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EFFECT OF COST INDEX ON OPTIMIZATION OF ECONOMY CRUISE SPEED FOR A JET AIRLINER

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ABSTRACT

This paper discusses the effect of cost index on the optimization of economy cruising speed for a jet airliner, for the purpose of minimizing the direct operating cost of the commercial flights. An algorithm is developed to calculate the optimum economy cruise speed for Airbus A320ceo. The aerodynamic and the propulsive coefficients are obtained from the base of aircraft data (BADA) provided by EUROCONTROL. The algorithm is capable of computing aircraft performance parameters for all atmospheric conditions, such as ambient temperature and pressure at optimum cruising altitude, the effect of wind, and the impact of those conditions on aerodynamic forces and fuel consumption. The optimization of the model for this paper is conducted for standard atmospheric 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 direct operating cost. The algorithm determines the optimum economy speed by computing the minimum value of the economy cruise cost function, which represents the minimal costs and fuel-burn. The results discuss also the penalties of using uncertain estimations of cost indices on the direct operating costs.

Key words: Cost Index, Economy Cruise Speed, Speed Optimization, Direct Operating Cost.

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INTRODUCTION

This paper discusses the effect of cost index on the optimization of economy cruising speed for a jet airliner, to minimize the direct operating cost of the commercial flights. An algorithm is developed to calculate the optimum economy cruise speed for Airbus A320ceo. The aerodynamic and the propulsive coefficients are obtained from the base of aircraft data (BADA) provided by EUROCONTROL. The algorithm is capable of computing aircraft Minimizing trip costs has become an increasingly important factor for airline companies in recent decades which is mainly achieved by reducing aircraft fuel consumption. The main reason for that is the fuel, which is the largest section of airlines operating costs. According to IATA, this section is expected to be about $180 billion in 2018 (accounting for about 23.5% of operating costs at $73.0/barrel Brent). This is an increase of 20.5% over 2017 and is almost twice the $91 billion fuel cost for 2005, which equivalent to 22% of operating costs at $54.5/barrel Brent. In the year 2019, the fuel bill is expected to be $200 billion, accounting for around 24.2% of operating costs at $65/barrel Brent [IATA, 2018].

Turkish Airlines, for instance, report an increase in the number of flights in the year 2017 by 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% [THY, 2018]. Generally, aircraft operators aim to operate efficient flights by reducing the costs of operations. However, the costs are not only directly connected to the amount of fuel consumed for a specific flight, rather it is a function of the time of the operation. In general, the cost of the fuel is directly associated with the direct operating costs (DOC), which can be defined as all expenses associated with operating the airplane, it can be easily calculated based on fuel prices in the site of the operation. On the other hand, there are indirect operating costs (IOC), which include other costs of operations other than the fuel costs, those are not considered as the operating costs of the aircraft itself, rather, they are classified in two different sections which are ground operating costs and system operating costs, such as, station and ground expenses - e.g., ground crew; and transport; handling fees paid to others, passenger services - e.g., flight crew salaries (could be DOC), and passenger insurance, ticketing, sales, advertisement, and administrative duties [Belobaba et al.,2016 , Eller and Moreira, 2014].For an airline, the decision of which choice is better to be adopted, flying faster to save time or slower to save fuel, is a direct function of the cost index (CI), which is considered as a base of all economic performance calculations. [EUROCONTROL, 2012]. In order to help airline operators to investigate the effect of selecting the most accurate cruising speed, a precise aircraft performance model is needed which will result in accurate estimation of the fuel and the time needed for the flight.

The APM algorithm, developed in MATLAB, was applied on an aircraft performance model that considers the geometry, aerodynamic and propulsive characteristics of Airbus A320-214. For the validation of the model the optimal speed and fuel burn calculations were compared with the data provided by the Flight Crew Operating Manual (FCOM) [Airbus 1,2005], and from real flight data, which is collected from several flights in different flight conditions.[Gilani, 2019]. Graphical optimization method is used and the data for the analysis was obtained by MATLAB, this method is found to suitable when there are one or two variables.

Real scenarios are analyzed by the algorithm to determine the optimum economy speed in terms of economy Mach number (MECON), by computing the minimum value of the cost index function that represents the minimal costs and fuel-burn. The results discuss also the consequences of using uncertain estimations of cost indices on the direct operating costs.

METHOD

Base of Aircraft Data (BADA)

One of nowadays methods for estimating aircraft performance is the mathematical modeling, the concept of the modeling in this study is built based on the approach of the Base of Aircraft Data BADA which is an Aircraft Performance Model APM developed by EUROCONTROL, via mutual cooperation with the manufacturers and operators of the air fleets.

The BADA APM is developed for estimation of aircraft trajectories for the research and operations of Air Traffic Management (ATM). [Delgado,2009 , Eurocontrol, 2019,2016]

Aircraft Performance Model (APM)

BADA consists of two main components which are the model specifications and the aircraft database. The motion of the aircraft model is describe based on the model specifications through basic aerodynamic, propulsive and gravitational equations.

The model can perform nonlinear simulation according to the initial inputs and change in the mass due to fuel consumption during flight. APM diagram is shown in (Figure 1).

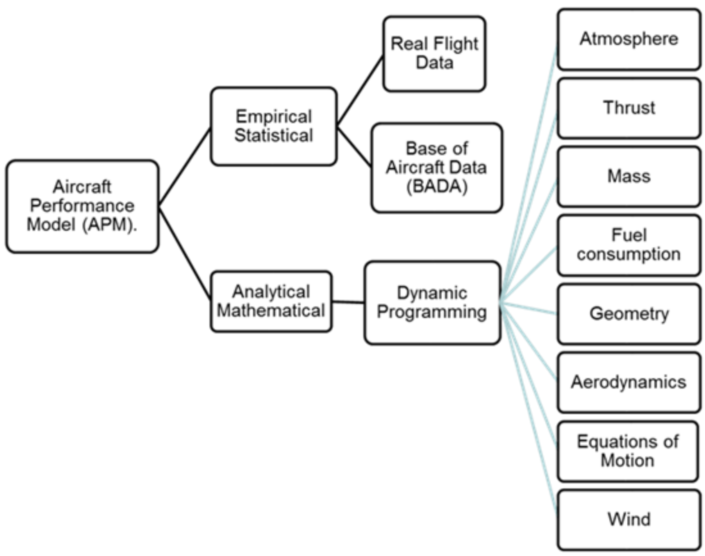

Figure 1. APM diagram

In this paper, APM of A320-214 equipped with CFM 56-5B4 is individually developed by developing a Matlab algorithm, the model is developed based on the polynomial equations provided by BADA, those equations provide a general approach for modeling of a jet airliner. [BADA4, 2012].

The model is capable of calculating the performance of the aircraft at all aircraft configurations within its flight envelop and for all atmospheric conditions including ISA deviations and variations in wind and tropopause.

Airbus A320 general view is shown in (Figure 2).

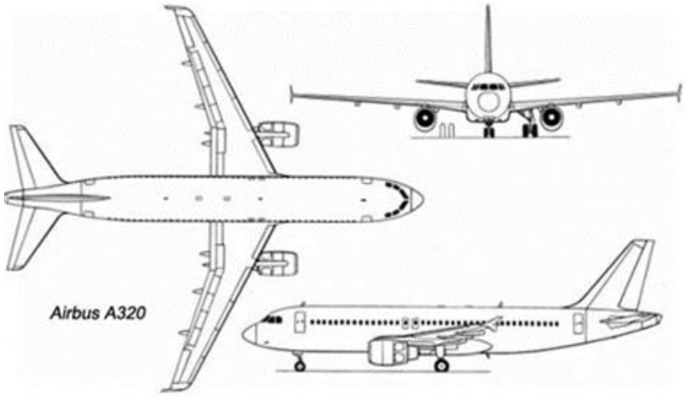

Figure 2. Airbus A320 General View [Airbus FCOM,2005]

Bada provides Propulsive Forces Model (PFM), for this work Airbus A320-214 PFM is used, which is Turbo Fan Model (TFM). The model provides the thrust as a function of reference aircraft mass, atmospheric conditions and thrust coefficient C_T, which is the general formulation of the thrust force as expressed in Equation (1).

$$Th = \delta . W_{mref} . C_T \tag{1}$$

where $\mathbf{W_{mref}}$ is the aircraft reference weight which is 77000 kg for Airbus A320 [Airbus 1, 2005].

The thrust coefficient C_T provided for this model is based on cruise configuration as a function of Mach number, throttle parameter δ_T and thrust parameters a_n, which are given in the BADA database [BADA4, 2016], as shown in equation (2).

$$C_T = f\,(a_{1\text{-}36},\, \delta_T,\, M) \tag{2}$$

where

$$\delta_T = f\,(b_{1\text{-}36},\, \delta,\, M) \tag{3}$$

where, $a_{1\text{-}36}$ and $b_{1\text{-}36}$ are the parameter given in the BADA database for the cruise phase.

One of the most important parameters of aircraft performance is the fuel consumption which is expressed as the rate of fuel flow per fraction of time. Fuel flow formula is shown in Equation (4),

$$FF = \delta . \sqrt{\theta} . W_{mref} . a_0 . L_{HV}^{-1} . C_F \tag{4}$$

The fuel flow FF is a function of pressure ratio δ, speed of sound (a) and temperature ratio θ, which is varying with the recommended altitude and atmospheric conditions. It is also a function of fuel low heat value LHV, which is the parameter for the quality of the jet fuel, and the fuel coefficient CF which is provided as a function of Mach number, C_T and fuel coefficients f_n which are 25 parameters given in the BADA database as shown in Equation (5), the propulsive coefficients used for this code are those provided for CFM 56-5B4 turbo fan engine [BADA4, 2016].

$$C_F = f\,(M, C_T, f_{1\text{-}25}) \tag{5}$$

The BADA coefficients provided in equations (5) are identified as a non-linear coupled multivariate parameters. Instead of dealing with each engine type, aerodynamic configuration and thrust level setting as separate models, generalized models are presented for engine thrust, aerodynamic drag, and fuel consumption that are valid for all cases.

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. The cruising speed of the aircraft at that altitude yields to greatest SAR is known as the Maximum Range Cruise (MRC) speed. Flying at the MRC speed will minimize the fuel required to travel a specific cruise distance [Young, 2016] .

Long Range Cruise Speed (LRC)

The LRC speed can be achieved by sacrificing a 1% from the maximum SAR and selecting the higher between MRC and LRC speeds.

The LRC speed depends only on the performance characteristics of the aircraft, that is, without considering a specific costs related to a specific operator, LRC speeds are calculated and published in the Flight Crew Operating Manual (FCOM) of the aircraft by the manufacturer [Young, 2016].

Economy Cruise Speed (ECON)

Practically, airlines choose to maintain a little higher speed than the MRC speed. The penalty for this faster speed is burning some extra amount of fuel, to gain some minutes from a shorter cruise time, as a result, the flight cost can be minimized. Time-related costs include all or part of the crew, maintenance, and operational costs can be reduced by flying shorter times by flying faster at a speed called the Economy Cruise Speed (ECON). ECON speed calculations are based on the individual cost structure, of the airline company, which is computed as a function of a cost index determined for the specific aircraft type and route.

ECON is optimized to capture maximum benefit from speed optimization, assuming flexibility for small speed variations throughout the cruise phase in small intervals. These variations are driven by the reduction in aircraft weight due to fuel consumption. The results from the algorithm show speed changes on the order of ±0.0001 Mach. Such speed variations are not operationally practical, however, they make use of the maximum possible benefit from the speed optimization. In practice, the small changes from the optimization will be more effective on longer routes rather than short routes [Young, 2016].

Optimum Altitude

The Optimum altitude of an aircraft is that geopotential pressure altitude which would result in the maximum SAR for a particular aircraft weight, Mach number, and atmospheric conditions. The optimum altitude is correlated to the maximum lift to drag ratio (L/D) [BADA4, 2016].

SAR can be represented mathematically in equation (6) as the distance that can be flown per unit of fuel.

$$\boldsymbol{SAR = -\frac{dr}{dm} = \frac{GS}{FF}} \qquad [\boldsymbol{NM/kg}] \tag{6}$$

Where:

r is the flown ground distance [NM]

m is the aircraft mass [kg]

GS is the ground speed [kt]

FF is the fuel flow [kg/h]

As it can be seen from (Figure 3), the optimum altitude for a given cruise Mach number tends to increase linearly with reducing aircraft weight due to fuel consumption.

The results shown in (Figure 3) were obtained from the APM algorithm in ISA conditions and Mach number of 0.78

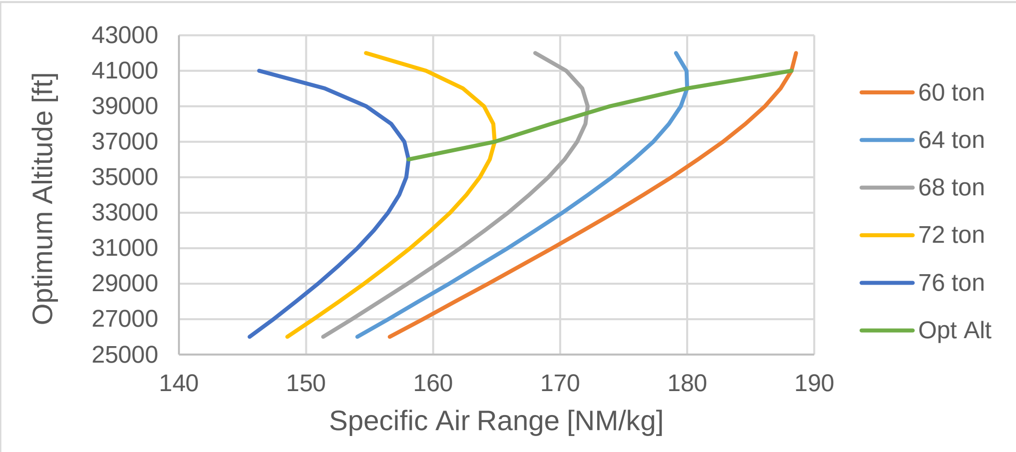

Figure 3: Optimum Altitude vs Specific Air Range

Recommended altitude

According to the air traffic control rules all aircraft must maintain a specific constant flight level, those flight levels are assigned to ensure safe vertical separation between aircraft.

The semicircular rule applies inside controlled airspace. 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 air craft management system FMS recommend a flight level that is as close as possible to the optimum altitude and/or climb to higher altitudes as a step climb procedure in case of relatively long flights.

Cost index

The basic objective of the cost index concept is to attain minimum trip cost through a trade-off between operating costs per hour and fuel burn. Essentially, the cost index is used to take into consideration the relationship between fuel-and time-related costs.

This relation is expressed as the ratio between cost of time per minute CT [$/min], and cost of fuel per kilogram CF [$/kg] [Airbus 2, 1998], as expressed in Equation (7).

$$CI = \frac{CT}{CF} \tag{7}$$

The range of CI values usually varies from 0 to 99 or 999 [kg/min] depending on the FMS manufacturer and aircraft type. The system adopted for this paper is from 0 to 99 the one used for airbus A320-214. The minimum value of CI 0 which indicates that the cost of time is zero and CI 99 represents minimum fuel cost and minimum flight time, hence flying with maximum possible speed. For instance, when a company adopted CI=15 it implies the cost of 15 kilograms of fuel being equal to the cost of 1 minute of flying according to its cost analysis.

Cost Index Cruise Management

The optimum cruise speed is the key factor in the management of the cost index, that speed is expressed in terms of Mach number which is called Economic Mach number (MECON). MECON reduces the total cost of the cruising segment for a specific value of CI, aircraft weight W, cruise geopotential pressure altitude H_p , and atmospheric conditions which are expressed as the ISA temperature deviations.

The reduction of the total cost can be achieved by minimizing the Economy Cruise Cost Function ECCF, which is expressed as a relation between cost index, fuel flow rate and ground speed GS of the aircraft. As shown in Equation (8).

$$\mathrm{E}CCF = \frac{CI + FF}{GS} \tag{8}$$

Cruise Speed Optimization

In this specific optimization problem the economy speed is optimized by calculating the minimum value of ECCF. Since the problem contains one variable the graphical optimization method is used for solving such optimization problems [Bhatti, 2000].

APM Accuracy

The accuracy of APM is checked by comparing the results obtained from the algorithm with BADA economy cruise speed data for A320-214 which gives accurate results of MECON as a function of Cost Index Function CCI equation (9) and Coefficient of Weight CW equation (10)

$$CCI = \frac{CI.\, L_{HV}}{60.\, \delta.\, W_{mref}.\, \mathrm{a}} \tag{9}$$

$$CW = \frac{m}{\delta.\, m_{mref}} \tag{10}$$

where m is the instantaneous mass of aircraft during cruise.

The comparison for model validation is presented in (table 1), it can be seen that the error within the flight envelop with different flight conditions is less than 0.5% for all cases

Table 1: Comparison between BADA and APM results at different CW and CCI values

CCI	CW	BADA MECON	APM MECON	Error %
0.1054	2.5896	0.6973	0.6940	0.476
0.1300	3.3954	0.7413	0.7380	0.447
0.7496	3.475	0.7531	0.7496	0.467
0.0173	3.8223	0.7559	0.7541	0.239
0.6873	4.8585	0.7763	0.7747	0.207
0.5788	4.3062	0.7746	0.7752	-0.077
0.6452	4.3068	0.7746	0.7763	-0.219
1.6372	4.9619	0.7767	0.7788	-0.270
1.1086	3.7344	0.7875	0.7889	-0.177
1.4193	3.7328	0.7946	0.7935	0.139

RESULTS

In this paper, the APM algorithm is performed for different flight scenarios conducted by Airbus A320-214 to investigate the effect of 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 which is 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 is used CI 99 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 each 10 NM, this is found to be the best value for the segments of calculations along the cruising phase.

The effect of CIs is examined for two different scenarios as follows:

The short route of 600 NM which is relatively considered as a short-range for Airbus A320, this flight scenario is similar to a flight from Rome to Istanbul with about 600 NM of cruise distance at 37000 ft with a gross weight of 64 tons at the top of climb TOC and standard ISA conditions. As it can be seen from (Figure 4) economy Mach number MECON is decreasing with progressing of cruise distance because of the reduction in aircraft gross weight due to fuel consumption.

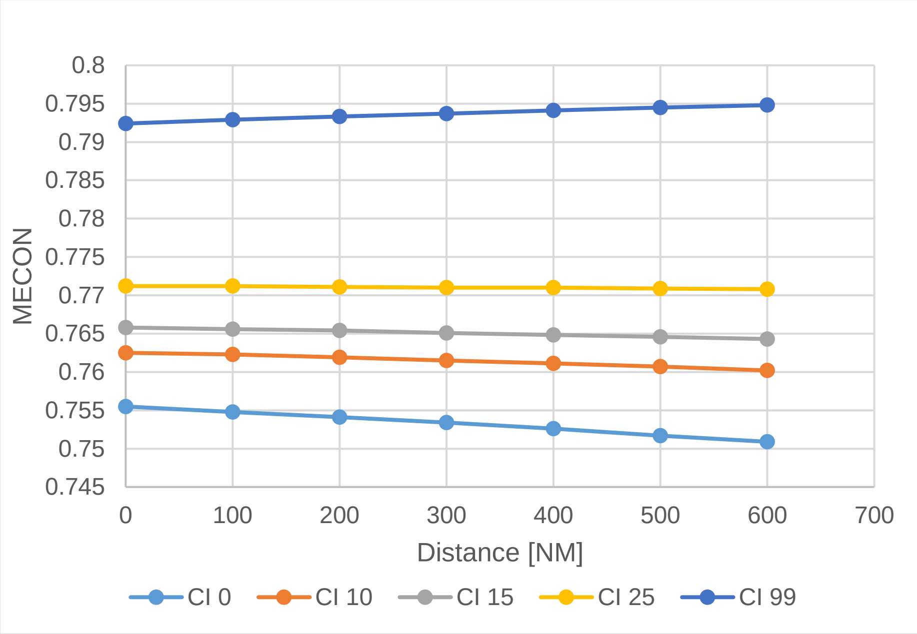

Figure 4: Short Cruise - Effect of CI on MECON vs Travelled Cruise Distance

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 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.

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

As it can be seen in (Figure 5), the optimum MECON 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 time 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 [Airbus 2, 1998, Airbus 3, 2004], the speed of LRC which can be achieved by inserting CI 99 is maximum operating speed MMO-0.02, for A320 family it is equal to M 0.80, according to the algorithm results the error in MECON is less than 1%.

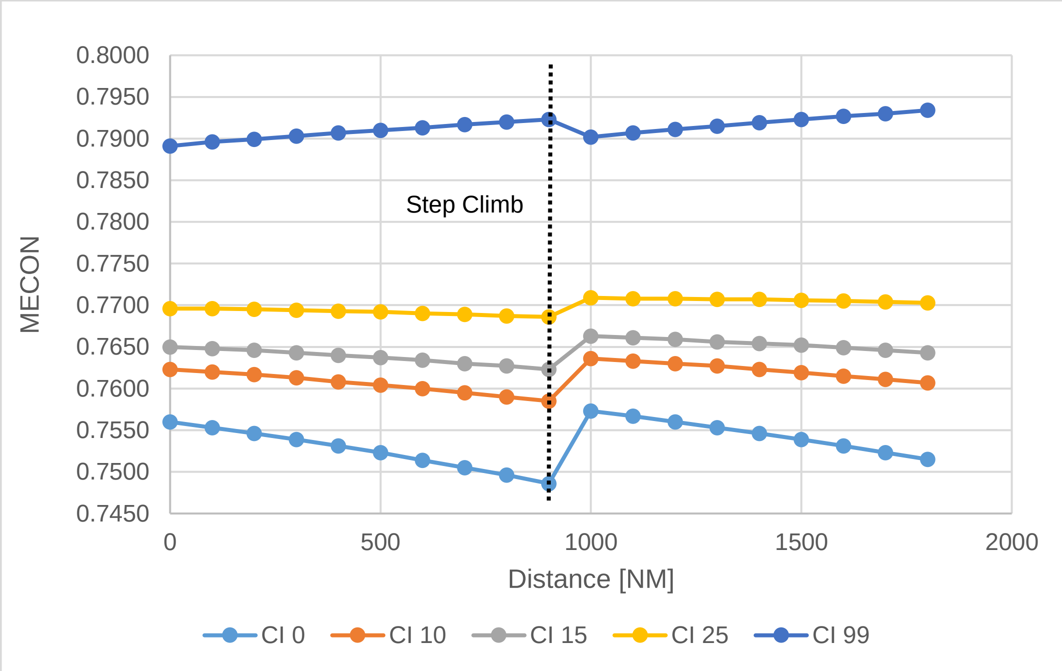

Figure 5: Long Cruise - Effect of CI on MECON vs Travelled Cruise Distance

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 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 Aug, 2019 prices in Turkey). Table (2) 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 lower or higher value than that adopted by the company, which is the case for many pilot 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 2: Effect of CI on DOC in Short Range Cruise

CI	MECON @ TOC	MECON @ 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 effect of CI on DOC in short route cruise is shown in (Figure 6), more points are shown in the graph than those presented in Table 2, 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 airline companies.

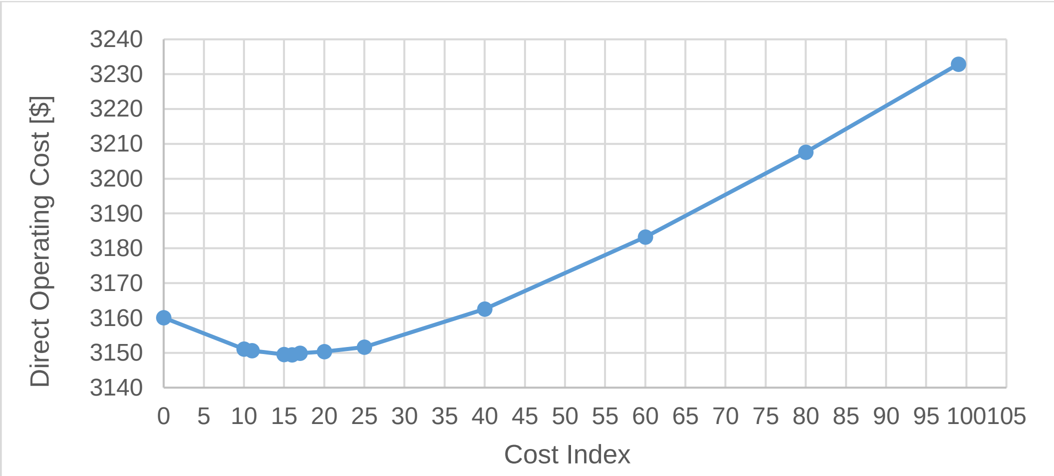

Figure 6: Effect of CI on DOC

In the case of long range cruise the effect of CI is more significant, as shown in Table (3), 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 value 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 3: 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 7), as for the short range cruise case more points are shown in the graph than those presented in Table 3, 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 airline companies.

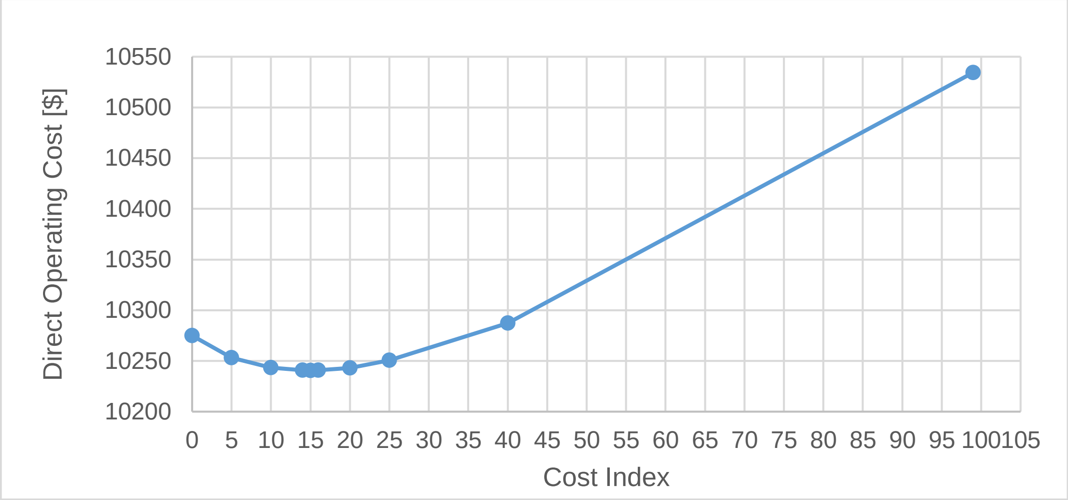

Figure 7: Effect of CI on DOC

In general, the cost index is only sensitive within the medium lower margin of the whole range and all the calculation where based on the selection of cost index value.

CONCLUSIONS

It can be concluded that the selection of cost index effectively provides a flexible tool to control flight time and fuel burn. Accurate calculations of the airline cost structure and operating priorities is essential when aiming to optimize cost by trading trip fuel for trip time or vice-versa.

The cost index and initial flight conditions such as the aircraft gross weight and atmospheric conditions are the bases of aircraft performance calculations. The optimum performance of the aircraft which gives minimum 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 MECON along the route, those elements are not possible to be kept all the time due to air traffic control constraints, however, flight crew are responsible to keep as close as possible to those values.

This paper aimed to shed some light on 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 not recommended by the manufacturer especially when moving to higher values, the scenarios presented in this paper were real cases where there is a tendency from some pilots to increase cost index attempting to save some time especially in loge 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 a strong recommendations to respect cost index values adopted by the company.

It is recommended for future studies to consider more variables and constraints where more advanced optimization methods like gradient based method or evolutionary optimization methods can be considered

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