Use of turboprop propelled aircraft and Cargo UAV's for long haul flights.

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SUMMARY

The purpose of this project was to investigate how turboprop and turbofan aircrafts direct operating costs differ for a set of given conditions, e.g. what are their costs per flight for a given range and payload or their annual profits. Adding to this the prop-fan engine which is aimed to have the fuel economy of the turboprop and performance of the turbofan, despite its technical success it was never fully integrated, thus it has also been included into the model to see how it competes with the turboprop and the turbofan. Using simple yet effective aircraft sizing methods, aircraft models were developed for testing purposes that could be used with the direct operating cost model which is based on the AEA method with some alteration in the engine maintenance cost formula. With the emergence of advanced UAVs and a growing market the model also took account for UAVs that generally showed a different profit margin compared to its crewed aircraft. Emphasis has been laid on cargo UAV because of lack of support for passenger UAV from the public and the government at the moment.

As predicted the turboprops did have lower costs compared to the turbofans, mainly due to its significant fuel efficiency but lacked in utilization due to its poor speed and thus it wasn't able to complete as many flights as the turbofan, which ultimately lead to lower annual profits compared to the turbofan. Despite less total investment in a turboprop aircraft the cost of its maintenance was found to be higher than the turbofan along with higher flight and cabin crew cost again due to poor utilisation.

1 INTRODUCTION

Rising fuel prices and the fear of unstable oil rich nations concerns every industry and it's not new to the aviation industry, it has constantly been growing and the demand for fuel efficient engines are being met at a pace. What's needed is urgency and a review of how these sophisticated technologies are being used. An aim of this project is quantify an airlines operation and determine commercially whether there could be more efficient approach from the use of aircrafts and most importantly the aircrafts power plants.

Fuel cost is a substantial ratio of the overall operating costs for an airline, for the financial year of 2012-2013 the percentage of fuel cost as of the total operating cost for The Emirates Group was 39.6%, it's the highest source of cost, 3 times higher than the second major source of cost, Employees. The airline as business has little control over the fuel efficiency of their aircrafts as opposed to the cost of employees where it's a deliberate tactic and simply their business model to offer luxury and better service through more employees or more trained employees. So can turboprops as an alternative to the turbofan engines provide a more efficient operation and cut down the costs? It might be obvious knowing that turboprops are nearly 20% more fuel efficient but you must also consider that turboprops are slower and also the engine maintenance costs play a role too.

In this report there will be an analysis of the use of turboprop or their advanced versions the prop-fan/un-ducted-fan powered aircrafts to see whether they can replace the turbofan propelled aircrafts for long haul flights. There will also be a direct comparison between normal crewed aircrafts and UAVs for cargo transportation.

1.1 BRIEF HISTORY OF ADVANCED TURBOPROPS

The energy crisis of the 1970s lead to the deliberate focus on fuel efficient engines and aircrafts, although the focus was on variety of areas in which efficiency could be improved, here the focus will be on the engines part and NASAs Lewis Research Center's Advanced Turboprop Project (1976-1987) (1) whom lead the way for this. The advancement of turboprop engines promised the highest fuel efficiency percentage amongst all of NASAs objectives.

Figure 1: Boeing 7J7, a proposed design by Boeing with prop-fans as the powerhouse. (2)

New and redesigned propellers were the key to this advancement. The major drawbacks of the propeller was its limit on how high and fast it could fly and also the high noises it produced. It was the task of Daniel Mikkelson from NASA Lewis, and Carl Rohrbach of Hamilton Standard (1) to overcome these technical difficulties; however they were able to solve this through sweeping the propeller blades along with other technical improvements.

Eventually their success gained more attention and support from the likes of Pratt & Whitney, Allison, General Electric, Boeing, Lockheed, and McDonnell Douglas that paved the way for greater success. The project was able to complete all of the four technical stages, "concept development", "enabling technology", "large scale integration" and finally "flight research" in 1987. However despite these victories this new efficient engines never replaced the jet rivals and the reason for this was down to social and economic reasons, the falling fuel prices during the 1980's certainly was in no favour of the project. Thus it's considered a technical achievement but a commercial failure where the industry has failed to take advantage of this technology.

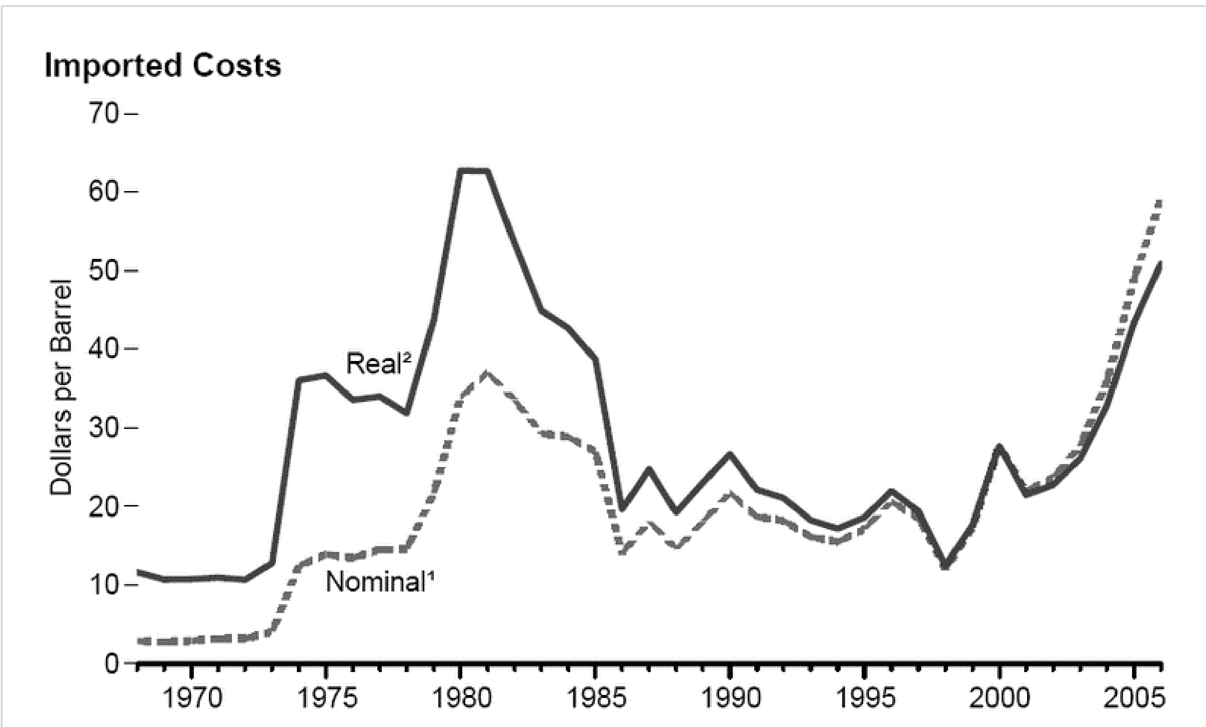

Figure 2: Graph showing the real and nominal prices of oil for the period of 1970-2005. (3)

Basic supply and demand tells us that fuel prices will always be on the rise, there will be sharp rises and falls but the overall trend is positive as there is a finite amount of the energy resources that is being used to power these engines, with no competition for the oil and natural gas energy source this trend will likely to continue. Integration of the advanced turboprops that eventually became to be called prop-fans or un-ducted fans will have commercial advantage over turbofans in terms of fuel efficiency, it will be this projects task to analyze that success, especially on long haul flights were jet engines have the highest advantage.

1.2 TURBOJET VARIATIONS

Normal turboprops are not flown at speeds such as Mach 0.8 which most turbofan propelled aircrafts are flown at because of the poor efficiency that it has at those speeds due to stagnation pressure losses at the blade tips.

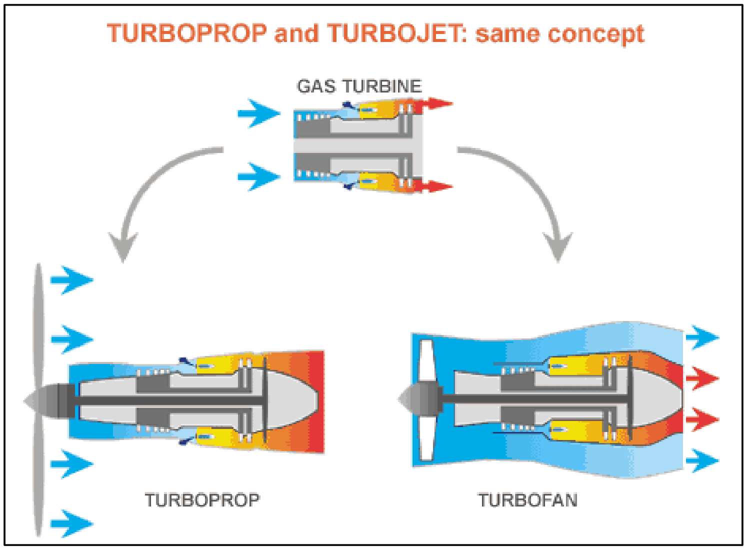

Figure 3: Graphic showing an overview of the variations of the turbojet gas turbine engine. (4)

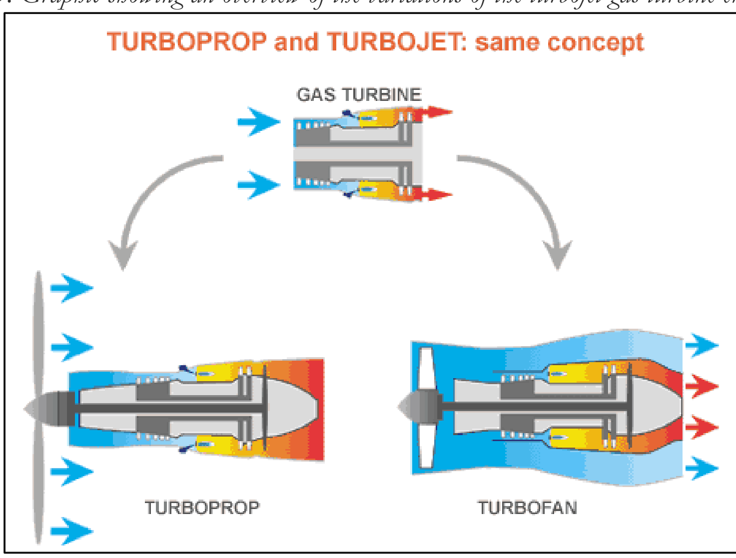

Figure 3 shows the difference between a turbofan and a turboprop engine, both are a variation of the turbojet gas engine, in a high by pass turbofan nearly 80% of the thrust comes from the gases that bypass the engine, in a turboprop nearly all of the thrust comes from the propeller and the exhaust gases produce negligible amount of thrust. Currently the turbofans are mostly used on airliners and aircrafts that are primarily designed for long-haul flights, whilst the turboprops application is the opposite, it is used for smaller aircrafts that are designed for shorter distances, regional purposes.

Their efficiency allows them to be utilised for this short distance flights but because of their slower speeds, it will be the projects aim to quantify all these claims and to see how the turboprop compares to the turbofan for a long flight whilst having the advantages of both engines under consideration.

The prop-fans on the other hand that never really took off is making a comeback with the French engine maker Snecma testing the open-rotor mock-ups in the wind-tunnels (5).

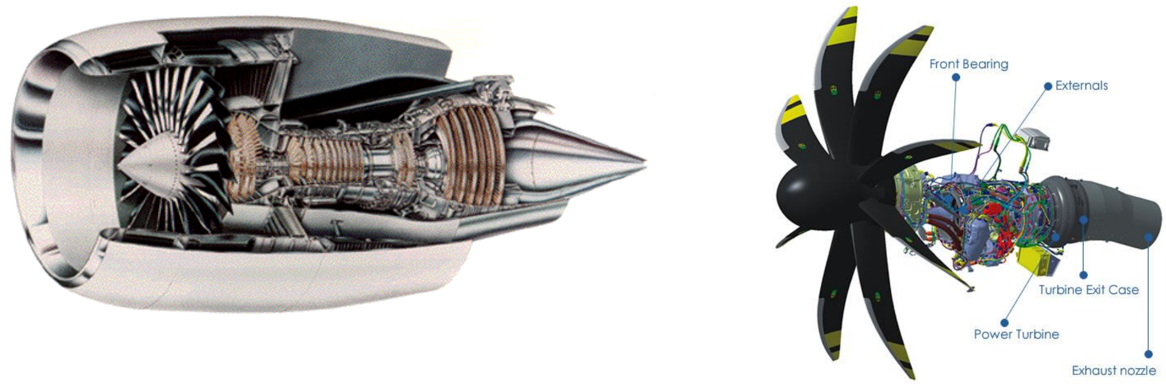

Figure 4: General Electric GE90-115B high bypass turbofan (LEFT) and The Europrop International TP400 Turboprop engine (RIGHT)

The turbofan can perform better at higher altitudes because what the turbofan essentially does is takes little amount of gas (air) and produce enough thrust whilst the turboprop takes large amounts of gas and produces thrust, thus the turboprop where the air is thinner is unable to perform efficiently.

1.3 UAV IMPLICATIONS

Unmanned Aerial Vehicles (UAV) market is growing and its growing fast, it's set to be worth $114.7B by 2023 (6), with its highest use in military applications it has gathered a poor reputation because of the collateral damages it has caused whilst on missions. However it is a technology to be embraced as it also has had positive impact in various sectors. Recognizing public and governments resistance in accepting unmanned aerial vehicles at the early stages is crucial for designers of such aircrafts and consequently for the businesses.

A study conducted by Sandra MacSween-George at Embry-Riddle Aeronautical University on the public acceptance of UAVs for cargo and passenger transportation (7) concludes that UAV passenger aircrafts cannot be implemented at this time because the public are not fully educated about the technology for them to have full trust of it. The study found that only 17% of the participants in the study would fly on a UAV even at paying 50% less fares.

The study also concluded that there is 52% acceptance for cargo transportation, so it's evident that for there to be flying passenger UAVs then we must implement cargo UAVs and obtain the public's trust in the technology first. However poor and careless use of the technology can have negative effects and it will certainly be amplified by the media like what is happening with the military drones; consequently this would cause the public to have less trust in it.

There will be an analysis of the UAV to understand if it will have any advantages over the normal crewed aircrafts from a commercial perspective. If it is not financially sound then it will not gather support from investors and consequently it will have no future.

2 MODEL

Here the backbone of the model which was created using excel will be described with all the equations. There is two distinct part to the model, firstly, using a method described by Daniel Raymer (8) an aircraft model will be developed that will later be used in the direct operating cost model which is the second important part of the overall model.

2.1 AIRCRAFT SIZING

This method is used to obtain a rough sizing for an aircraft so that they can be used for comparisons reasons as you will see later on. This is not detailed but it is enough to generate a model to work from, it is an efficient sizing method. It is used to obtain important data such as the Maximum take-off weight which we can use to develop a financial model for the direct operating cost based on this aircraft.

The proposed aircraft will be based on the following sketch, as you can see the aircraft has high-wing, with engine placement on the wings, this high wing provides enough propeller clearance from the ground.

The Maximum take-off weight (W_0) can be obtained using the following method.

It is composed of the weights of the crew, payload, fuel and empty shell weight. Most are self-explanatory but empty weight requires a bit more explanation. Empty weight is composed of anything that is not part of the other 3, thus it includes things like the weight of the structure, engine, avionics, landing gear and so on.

$$W_0 = W_{crew} + W_{payload} + W_{fuel} + W_{empty}$$

At this stage we are trying to obtain all the weight values of the 4 elements so that the maximum take-off weight can be calculated. We already know the crew weight and the payload as they are part of our specifications for the aircraft.

$$W_0 = W_{crew} + W_{payload} + \left({W_f}/{W_0} \right) W_0 + \left({W_e}/{W_0} \right) W_0$$

$$W_0 - \left({W_f}/{W_0} \right) W_0 + \left({W_e}/{W_0} \right) W_0 = W_{crew} + W_{payload}$$

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - \left({W_f}/{W_0} \right) + \left({W_e}/{W_0} \right)}$$

Fuel weight and Empty weight of the aircraft will be expressed as a fraction of the Maximum take-off weight; each element will be explained in the following sections.

2.1.1 Estimation of Empty weight fraction

The empty weight fraction $\left({W_e}/{W_0} \right)$ will be calculated using historical data.

2.1.2 Estimation of Fuel fraction

The fuel weight which is the amount of fuel required to fly our mission "mission fuel", and also fuel for loitering and emergency procedures "reserve fuel".

We can therefore predict the fuel fraction $\left({}^{W_f}/_{W_0}\right)$ based on estimated fuel consumption for our specific mission and also aerodynamics.

To calculate this fuel fraction, let's acknowledge our mission profile which consists of different segments as shown in the diagram below.

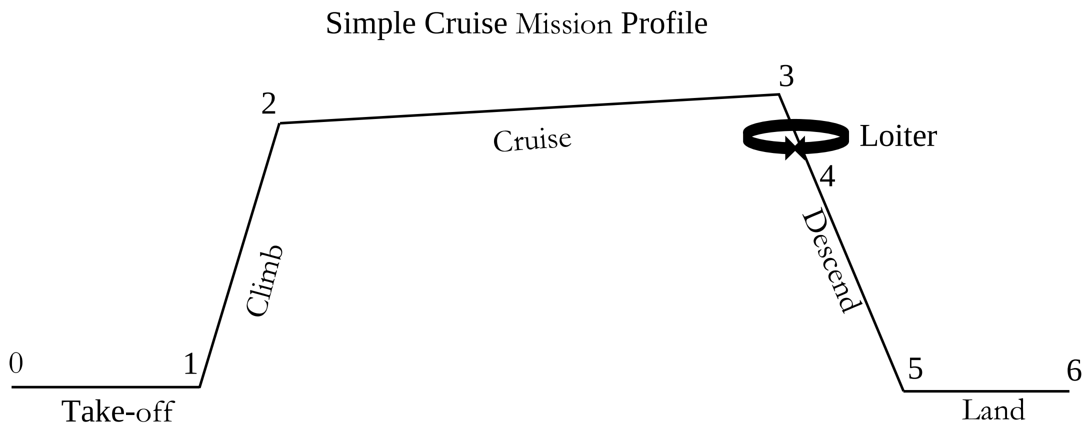

Figure 5: Diagram showing a simple mission profile of a typical mission for a commercial aircraft.

Fuel consumption will be different at each segment due to the conditions and duration of those conditions which the aircraft will be subjected to. Therefore finally using the equation below the fuel fraction can be calculated.

$$\frac{W_f}{W_0} = 1.06\left(1 - \frac{W_x}{W_0}\right)$$

2.1.3 Weight fractions

As you saw from the mission profile diagram we will divide the mission into different segments, and each segment represents a crucial moment in the mission. Beginning and end of each segment will represent the aircrafts weight at that stage, since there is no payload drop in our mission the only way the aircraft would lose weight is by burning off the mission fuel.

So for our example this is how the mission will be divided into different segments:

Note: Descent is calculated as part of cruise.

Segment weight fraction symbol	Segment
${}^{W_1}/_{W_0}$	Warm-up and takeoff
${}^{W_2}/_{W_1}$	Climb
${}^{W_3}/_{W_2}$	Cruise
${}^{W_4}/_{W_3}$	Loiter

W_5/W_4	Land

Finding all the mission segment weight fractions allow us to calculate the aircrafts weight ratio at the end of the mission by multiplying them all together, consequently through this the total fuel fraction required can be calculated.

The initial warm-up/takeoff, climb and the final landing segments weight fractions can be selected from a table of historical data.

Segment	$\frac{W_{i-1}}{W_i}$
Warm-up and take-off	0.970
Climb	0.985
Landing	0.995

Table 1: Historical weight fractions for specific mission segments. (8)

The other segments cruise and loiter are calculated using the ***Breguet range equation***:

$$R = \frac{V}{C}\frac{L}{D}\ln\frac{W_{i-1}}{W_i}$$

$$\frac{W_i}{W_{i-1}} = e^{-\frac{RC}{V L/D}}$$

$R = Range\ (ft\ or\ m)$
$C = Specific\ fuel\ consumption$
$V = Velocity\ (ft\ or\ m\ per\ second)$
$\frac{L}{D} = lift\ to\ drag\ ratio.$
$i = Segment\ number$

The above equation range equation is different for propeller aircrafts (turboprop and prop-fans):

$$R = \frac{n_p}{C_{power}}\frac{L}{D}\ln\frac{W_{i-1}}{W_i} = \frac{550 n_p}{C_{bhp}}\frac{L}{D}\ln\frac{W_{i-1}}{W_i}$$

Lastly, loiters segment weight fraction can be calculated by using the **Endurance equation**:

$$E = \frac{L/D}{C}\ln\frac{W_{i-1}}{W_i}$$

$$\frac{W_i}{W_{i-1}} = e^{-\frac{EC}{L/D}}$$

2.1.4 Specific fuel consumption

Specific fuel consumption denoted by the letter 'C', also other sources conjugate it to 'SFC', is the rate of fuel consumption divided by the total thrust. SFC is measured differently for jet and propeller engines.

Jet Aircraft	**Turboprop**
Measured in fuel mass flow per hour per unit thrust force. In British units this is pounds of fuel per hour per pound of thrust.	Given as C_{bhp}, pounds of fuel per hour to produce one horsepower at the propeller shaft (One brake horsepower)

2.1.5 Lift to drag ratio

Lift to drag ratio is simply a measure of the aircrafts aerodynamics efficiency, the aircraft designer at this point has total control over this value, we must calculate this for use in the Breguet range equation.

At the speed which we are most concerned about, subsonic, L/D is mostly affected by wing span and wetted area of the aircraft.

For initial designs we shall select our values based on historical data as shown in the graph below.

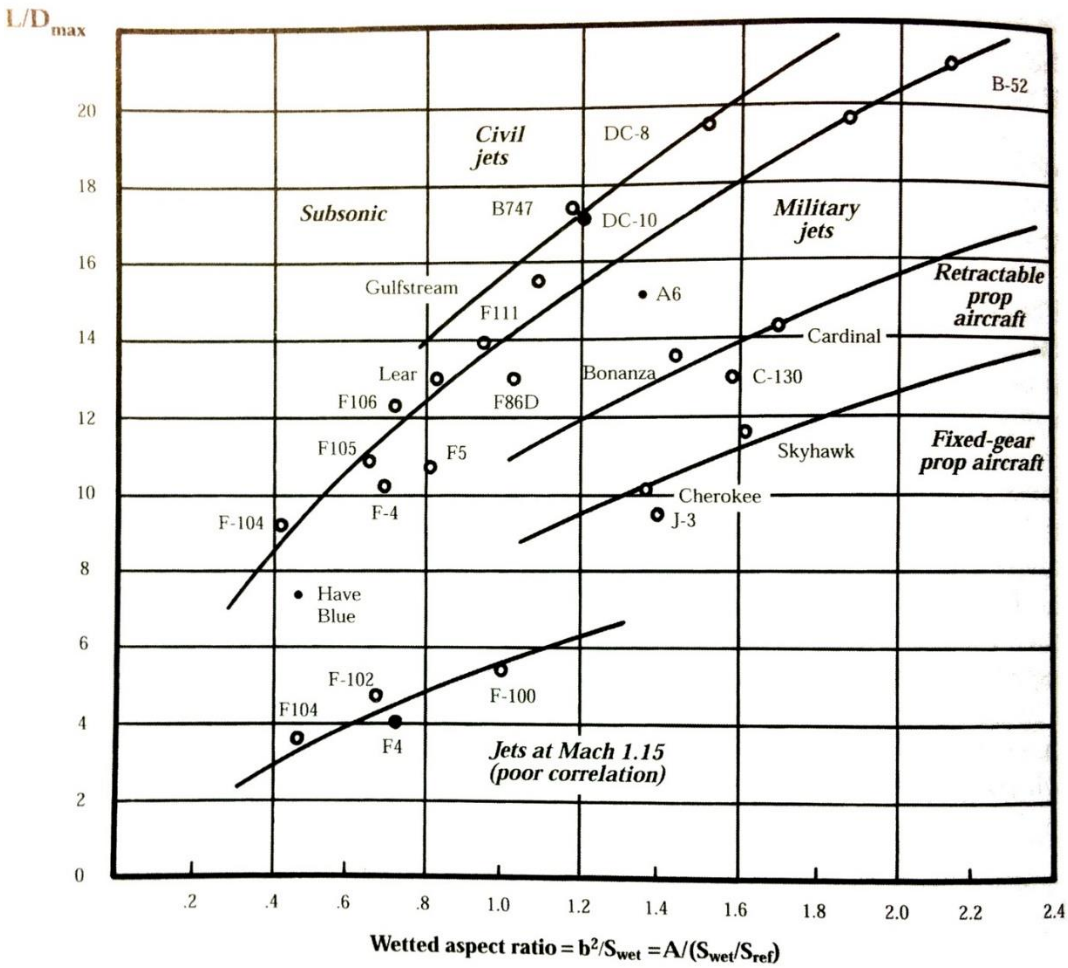

Figure 6: Maximum lift to drag ratio historical statistical trends. (8)

2.1.6 Take-off weight calculation

Once all the data from the previous segments are calculated the MTOW can be calculated using the following equation:

$$W_0 = \frac{W_{crew} + W_{payload}}{1 - \left({}^{W_f}/{}_{W_0}\right) + \left({}^{W_e}/{}_{W_0}\right)}$$

2.2 OPERATING COSTS MODEL

Now that we have an aircraft modelled and ready to be used, we produce a financial model for the direct operating costs. That is the all the costs that are involved during every flight.

The following model is the AEA (Association of European Airlines) method of calculating the DOC (direct operating costs), other similar methods includes the one developed by (9) Liebeck, R.H in *Advanced Subsonic Airplane Design & Economics Studies*. The methods are slightly mixed to provide a better model for the experiment, however the majority of the model consists of the AEA method.

Equation title	Equation	Explanation
Utilisation	$\boldsymbol{U} = \frac{3750}{t + 0.5}$	Based on statistical analysis, it is based on the time spend on the ground, and it has dependencies on numerous factors.
Total Investment	$\boldsymbol{TI} = MSP + Air\ frame\ Spares + Engine\ Spares$ This is the overall investment that the airline has made per aircraft. $MSP = Manufacturers\ study\ price$ $Airframe\ spares = 10\%\ of\ airframe\ price$ $airframe\ price = Aircraft\ price - Purchase\ price\ of\ all\ engines$ $Engine\ spares = 30\%\ of\ the\ purchase\ price\ of\ all\ engines$	
Depreciation	$\boldsymbol{DEP} = \frac{TI}{14 \times U}$	Here we assume that the aircraft would be a full write off over 14years (7% per annum)
Interest	$\boldsymbol{INT} = \frac{0.05 \times TI}{U}$	This is 5% of the total investment; this interest is for loans for the purchase of the aircraft.
Insurance	$\boldsymbol{INS} = \frac{0.006 \times MSP}{U}$	This is the annual insurance for the aircraft which is 6% of the purchase price.
Cockpit crew cost	$\boldsymbol{CPC} = (2 \times 190)t$	2 man crew whom are paid $190 per hour.
Cabin crew cost	$\boldsymbol{CAC} = 60 \times NCAB \times t$	The number of cabin crew will be 1 per 35 passengers; each would be paid hourly at $60.
Landing fees	$\boldsymbol{LAF} = 6 \times MTOW$	Landing fees will be charged at $6 per MTOW, which is the maximum take-off weight.
Navigation fees	$\boldsymbol{NAV} = 0.5 \times Stage\ length \times \left(\frac{MTOW}{50}\right)^{0.5}$ $MTOW = Maximum\ take-off\ weight\ (tonnes)$ $Stage\ length\ in\ kilometers$	
Airframe maintenance costs (AFM)	$\boldsymbol{Labour} = \left(0.09 \times AFW + 6.7 - \frac{350}{AFW + 75}\right)\left(0.8 + 0.68(t - 0.25)\right)R$ $\boldsymbol{Materials} = AFP\left(4.2 + 2.2(t - 0.25)\right)$ $\boldsymbol{AFM} = Labour + Materials\ \$\ per\ sector$	

	This value is impacted by number of flights and also the flight hours. $AFW = airframe\ weight\ (tonnes) = MWE$ $MWE = Manufacturers\ empty\ weight\ (tonnes)$ $AFP = Airframe\ price = MSP - Engine\ prices\ (\$M)$ $R = Labour\ rate = \$66\ per\ hour$	
Total engine maintenance cost (EMC)	$\boldsymbol{Labour} = 0.21C1C3(1+T)^{0.4}R$ $\boldsymbol{Materials} = 2.56(1+T)^{0.8}(C2+C3)$ $\boldsymbol{EMC} = NE(LT+MT)\left(t_f + 1.3\right)$ This is for the turbofan engines, where: $T = Sea\ level\ static\ thrust\ (tonnes)$ $BPR = Engine\ bypass\ ratio$ $NC = Number\ of\ engine\ compressor\ stages$ $OAPR = Engine\ overall\ pressure\ ratio$ $t_f = Flight\ time = \ (block\ time - 0.25)hrs$	
Fuel cost	$\boldsymbol{FC} = Block\ fuel \times F_{price}$	Fuel cost would simply be amount of fuel burned in US gallons multiplied by the price of fuel. Current fuel prices would be used in the model.

Therefore the cost of the trip per aircraft would be the sum of all the costs listed above, and we have it as shown below.

$$Aircraft\ trip\ cost = DEP + INT + INS + CPC + CAC + LAF + NAV + AFM + EMC + EMC + FC\ \$\ per\ trip$$

2.3 UAV ADDITIONAL COSTS

With the UAV comes some additional costs that can be considered as an operating cost, thus this can be taken into account for each flight. Although there will be no pilot on board there will be pilots on the ground managing the airborne aircrafts, it will be their duties to oversee the flight and make decisions in unplanned and emergency situations.

For long haul flights SatCom can be used as a method of communication. Inmarsat, a satellite communication business provides a service called Swift Broadband. This services provides high-speed data and voice transmission through their constellation of satellites.

A direct quote from one of Inmarsat partners, SatCom direct, who 'distribute' the services that Inmarsat has to offer came back with the following pricing plans.

Inmarsat SwiftBroadband 200 Services

Plan (MB Monthly)	Monthly fee	MBs included	Voice included *(Minutes)*	Plan MB	Additional MB
10	$99.95	10	20	$9.95	$7.50
150	$1,050	150	20	$7.00	$7.50
300	$1,495	300	20	$4.98	$6.50
700	$1,995	700	20	$2.85	$3.00

Table 2: Services provided by SatCom direct, the plans include a limit of data for a fixed monthly fee, additional MB used will be charged at a fee.

Inmarsat SwiftBroadband 200 Unlimited Plan

Plan (MB Monthly)	Monthly fee	Includes	Requirements
SB200 Unlimited	$2,495	Unlimited Voice/Data	• 1 Year Contract • Part 91 Operation • Tier 3 SkyShield • Low Gain Antenna

Table 3: SatCom directs' unlimited plan for a fixed monthly fee subject to requirements as stated.

Thus a simple formula to calculate the size of data used per flight:

$$data_{per\ flight} = \frac{t}{n} d$$

$t = Journey\ time\ (minutes)$
$d = Size\ of\ data\ per\ transmission (kb)$
$n = Transmission\ interval (minutes)$

3 RESULTS

3.1 ANNUAL PROFIT VS. VARYING PAYLOADS

The following graph shows data for all of the different aircrafts with added real turbofan aircraft data, these aircrafts are all Airbus aircrafts.

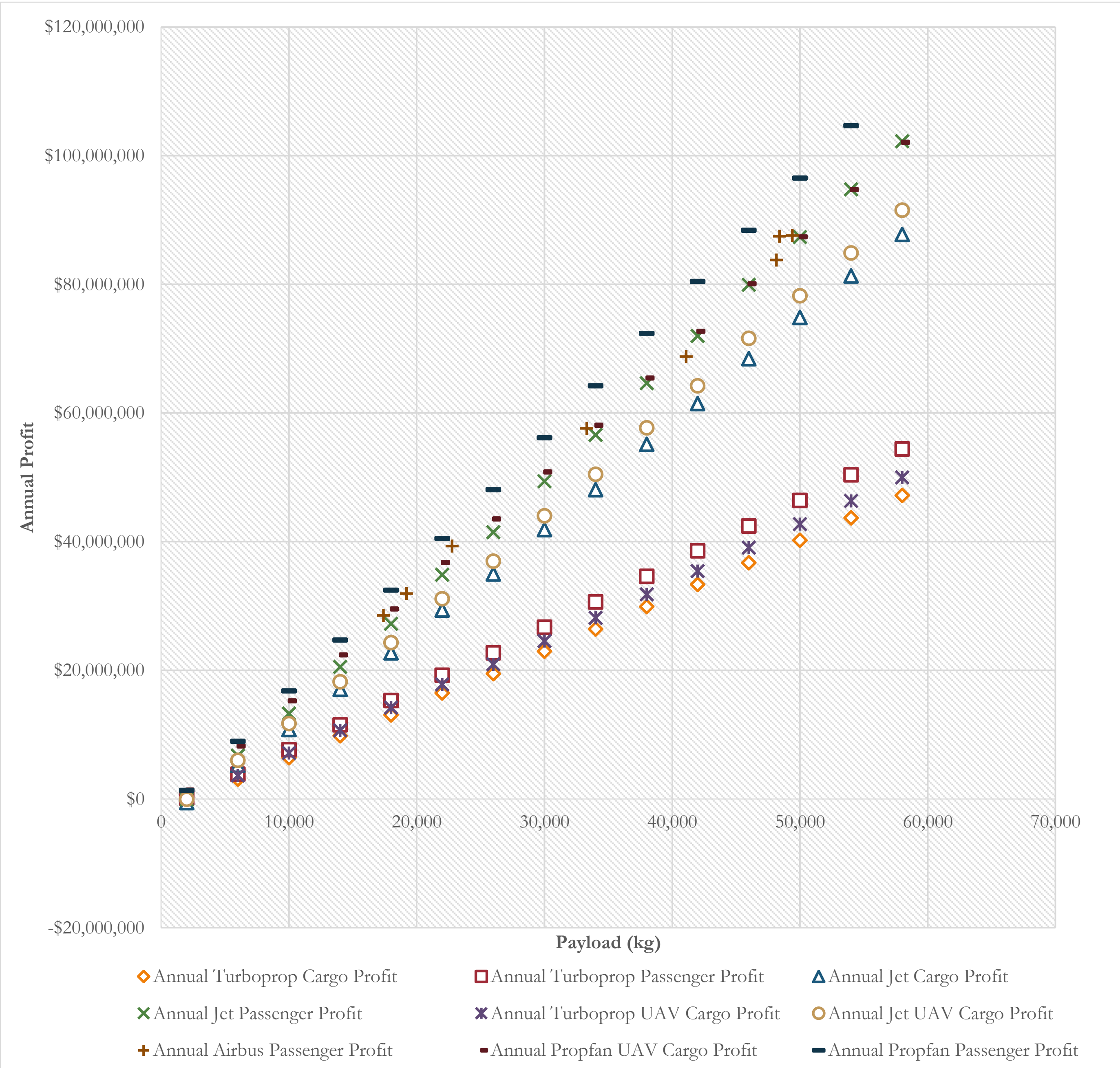

Figure 7: Graph showing annual profit vs. Payloads for different aircrafts with different powerhouses.

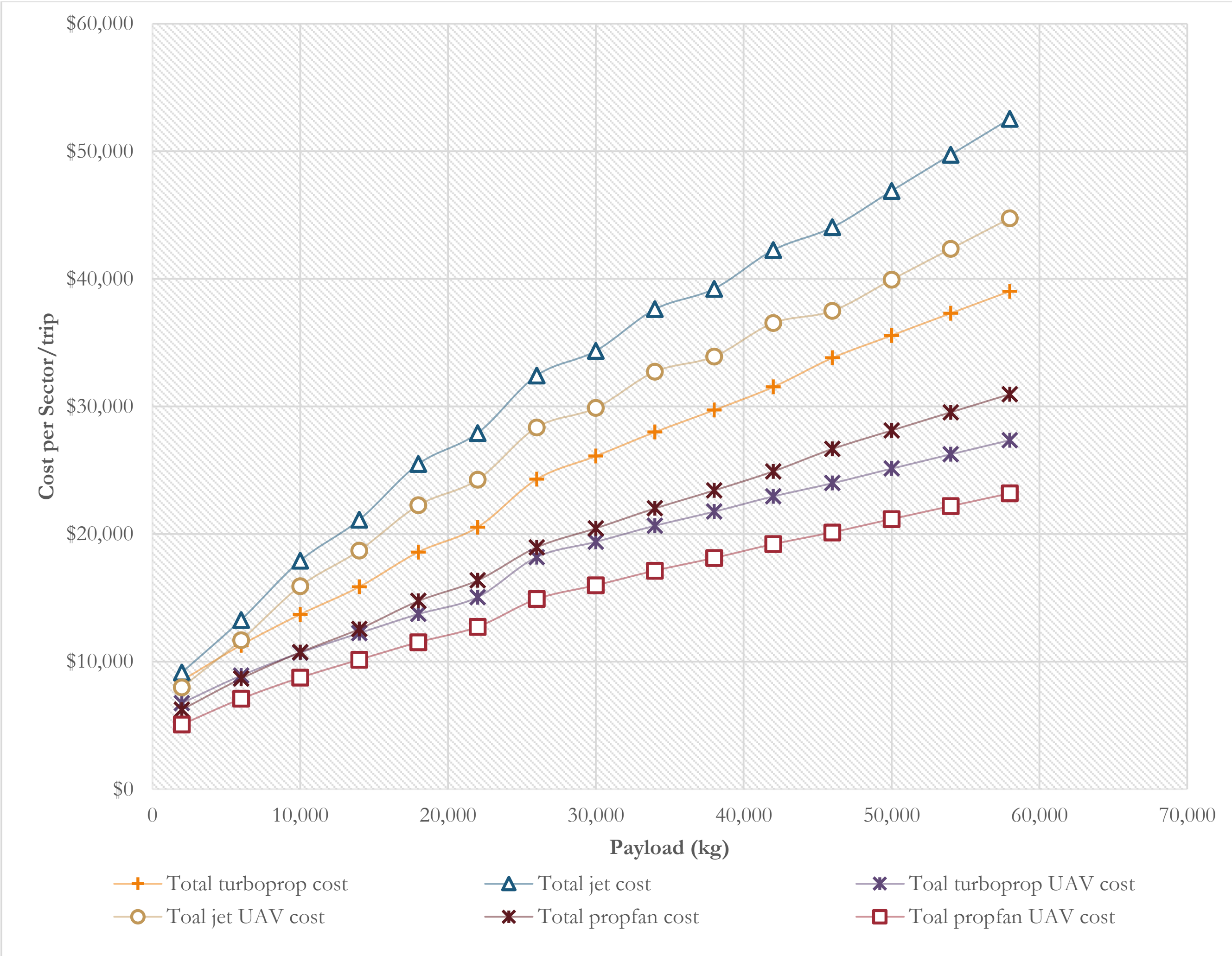

Figure 8: Graph showing cost per sector for different aircrafts.

Cargo (kg)	Turboprop	Propfan	Turbofan	Difference
2000	$242.33	$242.33	$1,929.49	696.22%
6000	$654.83	$654.83	$3,769.82	475.69%
10000	$1,077.30	$1,077.30	$6,201.96	475.69%
14000	$1,445.15	$1,445.15	$7,733.24	435.12%
18000	$1,852.24	$1,852.24	$9,911.62	435.12%
22000	$2,185.95	$2,185.95	$10,970.58	401.87%
26000	$2,579.82	$2,579.82	$12,947.26	401.87%
30000	$2,886.99	$2,886.99	$13,684.66	374.01%
34000	$3,269.38	$3,269.38	$15,497.20	374.01%
38000	$3,555.63	$3,555.63	$16,009.33	350.25%
42000	$3,927.95	$3,927.95	$17,685.70	350.25%
46000	$4,197.51	$4,197.51	$18,036.42	329.69%

Table 4: Table showing cost of fuel in USD per sector for different aircrafts for different payloads. All are for a range of 6200km

	Turboprop	Prop-fan	Turbofan
Total fuel price $	$242.33	$242.33	$1,929.49
Landing Fees ($/sector)	$47.42	$47.42	$104.04
Nav. Charges ($/sector)	$1,768.03	$1,768.03	$2,618.87
Flight Crew ($/sector)	$2,480.00	$1,653.33	$1,653.33
Number of cabin crew	1	1	1
Cabin Crew ($/sector)	$620.00	$413.33	$413.33
Utilisation (sectors/year)	346	507	507
Aircraft Price ($USM)	$7.51	$7.51	$9.05
Airframe Price ($USM)	$1.51	$1.51	$3.05
Airframe Spares ($USM)	$0.15	$0.15	$0.30
Engine Spares ($USM)	$2.28	$2.28	$2.28
Total Investment per aircraft ($USM)	£2.43	£2.43	£2.58
Depreciation ($/sector)	$501.84	$342.48	$364.13
Interest ($/sector)	$351.29	$239.74	$254.89
Insurance ($/sector)	$130.22	$88.87	$107.05
Airframe Maint. Labour ($/sector)	$878.75	$609.93	$743.95
Airframe Maint. Materials ($/sector)	$39.82	$28.38	$57.28
Airframe Maintenance ($/sector)	$918.57	$638.32	$801.23
Attained period between engine overhaul	0.811	0.811	0.811
Engine labour cost ($/sector):	$1,149.59	$510.93	$598.26
engine maintenance manhours per block hour	$997.02	$997.02	$1,167.44
Engine Maint. Materials ($/sector)	$300.72	$300.72	$300.72
Engine Maintenance ($/sector)	$1,450.30	$811.64	$898.98
UAV Ground Personnel ($/Sector) @$65 pp	$1,343.33	$895.56	$895.56

Table 5: Table showing cost breakdown of 3 aircrafts for a Range of 6200km at 2000kg of payload.

3.2 SECTOR COST AND ANNUAL PROFIT VS. RANGE

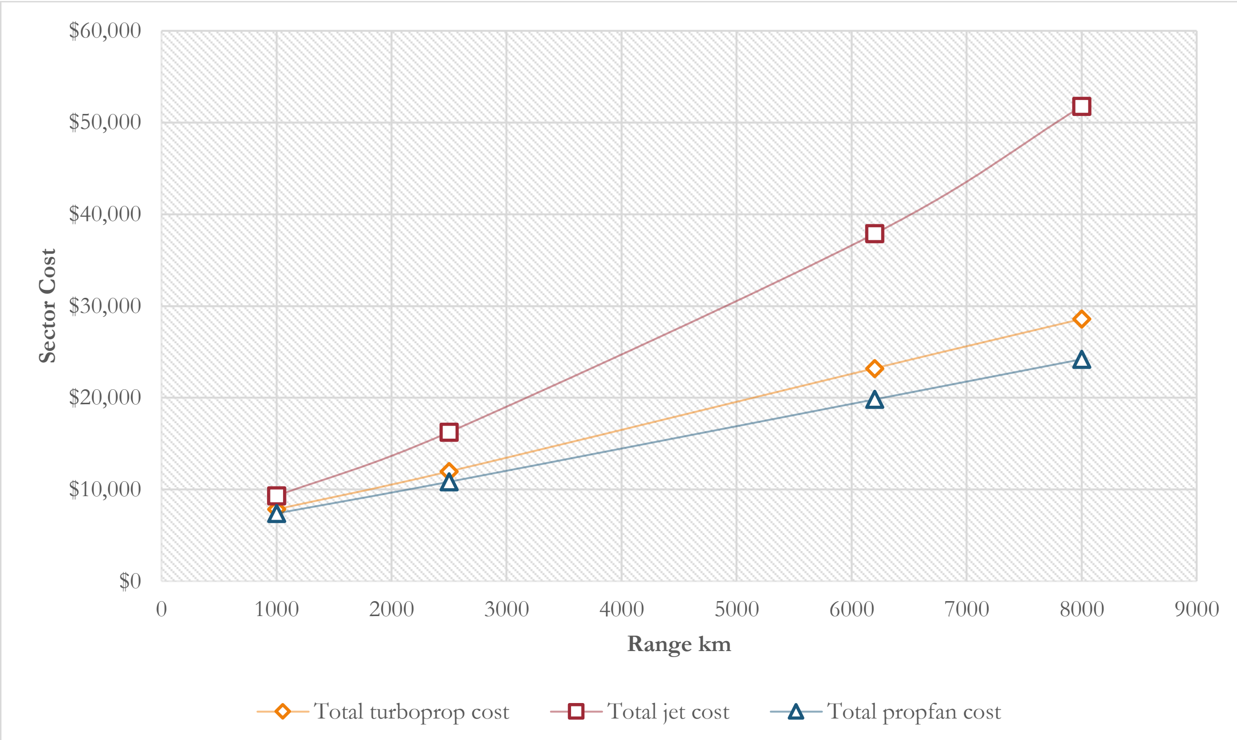

Figure 9: Graph showing sector/trip cost Vs Range for turbofan, propfan and turboprop fan propelled aircrafts.

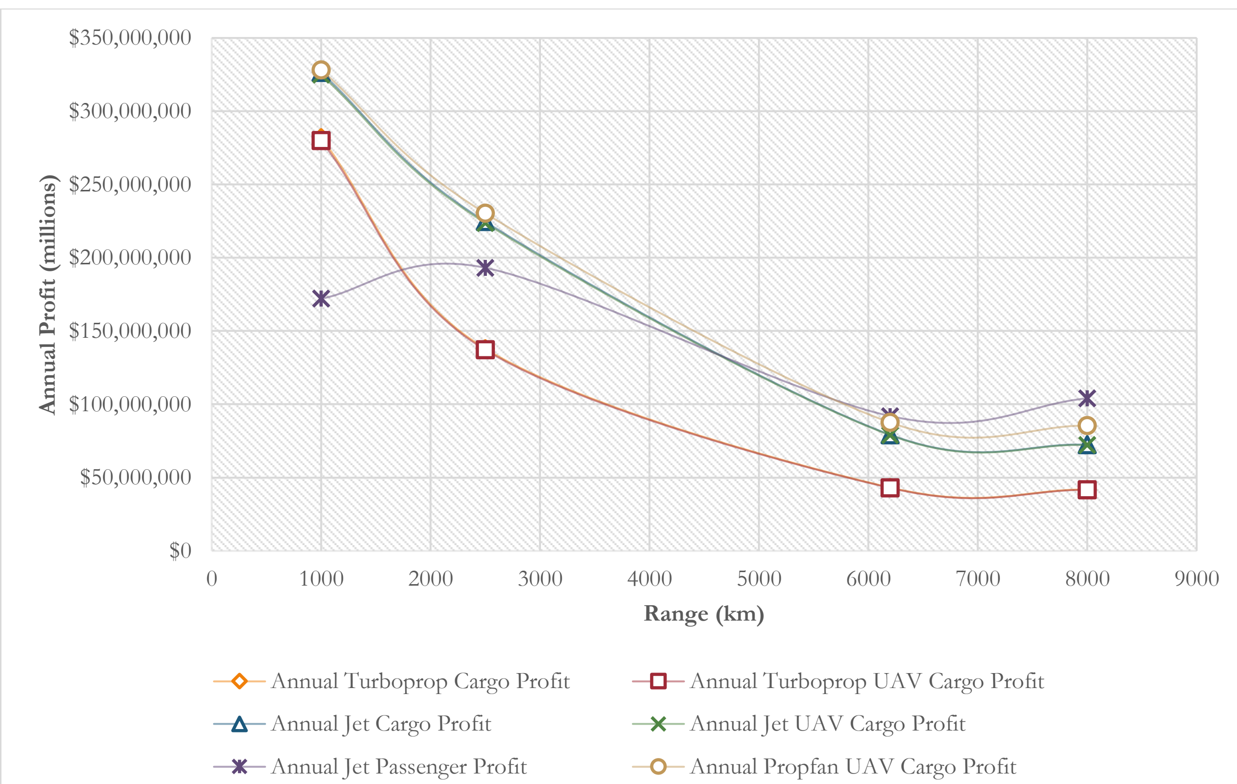

Figure 10: Graph showing the annual profit with different aircrafts of different payloads and engines.

4 DISCUSSION

What we expect from the turbofans are higher cost simply due to fuel costs and as you can see from Table 4, fuel costs are significantly more for turbofans. The turboprops and prop-fans have the same fuel consumption because that is the assumption in the model which is based on historical figures, due to lack of statistical data for the prop-fan it is assumed to have same fuel economy as a turboprop and same performance as a turbofan. It's also important to consider that as the payload is increased the difference in the fuel economy also decreases exponentially and beyond the 46000kg payload the difference starts becoming constant.

So it's clear that fuel is a major advantage for the turboprop and the prop-fans in this case, let's consider a complete cost breakdown of the 3 engines for an aircraft of range 6200km at 2000kg payload. As you can see from Table 5 there are other important factors that have a slight disadvantage to the turboprop aircraft model. Firstly due to the slower speed of the aircraft the cost of flight crew and cabin crew would be much higher than the turbofan aircrafts as they would reach their destination faster. Flight crew and cabin crew are simply a function of the sector time (number of cabin crew as well for cabin crew cost), so speed of the aircraft plays a major role up to this point. Moving on, the turbofan aircraft has a higher price but also a higher utilization which is a positive as it leads to lower depreciation, interest and insurance costs compared to the turboprop. These values are lower for the prop-fan aircraft as the total investment for the aircraft in total is the same as the turboprop aircraft but it has a higher utilization.

Airframe maintenance like the values above is lowest for the prop-fan followed by turbofan and lastly turboprop, this value takes into account the engines and the sector times, in the data the number of engines is kept to the same value for all the aircrafts so again the sector times which is linked to the speed of aircraft has an impact on this value too. Similarly the engine data shows higher costs for the turboprop, the turboprop and the turbofan use different equations to work out the cost but the prop-fan uses the same equation as the turboprop. Maintenance costs has always been a drawback for the turboprop, the gearbox maintenance along with the maintenance of the propellers drives the cost higher.

So it's clear from the data that our previous assumptions about the fact that costs of maintenance of the aircraft as a whole would be higher for the turboprop is right and the major influence is sector time, higher utilization of the prop-fan and the turbofan due to higher speeds saves costs. But the incredible difference in fuel prices offsets all these and the end costs of a turboprop aircraft is lower per sector compared to the turbofan and the best of all is the prop-fan which is a hybrid of the two.

The graph in Figure 7 shows data points for varying aircrafts that have different payloads, firstly to demonstrate the accuracy of the model in comparison to real aircrafts a set of Airbus aircraft data has been collected and used within the Direct Operating Cost Model, the data points of the Annual jet and airbus passenger profits are very close together and almost identical, due to the approximation of the model where many key features of the aircraft are based on historical data this slight difference is expected.

As you can see from the graph the passenger aircrafts are much more profitable than the cargo models and this is simply due to the ticket prices that varies as flight distance is increased. Therefore less attention will be paid to the difference in passenger and cargo profits or costs within the same engine category. At the smaller aircrafts where the payload is around 2000kg all of the aircrafts annual profits are very similar, it is from 10,000kg onwards that we see a clear pattern, the rate at which the prop-fans and turbofans annual profits increase is higher than the turboprop aircrafts and their differences as the payload increases gets higher and higher. So for a fixed range of 6200km as bigger aircrafts that are able to carry larger payloads (in this case greater than 30000kg) would benefit with having turbofans or prop-fan engines, this is assuming that prop-fans would have similar efficiency as turboprops with similar speeds to a turbofan. So why doesn't the cost advantages of the turboprop over the turbofan add up to give higher profitability annually? The answer is simple, again it's due to its utilization, in the model it is considered that every journey the aircraft would be idle for 2 hours (refueling, cargo loading/unloading etc...), adding this 2 hours to the sector time and it is possible to calculate the amount of time the aircraft is able to make a journey every day and consequently for any period of time. Considering 253 days (amount of UK working days) the turbofans would be able to make more journeys and the small profits add up to cover for the higher cost margins compared to the turboprop. As the payload of the aircrafts are increased the profit difference are amplified between the turbofan and the turboprop and it becomes easier to see that the turbofans are more profitable over a period of time for a long-haul flights, if we consider London to New York to be approximately 5600km then 6200km is clearly a long-haul flight.

Let's consider the cost per trip to understand this a little bit better, from Figure 8 you can see the cost of all the aircrafts, the UAVs compared to their manned aircraft counterpart have lower costs, the prop-fans thus have the lowest costs followed by the turboprops and finally the turbofans. It's clear to see that the biggest difference is between the prop-fan UAV and the turbofan aircraft and as payload is increased their difference is increased too as the cost of the turbofan is increasingly sharply compared to the prop-fan, however the rate of difference as payload is increased is smaller between the turbofan and the turboprop. Despite the higher and yet increasing costs as payload is increased the turbofans still have the advantage over a period of time and as shown in Figure 7 and explained earlier.

How would varying the range would affect costs and annual profits? Figure 9 and Figure 10 provide the answers to this question, the figures show costs and annual profits respectively. Similar to the earlier example of varying the payload there is a similar pattern again, lower cost for the turboprop and prop-fan and which increase linearly with range whilst turbofan costs seem to increase exponentially.

5 CONCLUSIONS

In conclusion it is found that turboprops as assumed have a lower cost compared to the turbofan mostly due to their fuel economy but lack in utilization costs in crew, airframe and engine maintenance costs. Despite their lower cost, annually the turboprop have a much lower profit when compared to the turbofan. Thus based on the model where continuous use of the aircraft and assuming 2 hours of idleness after every flight the turboprops return is lower than the turbofan because of their lower speed.

However, with the prop-fan (assumed to have same fuel efficiency as the turboprop and same performance as the turbofan) the returns are much greater than the turbofan. The UAVs provide slight profit margins which increases with payload of the aircraft, in the model the UAV is not totally autonomous as there is a ground control group.

The project has had an obvious limit, if there could be improvements then the models of the aircraft can be refined more despite the low error margin between it and the real airbus jets that were considered earlier in the discussion. Sources of errors in the model could be the rate at which flight crews are paid or the engines as they were modelled in the financial model.

So commercially traditional turboprops cannot compete with turbofans, only prop-fans which are an advance form of the turboprop can perform better, whilst the UAV provide slight profit margins that may prove beneficial in the long term (10years plus).

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