned in previous chapters. Also, two route which are GCD and OPT routes, are planned. In this chapter, performance calculations of planned routes will be made.

As mentioned in previous chapters, since change in take-off and landing phases of flight have not significant effects on total cost and fuel consumption, they are not included in this project's performance calculations. The calculations are made for climbing, cruise, and descending phases of flight.

In calculations, aircraft parameters in PFPX program is used. The air conditions are set as ISA standards. In cruise, calculations will be made for two different season average values, because the major fuel consumption of flight is in cruise phase.

7.1 Climbing Performance

Climbing phase of aircraft is the time between take-off and cruise. In general, Boeing 777-300ER retracts its landing gear at 400 feet and flap at 1500 feet altitude. So, climbing phase will be taken as starting at 1500 feet altitude.

Optimum cruise altitude can be described as the altitude which a given thrust setting has the maximum range speed as a result. It is dependent on weight of aircraft, so it changes during the time at flight. Especially in long-range flights, the change in optimum cruise altitude has significant values, so that keeping flight at same altitude becoming insufficient for operator. In this case, pilots can change altitude to maintain the performance of aircraft is in satisfying limits.

To determine the altitude which climbing phase ends and cruise phase starts, Fig. 8.1 can be used. Our flight has set as starting with maximum take-off weight. So, at the cruise start, aircraft's weight is about to 349,000 kgs. So, according to Fig. 8.1, 29000 feet altitude is the optimum altitude for our cruise start. However, the altitudes of aircrafts which head to West are as 28000, 30000, 32000 feet. So, the cruise starting altitude is determined as 30000 feet.

It can be stated that climbing phase of this flight is from 1500 feet to 30000 feet.

Optimum Altitude

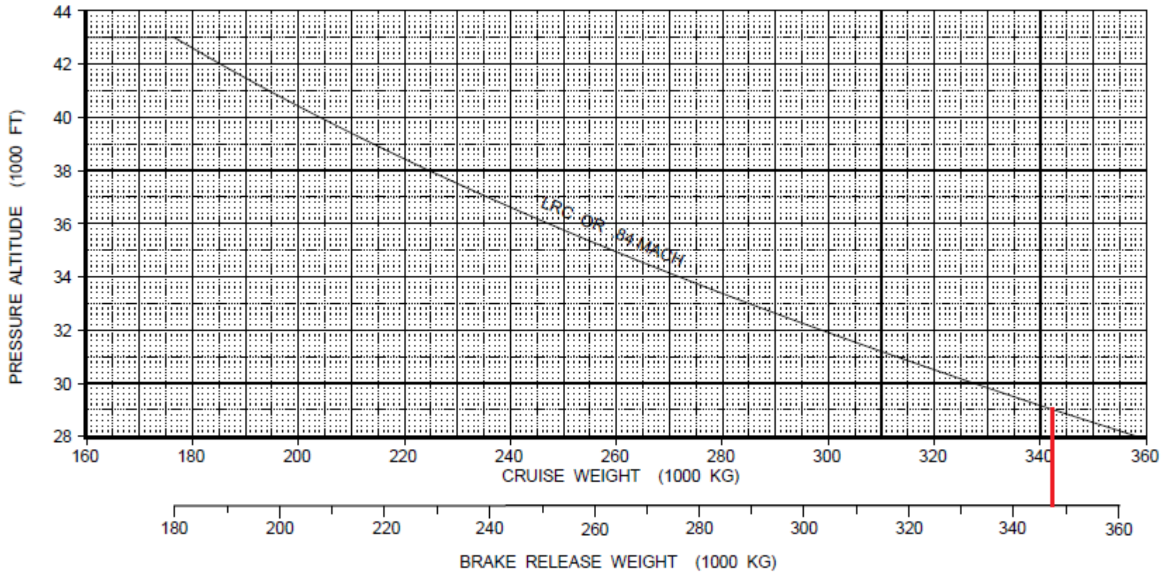


Fig. 7.1: Optimum Altitude for B777 [32]

At FPFX program, climbing performance parameters are used with speed (250/310/.84). Aircraft reaches FL300 in 14 minutes after take-off, and the distance taken is 87 nm. Fuel consumption from take-off to cruise is 4.6 tons. TAS at end of climbing is 483 kts.

```
--------------------------------------------------------------------------------
DEP: LTBA/IST 35L

AWY       WAYPOINT   MT     ALT  WND/VEL    TAS   REM  FUEL REM / USED    LEG   ACC
          NAME              TMP     FREQ     GS  DIST  POSITION           ETO / ATO
--------------------------------------------------------------------------------
          LTBA/35L     163                             115.8 /   1.0
          ATATURK                                5626  N4058.2 E02848.4 ...../.....


TUDB1X    BA010     354*CLB     000/000              7      114.3 /   1.8 :01   00:01
                                                 5620  N4104.8 E02848.3 ...../.....


TUDB1X    BA041     322*CLB     000/000              5      113.8 /   2.2 :01   00:02
                                                 5615  N4109.1 E02844.7 ...../.....


TUDB1X    RIMBO     322*CLB     000/000             16      113.0 /   3.1 :03   00:05
                                                 5598  N4122.9 E02833.1 ...../.....


TUDB1X    TUDBU     310*CLB     000/000             50      111.1 /   5.0 :07   00:12
-LBSR                                            5549  N4158.0 E02746.6 ...../.....


Q26       *TOC      309FL300    000/000  483        20      111.2 /   5.6 :02   00:14
                           -44           483   5529  N4211.9 E02727.6 ...../.....
```

Fig. 7.2: Flight Route and Fuel Consumption at Climbing

7.2 Cruise Performance

Cruise is the most important part of performance and cost calculations. Because most of flight time spends and major part of fuel consumes in this phase. So, improvements on cruise have significant effects. Because of this effect, the case is worked in different weather conditions.

Keeping altitude at same value in long-range flight causes performance decrease. In reference [32], the increase amounts in trip fuel when keeping flight at different altitude stated:

Cruise fuel penalties include:
· ISA + 10°C: 1% increase in trip fuel
· 2,000 feet above optimum altitude, 1 to 2% increase in trip fuel
· 4,000 feet below optimum altitude, 4 to 5% increase in trip fuel
· 8,000 feet below optimum altitude, 12 to 14% increase in trip fuel
· Cruise speed M.01 above schedule, 1 to 2% increase in trip fuel

It is decided that use step climb. Step climb is a series of altitude gains that is used to improve fuel economy. Step size in commercial flights usually is chosen as 2,000 feet. It is decided that to use 2,000 feet step size. There are two climbing steps, and cruise phase is ended at 34000 feet altitude (FL340).

Cruise Phase #	Starting Coordinates	Ending Coordinates	Distance (nm)
1 (FL300)	N4201.6 E02741.8	N5300.0 W03000.0	2388
2 (FL320)	N5300.0 W03000.0	N4520.4 W06744.3	1534
3 (FL340)	N4520.4 W06744.3	N3035.2 W09342.4	1509

Table 7.1: Steps of cruise flight for OPT

Cruise Phase #	Starting Coordinates	Ending Coordinates	Distance (nm)
1 (FL300)	N4203.4 E02714.7	N5306.1 E00318.2	1165
2 (FL320)	N5306.1 E00318.2	N3125.1 W09354.7	4169

Table 7.2: Steps of cruise flight for GCD

According to coordinates given above and operational flight plan (OFP), Phase#1 is overflown of Europe, Phase#2 is overflown of Atlantic and Phase#3 is overflown of United States. So, they can be worked with Europe’s, Atlantic’s, and United States average weather conditions.

Now, atmospheric conditions in cruise phases should be searched. First, ISA standards are as follows at given altitudes:

Flight Level	Temperature (℃)	Pressure (δ)	Density (σ)
FL300	-44.4	0.2970	0.3741
FL320	-48.4	0.2709	0.3473
FL340	-52.4	0.2467	0.3220

Table 7.2: ISA Standards for Flight Levels

Also, from the reference [33], average weather conditions for route is searched. Data of the year 2019 is used.

	Summer Averages			Winter Averages		
	Average Wind GCD / OPT	T (℃)	ISA (℃)	Average Wind GCD / OPT	T (℃)	ISA (℃)
Cruise Phase #1 FL300	+30 kts/+20 kts	-41.65	-44.4	+5 kts/+10 kts	-49.55	-44.4
Cruise Phase #2 FL320	+20 kts/+15 kts	-50.39	-48.4	+7 kts/+7 kts	-57.39	-48.4
Cruise Phase #3 FL340	+5 kts / +4 kts	-52	-56.3	+25 kts/+20 kts	-46	-56.3
Average	+18 kts/+13 kts	-48.01	-49	+9kts / +9kts	-50.98	-51

Table 7.3: Comparison of ISA and 2019 average weather conditions

As seen in table 7.3, temperature difference for Cruise Phase #1 is 3 ℃ in summer, -5 ℃ in winter, for Cruise Phase #2 is -2℃ in summer, -9℃ in winter, and in for Cruise Phase is -4 ℃ in summer, and 10 ℃ in winter. However, in average values of all cruise route, the difference is less. In summer 3℃ and in in winter 0.02℃ difference between average weather conditions and ISA Standards.

7.3 Descending Performance

Descending for Houston George Bush International Airport starts at FL340 and ends at 0 altitude. Also, descending speeds are set as 0.84/310/250 kts and the atmospheric conditions are set as ISA conditions.

According to flight route plan, aircraft starts to descend at location which N3041.9 W09330.5. The point where the descend starts is 62 nm away from arrival airport. Descending and landing phase takes 24 minutes time and 0.5 tons of fuel consumed.

```
HUDZY2   *TOD      237FL340    000/000  475     62      14.3 /  99.2 :08   11:32
                          -52           475    125  N3041.9 W09330.5 ...../.....


HUDZY2   BRWCK     236*DES     000/000          12      14.3 /  99.3 :02   11:34
                                             113  N3035.2 W09342.4 ...../.....


HUDZY2   WAPPL     236*DES     000/000          39      14.2 /  99.4 :05   11:39
                                              74  N3013.9 W09419.8 ...../.....


HUDZY2   HUDZY     251*DES     000/000          26      14.1 /  99.5 :04   11:43
                                              48  N3006.2 W09448.5 ...../.....


HUDZY2   CLWSN     251*DES     000/000           6      14.1 /  99.5 :01   11:44
                                              42  N3004.4 W09455.1 ...../.....


HUDZY2   SWWAA     251*DES     000/000          13      14.0 /  99.6 :03   11:47
                                              29  N3000.5 W09509.4 ...../.....


HUDZY2   LUDVG     194*DES     000/000          16      13.9 /  99.7 :03   11:50
                                              13  N2945.6 W09514.5 ...../.....


HUDZY2   KIAH/33R  33596                     13      13.6 / 100.0 :06   11:56
         GEORGE BUSH INTE                           N2957.5 W09520.4 ...../.....
```

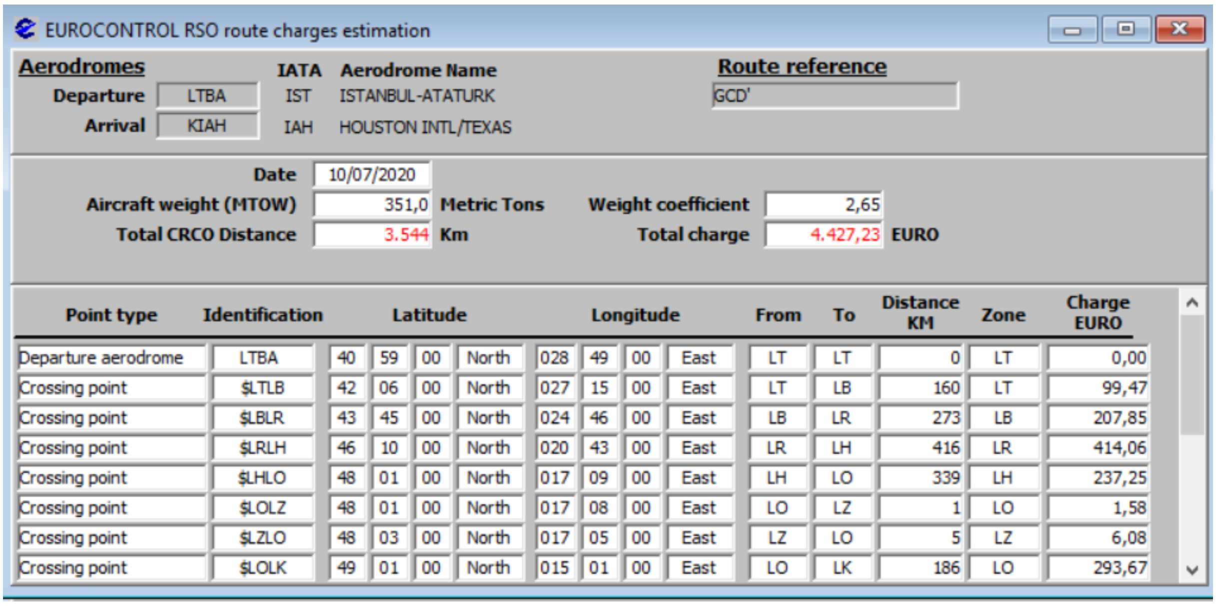
Fig. 7.3: Descending Phase Flight Plan

8. IST-IAH Flight Operation Cost Calculations

IST-HOU flight operation cost changes in time and route. Delay cost are not included in this study since it is different for each airline. So, it is assumed that there are no delays for planned flights.

- Overflight Cost

In GCD route, the aircraft flies over 4 main regions: Europe, Atlantic, Canada, and United States. The overflight cost of Europe is calculated with RSO Distance Calculator by Eurocontrol which is equal to 4,427.23 € or 4997.06 $. The other overflight fees are 168.30 $ for Atlantic, 1192.52 $ for Canada [1], and 1403.28 $ for United States. It is stated that USA does not demand overflight fee to aircrafts which makes landing or take-off to USA Airports. Calculated value is the fee of landing to Houston Airport [35]


EUROCONTROL RSO route charges estimation

Aerodromes | IATA | Aerodrome Name | **Route reference**

Departure: LTBA | IST | ISTANBUL-ATATURK | GCD'

Arrival: KIAH | IAH | HOUSTON INTL/TEXAS

Date: 10/07/2020

Aircraft weight (MTOW): 351,0 Metric Tons — Weight coefficient: 2,65

Total CRCO Distance: 3.544 Km — Total charge: 4.427,23 EURO

Point type	Identification	Latitude				Longitude				From	To	Distance KM	Zone	Charge EURO
Departure aerodrome	LTBA	40	59	00	North	028	49	00	East	LT	LT	0	LT	0,00
Crossing point	$LTLB	42	06	00	North	027	15	00	East	LT	LB	160	LT	99,47
Crossing point	$LBLR	43	45	00	North	024	46	00	East	LB	LR	273	LB	207,85
Crossing point	$LRLH	46	10	00	North	020	43	00	East	LR	LH	416	LR	414,06
Crossing point	$LHLO	48	01	00	North	017	09	00	East	LH	LO	339	LH	237,25
Crossing point	$LOLZ	48	01	00	North	017	08	00	East	LO	LZ	1	LO	1,58
Crossing point	$LZLO	48	03	00	North	017	05	00	East	LZ	LO	5	LZ	6,08
Crossing point	$LOLK	49	01	00	North	015	01	00	East	LO	LK	186	LO	293,67

Fig. 8.1: Overflight Cost Calculations of GCD Route at RTO Distance Software

OPT route has similar overflight cost calculation methods. The overflight cost of Europe is calculated with RSO Distance Calculator by Eurocontrol which is equal to 4971 $. The other overflight fees are 158.4 $ for Atlantic, 0 $ for Canada [34], and 1403.28 $ for United States which includes landing fee at Houston Airport.

	Regions	GCD	OPT
Overflight Fees	Europe	4997.06 $	4971.35 $
	Atlantic	168.30 $	158.4 $
	Canada	1191.52 $	0 $
	United States	1403.28 $	1403.28 $
	Total	7760.16 $	6533.03 $

Table 8.1: Overflight Fees of both routes

- Maintenance Cost

According to Fig. 6.2, maintenance costs for 10+ hour flights can be assumed as follows: 110$ for aircraft material, 150$ for aircraft labor, 18$ for engine labor, and 500$ for engine material. The total maintenance cost is 778$. However, the aircraft is not same as Fig. 6.2, so it is decided to assume maintenance cost for one hour as 900$ for Boeing 777-300ER.

	Airframe Materials	Airframe Labor	Engine Material	Engine Labor
B777-200	110$	150$	500$	18$

Table 8.2: Maintenance Cost for Boeing 777-200

- Crew Cost

Each airline has different salary standards for their crew. This causes that crew cost for each airline is different and obtaining the certain values is nearly impossible. As an average value, cost of crew members can be assumed as follows: 25$/h cabin crew and 100$/h for cockpit crew. It is known that IST-HOU flight is made with 3 cockpit crews and 13 cabin crews. The total crew cost is 625$/h.

- Fuel Cost

Fuel price is 321.63$/ton or 14.58 cent/lb., as mentioned in Fig. 6.3. The total fuel cost can be calculated by multiplying the price by total fuel consumed.

8.1 Cost Index

Cost Index is calculated that dividing cost depends on time by fuel price. In this divide, cost depends on time should be in $/hour and fuel price should be in cent/lb. form. As stated in pervious section, time dependent cost is calculated as 1525$/h and fuel price are 14.58 cent/lb. With using these values, cost index can be calculated.

$$CI = \frac{1525}{14.58} \sim 105$$

Different cost index values will be calculated for both routes and compared in performance and cost criteria. CI 0 that CI value that minimizes cost with regarding flight time optimization will be used in calculations. Also, the calculated CI value which is 105 and average CI value for B777 which is 120 according to Fig. 2.7 will be used. The results will be compared it terms that flight time, cost, fuel consumption, aircraft weight and payload. After the comparison, the optimum CI value for different seasons will be determined.

In PFPX program, performance calculations for different CI values and weather conditions are made and flight time, maximum payload, fuel weight and fuel consumption values for each flight have obtained.

Aircraft	Type	Cruise	Dist (nm)	EET	Payload	Release	Burnoff	Route/Remarks
TC-JJI	B77W	CI 120	5626.5	11:27	69.853 kg	111.794 kg	98.741 kg	OPT ROUTE WINTER+9 HW +0 TEMP. ISA
TC-JJI	B77W	CI 105	5626.5	11:30	69.853 kg	111.541 kg	98.500 kg	OPT ROUTE WINTER+9 HW +0 TEMP. ISA
TC-JJI	B77W	CI 0	5626.5	11:37	69.853 kg	110.785 kg	97.780 kg	OPT ROUTE WINTER+9 HW +0 TEMP. ISA
TC-JJI	B77W	CI 120	5626.5	11:15	69.853 kg	109.358 kg	96.513 kg	OPT ROUTE SUMMER +18 HW +1 TEMP. ISA
TC-JJI	B77W	CI 105	5626.5	11:16	69.853 kg	109.100 kg	96.268 kg	OPT ROUTE SUMMER +18 HW +1 TEMP. ISA
TC-JJI	B77W	CI 0	5626.5	11:23	69.853 kg	108.459 kg	95.657 kg	OPT ROUTE SUMMER +18 HW +1 TEMP. ISA

Fig. 8.2: Flight Performance Values of OPT Route for different CI and weather conditions

Aircraft	Type	Cruise	Dist (nm)	EET	Payload	Release	Burnoff	Route/Remarks
TC-JJI	B77W	CI 120	5551.4	11:18	69.853 kg	111.147 kg	98.125 kg	GCD WINTER +9 HW +0 TEMP ISA
TC-JJI	B77W	CI 105	5551.4	11:19	69.853 kg	110.905 kg	97.894 kg	GCD WINTER +9 HW +0 TEMP ISA
TC-JJI	B77W	CI 0	5551.4	11:28	69.853 kg	109.552 kg	96.608 kg	GCD WINTER +9 HW +0 TEMP ISA
TC-JJI	B77W	CI 120	5551.4	11:05	69.853 kg	108.693 kg	95.880 kg	GCD SUMMER +18 HW +1 TEMP ISA
TC-JJI	B77W	CI 105	5551.4	11:06	69.853 kg	108.452 kg	95.650 kg	GCD SUMMER +18 HW +1 TEMP ISA
TC-JJI	B77W	CI 0	5551.4	11:15	69.853 kg	107.125 kg	94.389 kg	GCD SUMMER +18 HW +1 TEMP ISA

Fig. 8.2: Flight Performance Values of GCD Route for different CI and weather conditions

Fuel Planning (kg)	ICAO	Fuel	Time
TRIP		94.290	11:06
CONT 5%		4.715	00:40
ALTN	KDFW	4.927	00:36
FINAL RESV		3.500	00:30
MIN T/O		107.432	12:52
TAXI		1.020	00:30
RELEASE	LTBA	108.452	13:22
ARR FUEL	KIAH	12.802	01:36

Load Planning (kg)	TC-JJI	Plan	Limit
Empty Weight		167.829	
Payload		69.853	
Zero Fuel Weight	Limit	237.682	237.682
Fuel		108.452	147.850
Ramp Weight		346.134	351.534
Take-Off Weight LTBA		345.114	351.534
Landing Weight KIAH		250.824	251.290
Underload		0	Lim ZFW
Max Extra Fuel		466	Lim LDW

Fig. 8.3: Planning Summary of GCD Route with 105 CI and Summer Weather Conditions

Now, total cost of each flight can be calculated with using calculated values in earlier sections.

Seasons	Routes	CI	Burnoff Fuel Weight (kg)	Flight Fuel Cost ($)	Flight Time (hour)	Flight Time Dependent Cost ($)	Overflight Costs ($)	Total Flight Cost ($)
Winter	GCD	0	96608	31011.2	11:28	17486.7	7760.16	56258.06
		105	97894	31423.9	11:19	17257.9	7760.16	56441.96
		120	98125	31498.1	11:18	17232.5	7760.16	56490.76
	OPT	0	97780	31387.4	11:27	17461.3	6533.03	55381.73
		105	98522	31625.6	11:30	17537.5	6533.03	55696.13
		120	98741	31695.9	11:37	17715.4	6533.03	55944.33
Summer	GCD	0	94389	30298.9	11:15	17156.3	7760.16	55215.36
		105	95650	30703.7	11:06	16927.5	7760.16	55391.36
		120	95880	30777.5	11:05	16902.1	7760.16	55439.76
	OPT	0	95657	30705.9	11:23	17359.6	6533.03	54598.53
		105	96268	30902.0	11:16	17181.7	6533.03	54616.73
		120	96513	30980,7	11:15	17156.3	6533.03	54670.03

- *Fuel price is 0.321 $/kg*
- *Time Dependent price is 1525 $/hr.*

Table 8.3: Costs of Mentioned Flights

8.3 Redispatch Technique

In this part, Redispatch Technique is applied on GCD and OPT routes. The first way of Redispatch Technique which is the contingency fuel is 10% of the fuel consumed between redispatch point and main destination airport.

In this manner, Redispatch Point for GCD Route is determined as waypoint ROD. The airports that have longer than 3000 meters runway and a distance from ROD less than 250 nm are searched. From the list of airports, Chicago O'Hare Airport (ICAO Code: KORD) is chosen because Turkish Airlines has regular operations in that airport. O'Hare Airport is located to 203 nm far away on northwest direction from ROD Waypoint. Also, Fort Wayne International Airport (KFWA) is chosen as intermediate backup aerodrome.

For the OPT Route, DGRAF Waypoint is chosen as Redispatch Point. New York Kennedy International Airport (KFJK) is chosen as intermediate airport, which has a 127.2 nm distance in southeast direction. The backup airport is New York Newark Airport (KEWR) which is 18.1 nm away from JFK Airport.

Aircraft	Type	Cruise	Dist (nm)	EET	Payload	Release	Burnoff	Route/Remarks
TC-JJI	B77W	CI 105	5626.5	11:21	59.844 kg	100.869 kg	92.355 kg	OPT SUMMER REDISPATCH
TC-JJI	B77W	CI 105	5626.5	11:34	59.391 kg	102.942 kg	94.342 kg	OPT WINTER REDISPATCH
TC-JJI	B77W	CI 105	5551.4	11:23	65.309 kg	103.397 kg	94.882 kg	GCD WINTER REDISPATCH
TC-JJI	B77W	CI 105	5551.4	11:10	65.572 kg	101.294 kg	92.852 kg	GCD SUMMER REDISPATCH

Fig. 8.4: Flight Performance Values for Redispatched Routes

The obtained values are used in total flight operation cost calculations.

Season	Route	CI	Fuel Burnoff (kg)	Fuel Cost ($)	Flight Time	Time Depen-ding Cost ($)	Over-flight Cost ($)	Total Flight Cost ($)
Winte	G	105	94882	30457.12	11:23	17359.58	7760.16	55576.86
	O	105	94342	30283.78	11:34	17639.16	6533.03	54455.97
Summ	G	105	92852	29805.49	11:10	17029.16	7760.16	54594.81
	O	105	92355	29645.95	11:21	17308.75	6533.03	53487.73

- *Fuel price is 0.321 $/kg*
- *Time Dependent price is 1525 $/hr.*

Table 8.4: FOC of Redispatched Routes

Fuel Planning (kg)	ICAO	Fuel	Time	Init Release	Fuel	Time
TRIP	LTBA-DGRAF	75.439	08:50	LTBA-DGRAF	75.439	08:50
TRIP	DGRAF-KIAH	15.556	02:31	DGRAF-KJFK	793	00:24
CONT 5%	DGRAF-KIAH	778	00:07	LTBA-KJFK	3.812	00:33
ALTN	KDFW	4.766	00:36	KEWR	1.275	00:08
FINAL RESV		3.310	00:30		3.514	00:30
MIN T/O		99.849	12:33		84.833	10:55
EXTRA		0	00:00		15.016	02:08
TAXI		1.020	00:30		1.020	00:30
RELEASE	LTBA	100.869	13:03	LTBA	100.869	13:33
ARR FUEL	KIAH	8.514	01:03	KJFK	23.277	03:09

Load Planning (kg)	TC-JJI	Plan	Limit
Empty Weight		167.829	
Payload		59.844	
Zero Fuel Weight		227.673	237.682
Fuel		100.869	147.850
Ramp Weight		328.542	351.534
Take-Off Weight LTBA		327.522	351.534
Landing Weight KIAH		236.527	251.290
Landing Weight KJFK	Limit	251.290	251.290
Underload		0	Lim LDW
Max Extra Fuel		14.763	Lim LDW

Fig. 8.5: Flight Summary of Redispatched OPT Route

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