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AIRFRAME SYSTEMS POWER OFF-TAKE MODELLING IN MORE-ELECTRIC LARGE AIRCRAFT FOR USE IN TRAJECTORY OPTIMISATION

Ravinka Seresinhe*, Craig Lawson*, Ahmed Shinkafi*, Daniele Quaglia*, and Irfan Madani*
***Cranfield University, Aerospace Department, MK43 0AL, UK**
c.p.lawson@cranfield.ac.uk

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Abstract

The classical approach to trajectory optimisation uses aircraft dynamics models coupled with engine performance models to optimise for different objectives such as fuel, time, noise and emissions. However, initial studies have shown that airframe systems loads and the resulting fuel penalties due to off-takes, is influenced and more importantly influences the optimum trajectories. Moreover, the need for such an enhanced approach is required to define the "*more electric aircraft trajectory optimisation*" problem.

This paper describes the methodology which has been used to represent the airframe systems operation and the subsequent penalties in the trajectory optimisation studies conducted within the GATAC framework, under the Systems for Green Operation (SGO) work package in the Clean Sky programme.

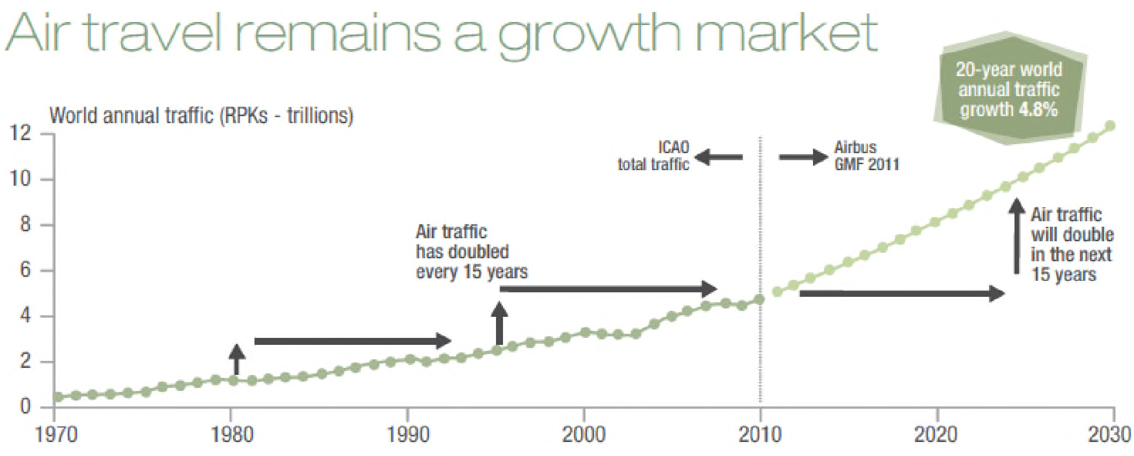
The purpose of the integrated airframe systems model is to model and interface the airframe systems power requirements or "secondary power" requirements within the optimisation framework and other models involved in the optimisation. The integrated model accumulates the requirements for the individual models and then computes the total bleed air mass flow and shaft power off-take requirements from the aircraft engine. In the case of the more electric aircraft, the off-takes are limited to shaft power off-takes since the bleed air is eliminated.

This paper presents a modelling methodology which focuses on modelling airframe systems based on the power requirements with regard to design and certification standards. Also considered is computational efficiency such that the models can be incorporated in exhaustive trajectory optimisation problems without causing significant performance penalties.

Preliminary trajectory optimisation results confirm that the inclusion of airframe systems influences the trajectory optimisation, especially when trajectories are optimised for minimum fuel burn. The significance is such that the penalties due to systems have to be accounted for when aircraft trajectory optimisation is studied for environmental gains. The combined effect and the enhanced approach to optimisation progresses the prediction of optimum flight trajectories for real aircraft.

1 Introduction

The ‘aircraft’ as a means of transport has played a vital role in economic and social globalization thus far. With the ‘potential to travel’ in emerging economies ever growing it can be assumed that air travel will increase in the coming years.



Source: ICAO, Airbus

Figure 1: Air travel growth [1]

The expected annual growth rate of 4.7-4.8% over the next 20 years will have significant influence on the environmental impact due to aviation, in the future. The challenge will be to have more aircraft operating more of the time yet have a lesser adverse environmental impact overall compared to the present.

To realise this challenge, in Europe, ACARE has set out certain goals which are to be achieved by 2020. These include a 50% reduction of the perceived noise compared to year 2000 average noise levels, a 50% cut in CO_2 emissions per passenger kilometre and an 80% cut in NO_x emission. [2] All these goals directly affect not only how an aircraft is operated but also how an aircraft is designed and built. In order to realise the goals, certain milestones have been defined.

This research focused on laying the platform to study optimised aircraft operation in more advance aircraft, specifically more-electric aircraft. It is very important to note that the concept of “more-electric” aircraft cannot be discussed by ignoring the airframe systems, since an aircraft can become more electric by only substituting the conventional pneumatic and hydraulic powered systems with electrically powered systems. Hence in the topic of trajectory optimisation for future aircraft, which most definitely includes the MEA, the airframe systems need to be represented in the problem definition.

2 Airframe Systems

The aircraft as a system is dependent on a number of sub-systems to achieve its objectives as a commercial, general or military vehicle. These sub-systems have various functions to perform and thus require energy to perform the tasks. This power may be supplied in various forms and are generally referred to as primary or secondary power. The primary power can be defined as the power produced by the propulsion system as the thrust. The secondary power can be defined, as the power required to operate all systems on-board the aircraft.

The systems on-board an aircraft are dependent on the role of the aircraft and the functionality required from the systems. For example some systems needed for a military aircraft may not be needed for a commercial aircraft. Moreover, systems between similar types of aircraft may vary with each other. For the purpose of this study the focus will be on the commercial aircraft. In aircraft design, these systems are usually referred to as per the referencing standards for all commercial aircraft documentation, which are named as ATA chapters. A typical commercial aircraft would have the following systems among others; air conditioning & pressurization (ATA 20), auto flight (ATA 21), communications (ATA 23), electrical power (ATA 24), equipment & furnishings (ATA 25), flight controls (ATA27), fuel (ATA 28), hydraulic power (ATA 29), ice & rain protection (ATA 30), indicating & recording (ATA 31), landing gear (ATA 32), lights (ATA 33), navigation (ATA 34), oxygen (ATA 35), pneumatic (ATA 36), water & waste (ATA 38) and the maintenance (ATA 45).

The conventional aircraft uses a combination of systems that includes pneumatic, hydraulic, mechanical and electrical power sources.

The ECS and the IPS mainly use hot air which is bled from the engines at a certain stage of the engine cycle. The actuation system which is vital for primary and secondary flight control is powered hydraulically. Systems such as avionics, loads in the galley and lighting require an electrical power source. The electrical generators and the main hydraulic pumps are driven by an engine shaft via mechanical or hydraulic gearboxes thus converting mechanical power to electrical or hydraulic power. [3]

The more electric aircraft will tend to use systems which are dependent on electricity rather than other types of power sources used in the conventional aircraft. The more electric aircraft is expected to be more reliable, have better maintainability, cost less and be more environmentally efficient. [4]

The trend is to move towards a more electric aircraft and have an all-electric secondary power system. The evolution of the secondary power system in commercial aircraft is discussed in [5].

2.1 Effect on trajectory

The power to operate the airframe systems is extracted from the aircraft engines. Commercial turbofan aircraft engines provide shaft power and bleed air power which is regulated and converted as required to operate the airframe systems. These power extractions can have a significant fuel penalty on the engines. [6] The magnitude of the effect depends on the amount of power extracted, the operating conditions of the engine the type of power extracted and also the point of power extraction within a turbofan engine.

The amount of power extracted is a function of the airframe systems and the functionalities within. The operating conditions of the engine are closely related to the aircraft flight and thus the aircraft trajectory. The point of power extraction is usually a design parameter and is not discussed within the research scope here.

The type of power extracted typically depends on the configuration of the airframe systems. An aircraft equipped with an all-electric secondary power system would only require shaft power extractions from the aircraft engine.

Hence the effect of the airframe systems on the trajectory is quite complex and can't be generalised. The type of trajectory flown and the configuration of the secondary power system influence the power extractions, while the power extractions influence the fuel burn and thus trajectory optimisation. [7] shows that the conventional secondary power system and the more electric secondary power system are both influenced by the trajectory flown. The more electric secondary power system is affected more than the conventional system. More importantly, it was established that the systems influence the trajectory optimisation.

This has been the motivation for the methodology discussed in this research which aims to provide airframe systems models which can be easily integrated with aircraft dynamics models and optimisation frameworks.

2.2 Classical approach to trajectory optimisation

The classical approach to trajectory optimisation has been typically to use an optimiser coupled with aircraft performance/dynamics models, fuel flow models and emissions models. In this sense the airframe systems impact is not accounted for. This research focuses on developing models which can be integrated within the optimisation loop as shown in Figure 2 thereby enhancing the classical approach. It also gives the ability to define the "more electric aircraft trajectory optimisation" problem.

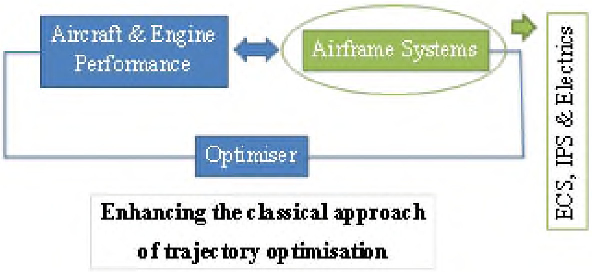


Figure 2: Enhanced approach to trajectory optimisation

3 Methodology

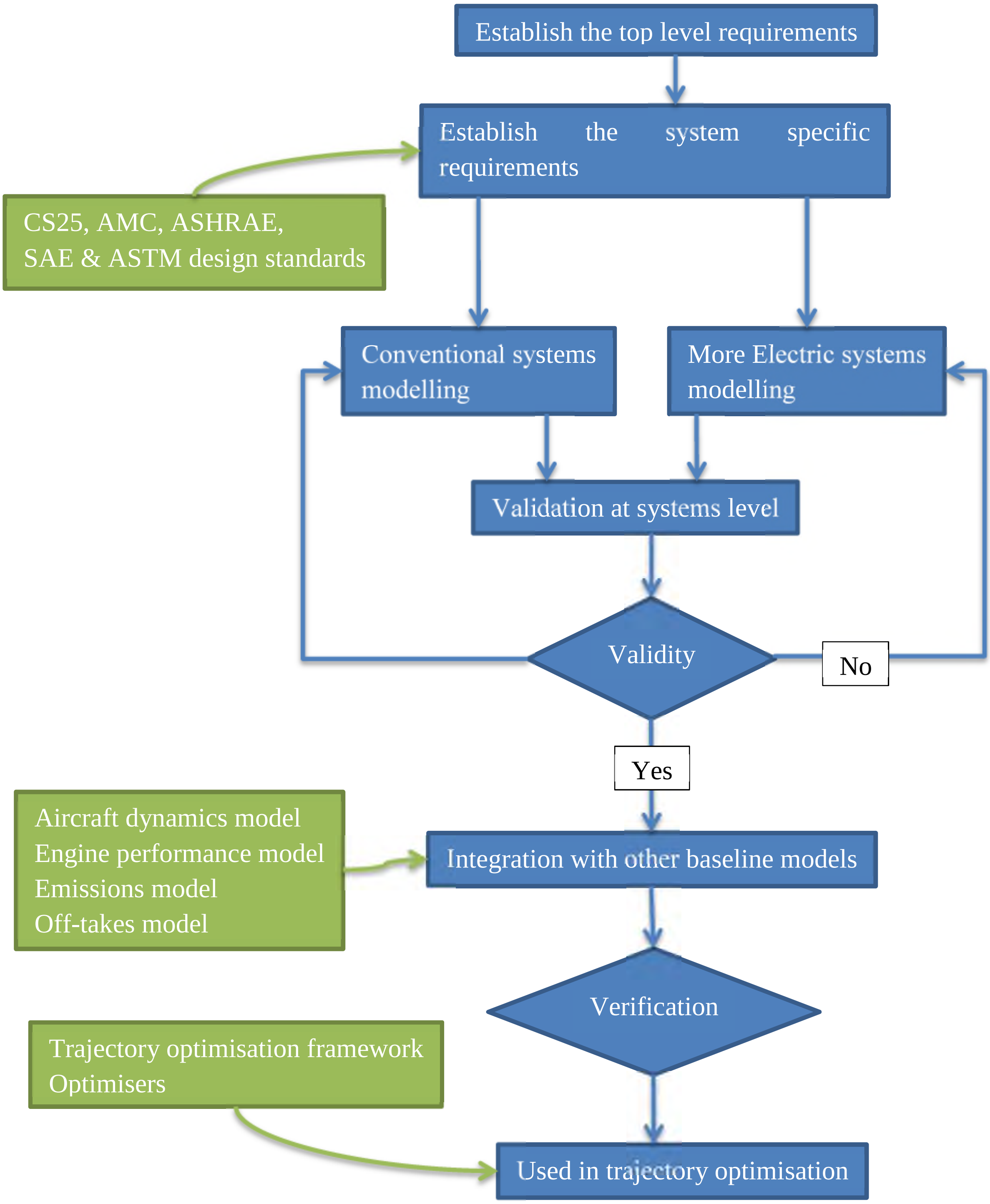


Figure 3: Modelling methodology

The methodology which was applied in the modelling process is shown in Figure 3. A top level requirements study for the airframe systems model was carried out to identify which systems were to be modelled to achieve the research goal.

Moreover, the characteristics to be modelled were also established. The ECS, IPS and electrics were established as the key systems to be modelled. It was established that the performance characteristics in terms of energy usage should be the key focus in each model. The actuators were not taken into account due to the instantaneous nature of power usage and short operational period. The same is true for intermittent loads in the electrical system which last for less than 5 minutes once activated.

The systems specific requirements were based on certification standards which affected the energy usage of the overall systems. Aspects such as reliability or safety were not modelled unless they had a direct impact on the power usage of the system.

Both more electric and conventional systems were modelled so that comparative studies could be performed. The performance of the systems was validated with published data. The integration with other models and the optimisation framework was a key driver in establishing the software requirements for the integrated systems model. From the onset the modelling approach was driven by the requirements of execution speed and ease of integration.

4 Airframe systems model

The baseline for the airframe systems model was a 180 passenger twin engine turbofan short haul aircraft which was similar to the Airbus A320. The objective of the airframe systems models was to provide the bleed air requirement and shaft power requirement to energise the secondary power system at any given operating condition. As mentioned, the ECS, IPS and the electrics were modelled in detail to represent the power requirements within the secondary power system.

The model was constructed in Matlab/Simulink and converted to a dynamic link library in order to improve execution times and integration capabilities.

4.1 Environmental control system

The ventilation, pressurisation and thermal regulation sub-systems are the main drivers in terms of the ECS power usage.

The CS25 standards specify the minimum requirements for ventilation in order to provide a safe environment for the passengers and crew. CS25.831, AMC25.8319(a), CS25.831[B(2)] and CS25.841 were some of the airworthiness requirements that were considered in the modelling approach.

Moreover, Commercial airplanes normally fly over a wide range of operating temperatures ranging from -70°C to +50°C or more. As per the recommendation of ASHRAE 55-1992 the comfort zone for human being lies between 19.5°C to 27°C.

4.1.1 ECS – conventional

The conventional model was based on an air cycle system which would use bleed air from the aircraft engines as the primary power source. This is a typical configuration which is commonly found on large commercial aircraft. The modelling focused on the required mass flow rate for adequate ventilation, pressurisation and thermal regulation.

The model included the following sub-modules;

- Mass flow calculation as per the ventilation requirements
- Calculation and control of the cabin altitude
- Calculation of the cabin heat loads
- Mass flow calculation for thermal regulation
- Modelling of the mixing manifold with provision for re-circulation

Detailed modelling of the dynamics in the ECS conditioning pack was avoided and assumptions were made to simplify the modelling. The main simplification was that the cabin inlet temperature of the flow was set as an input variable rather than an output of the ECS conditioning pack.

The kinetic heating, solar radiation, systems heat loads, passenger and crew heat loads and avionics heat loads were considered in the thermal regulation calculation. The necessary thermal regulation was achieved applying the steady state energy balance equation, which is reported as follows (1):

$$\dot{m}_a C_p (T_i - T_e) - U.A(T_c - T_s) + H_s + H_p + H_e = 0 \quad (1)$$

The ECS model was validated using data obtained from [8]. An ECS system (with re-circulation) with similar requirements to an Airbus A320 (150 passenger) variant was simulated (at a cabin pressure of 1 atm and an average cabin temperature of 293 K) and the difference in the "*ventilation capacity per passenger (L/s)*" was observed as 2.31%. The same was done for an ECS (without re-circulation) with similar requirements to a Boeing 727-100 ECS and the deviation was observed as 1.6%.

Moreover, [6] provides data for off-takes for an Airbus A320 flight from Hamburg to Toulouse. The ECS model was configured to represent a similar model to the A320 ECS and simulated to perform a comparison study. Since there was uncertainty as to the average cabin temperature, a range of between 293 K and 298 K was simulated. Initial experimentation with the ECS model showed that the cabin temperature influenced the ECS power requirement more than some others, hence this approach was followed. After experimentation with the cabin inlet and average temperatures, the inlet temperature was fixed to 275 K and the cabin average temperature (shown in Table -1) to 295 K.

Table -1: ECS comparison study

Simulated Cabin T (K)	Calculated bleed flow requirement (kg/s)	Deviation %
Climb (1,500 ft to 31,00 ft), maximum HP compressor off-take = 0.710 kg/s		
293	0.7683	8.21%
295	0.7186	1.21%
298	0.6605	6.97%
Cruise (31,00 ft at M=0.78), HP compressor off-take = 0.481 kg/s		
293	0.5635	17.15%
295	0.4965	3.22%
298	0.4181	13.08%
Approach (1,500 ft to ground), maximum HP compressor off-take = 0.429 kg/s		
293	0.4814	12.21%
295	0.4227	1.47%
298	0.3539	17.51%

The results suggest that at a cabin temperature of 295 K, the flow requirements agree very well with the measured data from Airbus.

4.1.2 ECS – more electric

The system requirements for the more electric ECS were similar to those of the conventional ECS. The ventilation, pressurisation and thermal regulation requirements were set to be the same. The difference was the source of power; the electrical ECS comprised of an electrically powered compressor to draw and compress ram air rather than extracting bleed air from the engine. The air mass flow calculation remained the same as the conventional ECS. The electrical compressor was modelled in a simplified manner to represent only the compressor work needed to supply the required mass flow.

The electrical power for the compressor

was based on (2), (3) and (4);

$$P_{net\_EECS} = W'UAT_c \tag{2}$$

$$W' = \dot{m}_a T'_e \left[P_e^b - 1 + \frac{\varepsilon}{\varphi}(\varphi - 1)(\varphi - P_e^b) \right] \tag{3}$$

$$b = \left(\frac{\gamma - 1}{\gamma} \right) \tag{4}$$

The efficiency of the heat exchanger was assumed to be constant. A major simplification of the modelling was that the aft temperature of the compressor was set as equal to the regulated bleed temperature of the conventional ECS. This simplification meant that the two systems, the more electric ECS and the conventional ECS, had similar performance constraints and that the overall system had comparable characteristics other than the source of energy. So the conventional and more electric baseline aircraft can be compared without having to make adjustments for major changes in design philosophy.

From [9] a benchmark for an electrical ECS power demand was derived. It suggested that for a typical hot day cruise at 40,000 ft, a typical electrical ECS will consume about 1.17 kW/per passenger for ventilation, pressurisation and cooling of the cabin.

The model developed calculated a ratio of 1.21 kW/per passenger for the baseline aircraft during a hot day cruise flight at 40,000 ft. It was a deviation of 3.8% thus the model was accurate to be used in further analysis.

4.2 Electrics

The aircraft electrical system requirements are driven by all other aircraft systems. The ASTM F2490-05e1 (standard guide for aircraft electrical load and power source capacity analysis) sets the standard for the aircraft electrical system sizing. An example is given by the Civil Aviation Authority (CAA) UK in [10] and it can be seen that each component needs to be listed and then a full analysis carried out.

In this research, the electrical loads were derived by using a model developed for electrical load sizing and analysis. [11] The tool was used to derive the electrical load profile so that it could be applied within the integrated model to represent the electrical generator loads. Engine shaft power off-takes provided the energy source for the electrical loads.

The electrical load sizing tool also gave inputs such as the airframe systems load and the avionics cooling load, for input to the ECS model. The airframe systems thermal load was calculated by analysing equipment in the cabin such as; the in-flight entertainment and galley equipment.

The conventional large aircraft has systems run purely on electricity as well as systems which require electrical power but use pneumatic or hydraulic power as the major type of power. In the environmental control system equipment such as the re-circulation fans, many pressure regulating valves, the monitoring and controlling computers, and a variety of controllers are powered electrically. In the anti-icing system the anti-icing of probes, the wipers, the ice detectors, the anti-icing and de-misting of cockpit windows, and the operation of some valves and most controllers, are powered electrically. Certain pumps and monitoring systems in the hydraulic system and fuel system are powered electrically as well.

The electrical model listed component loads for equipment in the following ATA chapters; ATA 36, ATA 21, ATA 22, ATA 23, ATA 25, ATA 27, ATA 28, ATA 29, ATA 30, ATA 31, ATA 32, ATA 33, ATA 34, ATA 35, ATA 38, ATA 45, and ATA 49. [12]

The model developed in [11] has been validated at the systems level for a Boeing 777-300 using data in [13], at the aircraft level for an Airbus A300 using data in [14] and for a Lockheed L-1011 Tristar using data in [15].

In the more electric aircraft, the definition of the electric system covers all powered systems on board. The conventional electrics as well as the electric ECS, electric IPS, electric actuators contribute to the total electrical load.

4.3 IPS

The IPS was modelled based on the Messinger method. The method utilises convection, sensible heating, evaporation/sublimation, kinetic energy, and viscosity terms in the conservation energy equation to find the equilibrium temperature of an unheated icing surface. A detailed description of the IPS modelling philosophy, equations, validation and verification is listed in [16].

Typically icing mostly occurs between 7,000 ft and 22,000 ft during flight. Icing heavily depends on the atmospheric conditions and predicting real weather icing clouds was beyond the scope of this study. So as a compromise, CS 25 Appendix C was used to formulate an artificial icing cloud. As a baseline, it was assumed that there would be an icing cloud between 7,000 ft and 10,000 ft at a uniform temperature of 253 K with a liquid water content of 0.23 g/m^3.

5 Integrated model

The integrated model consists of the Aircraft Dynamics model, Engine performance model, Airframe Systems Model, Emissions model and the Off-takes model. A modular approach was followed such that more models can be easily linked in future to form a comprehensive model which wasn’t computationally exhaustive.

5.1 Aircraft dynamics model

The Aircraft Dynamics Model (ADM) is in charge of the aircraft trajectory generation of a generic aircraft between two pre-defined positions in a 3D space. The generic aircraft is modelled using the rigid body idealisation with varying mass under aerodynamic, propulsive and gravitational forces, with the assumption of a symmetrical aircraft with thrust force parallel to the motion. In addition the assumptions of spherical, non-rotating Earth and no wind atmosphere are also introduced to simplify the problem. The aircraft motion is described by using point mass with three degrees of freedom and the resulting differential algebraic equations are listed in (5).

$$\left\{\begin{array}{c} m\dfrac{dV}{dt} = T - D - mg\sin(\gamma) \\ mVcos(\gamma)\dfrac{d\mathrm{X}}{dt} = L\,sin(\mu) \\ mV\dfrac{d\gamma}{dt} = L\cos(\mu) - mg\cos(\gamma) \\ \dfrac{dm}{dt} = -c\,T \\ (R_E + h)\dfrac{d\varphi}{dt} = Vcos(\gamma)\cos(\chi) \\ (R_E + h)\dfrac{d\lambda}{dt} = Vcos(\gamma)\sin(\chi) \\ \dfrac{dh}{dt} = Vsin(\gamma) \end{array}\right\} \qquad (5)$$

The aerodynamic forces are modelled by drag polar characteristic provided by BADA dataset [17] and the gravitational forces are modelled by International Standard Atmosphere (ISA) model with constant gravitational acceleration.

The ADM generates 3D trajectories based on variables provided by the optimiser regarding waypoint positions, and altitude and airspeed information along the trajectory. Several input parameters such as initial and final positions and speeds as well as aircraft initial mass are required to support the optimal variable to generate the trajectory and evaluate the overall fuel consumption, flight time, and emission indexes. The optimisation process will evaluate many possible trajectories by varying the trajectory variables previously introduced and refine the search by minimizing the imposed objectives.

5.2 Interface with engine – Off-takes model

The power required for the airframe systems is extracted in the forms of bleed air and/or shaft power from the aircraft engines in large commercial aircraft. This power extraction causes an increase in the fuel consumption. Accounting for these power extractions was identified as a key issue in this research.

The interface needed to be robust and calculate the fuel penalty by being independent of time. It also needed to calculate the penalty in a manner that detailed modelling of the engine components and efficiencies were not required. These requirements meant that methods suggested in [18] and [19] were not suited for the task. A new calculation approach was developed within the study which was established by studying the trends within turbofan engine performance. This provided a method of calculating the fuel penalty due to off-takes based on the aircraft operating conditions, engine operating conditions and systems operating conditions. The initial findings and formulae are presented in [6].

The development of the interface meant that the airframe systems model could be linked with an aircraft engine performance model and thus be used in the scope of trajectory optimisation.

5.3 Engine and Emissions

The engine modelled for this research is a high by-pass ratio twin spool engine with a maximum static take-off thrust of 121 kN. The engine is capable of providing both bleed air and shaft power for secondary power systems. The engine performance was modelled such that it was similar to the CFM-56-5B4 turbofan engine. The engine model was constructed in TURBOMATCH, which was developed at Cranfield University. TURBOMATCH is gas turbine performance software developed for engine performance simulation and fault diagnostics in which the engine is modelled to a very high detail. The high detail of modelling and computational accuracy has a significant computational penalty. In order to have the optimum balance of accuracy and executional speed, the engine was simulated over a vast envelop and the resulting database was incorporated in the Matlab/Simulink environment. Interpolation/extrapolation and polynomial evaluation techniques were used within the Simulink database to create a complete performance model of the engine.

Initially three methods were considered for the emissions modelling. These included; the Boeing-2 Fuel Flow [20] method, the DLR Fuel Flow method [21] and the P3T3 method. For this study, the P3T3 method was implemented to calculate the emissions. The P3T3 method relies upon the pressure and temperatures at the combustion stage and uses a correction based calculation method. The methodology is explained in [22] and [21]. The ground level indices for the emissions were taken from [23].

6 Results

6.1 Systems effect on a typical flight

In order to test the behaviour of the integrated model throughout the flight envelope, a test case with conventional systems on-board, was devised. The flight profile is shown in Figure 4 and Figure 5. The flight profile was based on a real aircraft flight on the 14th of April 2014, between Heathrow and Schiphol. The baseline icing condition (see 4.3) as well as the baseline ECS cabin configuration (see 4.1.1) was used in the simulations.

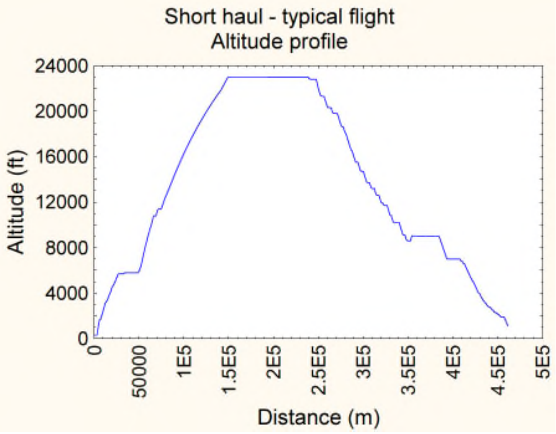


Figure 4: London to Amsterdam typical flight; Altitude profile

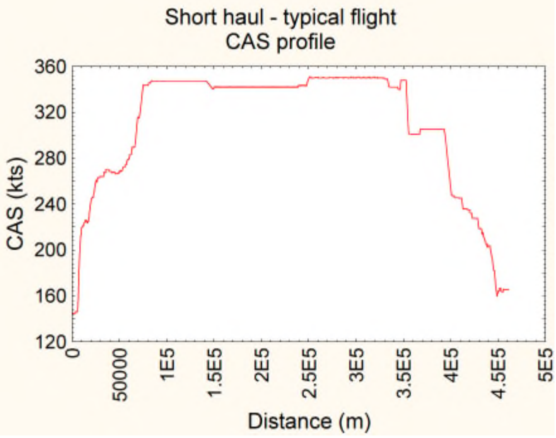


Figure 5: London to Amsterdam typical flight; CAS profile

Table -2: Results summary of a typical flight – Conventional systems

Trajectory definition	Fuel burn (kg)	Flight time (s)	Increase in fuel burn due to systems
Zero power off-takes	2330	2575	
With systems power	2565	2575	10.1%

The conventional systems causes an 10.1% increase in fuel burn for this particular trajectory.

With the more electric systems the total fuel burn was calculated as 2352 kg which was 8.2% less than the conventional systems.

It should be noted that this particular city pair has a relatively in-efficient in terms of aircraft performance. For example the cruise level is only 23,000 ft. It is expected that the overall systems penalty would be lower for a longer flight where aircraft cruise at design cruise altitudes. However, it should also be noted that the fuel penalty due to the systems can't be expressed as a constant independent of operating conditions. The results in this paper clearly show that it is relative to the flight conditions and should be expressed as such.

6.2 Trajectory optimisation – Impact with conventional systems

The model discussed in this research was developed for the specific purpose of being used in aircraft trajectory optimisation and enhancing the classical approach by including the airframe systems penalties.

The optimisation framework used in the study was developed under the Clean Sky program. [24] The GATAC framework has an in-built suite of optimisers and for the purpose of this study; an in-house developed genetic algorithm based on NSGA-2 was used the optimiser. A total of 30,000 evaluations were done in each optimisation run.

The departure phase for the London, Heathrow to Schiphol, Amsterdam was optimised with fuel and time as objectives.

Table -3: Waypoints of the departure phase

WP name	Latitude	Longitude
WP1	51 27 53.25 N	000 28 54.99 W
WP2	51 27 52.51 N	000 31 35.75 W
WP3	51 31 08.00 N	000 40 38.00 W
WP4	51 35 07.13 N	000 36 29.69 W
WP5	51 37 23.00 N	000 31 07.00 W
WP6	51 44 59.00 N	000 06 24.00 W

The terminology used to discuss the results as are follows;

Min. fuel = Trajectory optimised for minimum fuel burn.

Min. time = Trajectory optimised for minimum flight time.

Zero power off-take = No account is made for systems power off-takes.

With systems power = Conventional systems power off-takes are modelled in the optimisation.

Systems power post processed = Conventional systems power off-takes are not included in the optimisation, but are added on in post processing.

MEA = More-electric systems power off-takes are modelled in the optimisation.

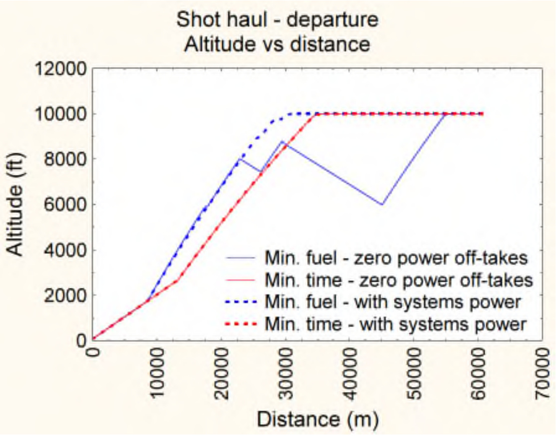


Figure 6: Altitude vs distance – departure

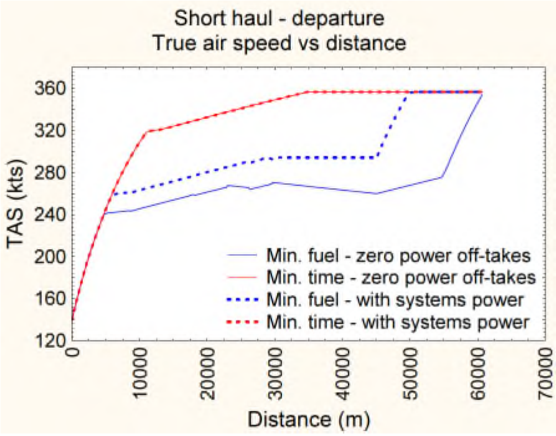


Figure 7: TAS vs distance – departure

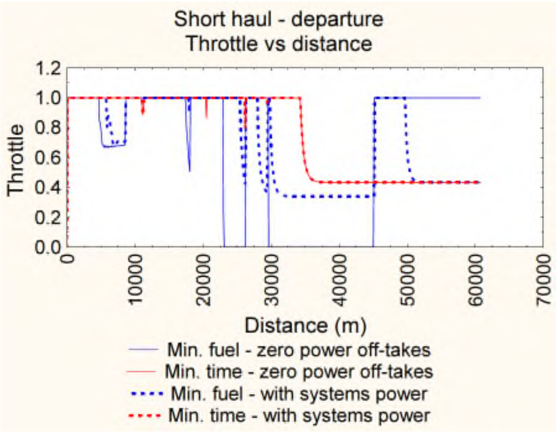


Figure 8: Throttle vs distance

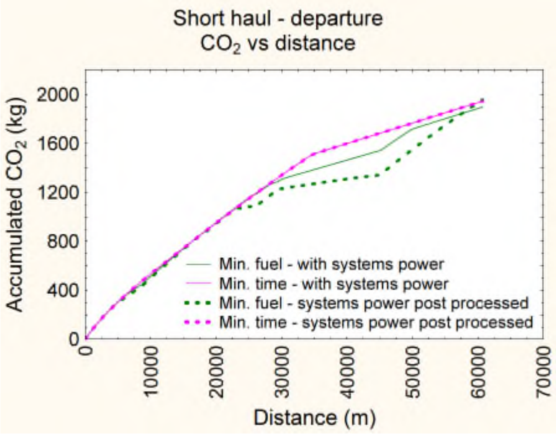


Figure 9: Total CO_2 vs distance

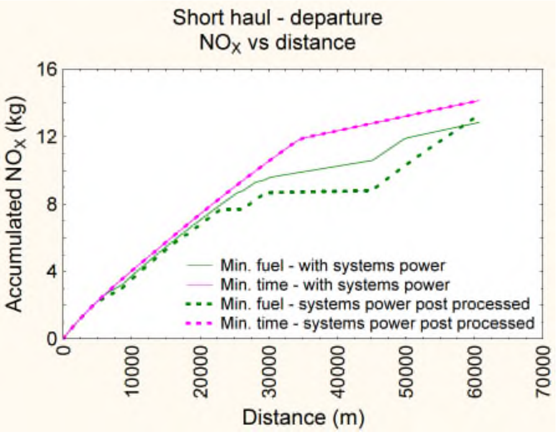


Figure 10: Total NO_X vs distance

The results for the optimisation are shown in Figure 6 and Figure 7 which illustrate the altitude and speed profiles for “zero power off-takes” and “with systems power” trajectories. The “Min. time” trajectories are very similar to each other but there is a distinct difference in the “Min. fuel” trajectory.

The fuel penalty due to systems is not significant enough to change the trajectory when the setup is optimised for time. But when the objective is to fly with the minimum fuel burn, the effect of the systems are significant. The effect of the off-takes is proportional to the amount of thrust that the engine produces. Hence off-takes at lower throttle settings will cause large fuel penalties than similar off-takes at higher throttle settings. By studying the trajectory using the characteristics of power off-take and throttle (shown in Figure 8), it was observed that for “systems power post processed” trajectories, there was a relatively high off-take at lower thrust conditions which caused a significant fuel penalty. It should be noted that the total power off-take is the sum of the shaft power off-take and the bleed air off-take. The bleed air mass flow was converted to a power by using (6).

$$\dot{Q} = \dot{m}_a C_p (T_e - T_i) \quad (6)$$

The exit temperature of air for the secondary power system is arguable. For this study the exit temperature of air has been established as the ambient temperature at the operating environment of the aircraft. Even though the exit temperature of the ECS is the cabin temperature and the exit temperature for the IPS is the temperature at the exit of the piccolo tubes, at the point of exit for both systems, there is still energy stored within the air. Hence only a proportion of the actual energy within the bleed flow is exhausted by the ECS and IPS. Since there is no energy recovery within the typical conventional secondary power system, using exit temperatures of the systems cannot be justified and can't be used to calculate the energy extracted from the engine to operate the pneumatic based systems.

A key difficulty in interpreting the results was that the behaviour of the optimised trajectory cannot be easily predicted since there are numerous parameters significantly influencing the optimisation process. This is especially true for the effect of airframe systems since the relationship between the airframe systems operation and optimum flight trajectory is twofold; the systems off-takes influences the trajectory due to fuel burn but the trajectory and the ambient conditions also influences the power requirements of the overall systems.

However, the summary of the results in Table -4 indicates the advantage in applying the enhanced approach to aircraft trajectory optimisation; which is to include the airframe systems within the optimisation loop. The systems add a penalty of 5.15%. Using the enhanced approach, a fuel saving of 2.78% is achieved. Both factors which include the different thrust profile and the different off-take profile influences the fuel reduction.

Figure 9 and Figure 10 illustrates the advantage in terms of emissions. CO_2 and NO_X emissions are lower for the "Min. fuel – with systems power" than the "Min. fuel – systems power post processed", which establishes the environmental gains that the enhanced approach offers.

It should be noted that, the departure phase studied in this research is relatively short, and larger gains are expected in longer phases of flights.

6.3 Trajectory optimisation – Initial results with more-electric systems

The enhanced classical approach to optimisation provided the platform to define and study the problem of "*more-electric aircraft trajectory optimisation*". The same city pair and constraints were applied to a more electric aircraft. The results showed that there was significant reduction in the fuel burn. The work presented here focuses on the minimum fuel burn trajectories, since one of the main advantages of the MEA is the expected environmental gain in terms of fuel efficiency. The starting mass of the aircraft was the same as for the conventional aircraft. There were many reasons for this. Firstly the increase in mass compared to the overall aircraft mass will likely be small. Furthermore, the systems mass is a fixed mass and is not a variable mass such as the fuel. This limits the effect the MEA mass increase has on the overall trajectory optimisation procedure. Finally, with the current trends in technology development, it could be assumed that the power to weight ratio of more electric aircraft components would improve to a level where the mass penalty is a minimal.

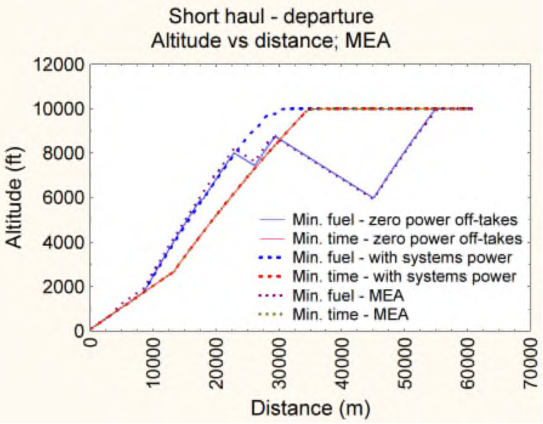


Figure 11: MEA; altitude vs distance

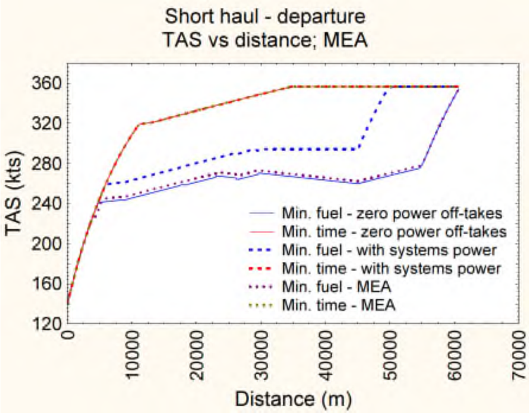


Figure 12: MEA; TAS vs distance

Figure 11 and Figure 12 show the difference in the "Min. fuel" flight characteristics for the three cases. The key observation is that the "Min. fuel – MEA" case is very similar to the "Min. fuel – zero power off-takes. This gives the preliminary indication that the MEA has a lower fuel burn compared to the aircraft with conventional systems.

It was inferred that the combined effect of the throttle setting and power off-take, allows the more electric aircraft to fly lower and accelerate heavily at the end of the phase to reach the final condition without a significant fuel penalty in the last segments. The power off-takes for the MEA are comparatively lower and that enables the aircraft to fly at lower throttle conditions (in the descending sections) without a heavy fuel penalty. Whereas the aircraft with conventional systems climbs constantly at a lower gradient until it reaches 10,000 ft and then levels off. This is further evidence on the importance of combining the systems operation and aircraft operation in optimisation studies and indicates that more electric aircraft operations should be different to conventional aircraft within trajectory optimisation.

The total fuel burn for the "Min. fuel – MEA" was 586 kg. This is 1.5% less than "Min fuel – with systems power". This results in lower CO_2 emissions but higher NO_X emissions as shown in Figure 13 and Figure 14. The higher NO_X is a result of the engine operating at a much higher temperature during the later stages of the departure to climb to 10,000 ft, whereas in the aircraft with conventional systems, the aircraft reaches 10,000 ft much quicker and flies level as shown in Figure 11.

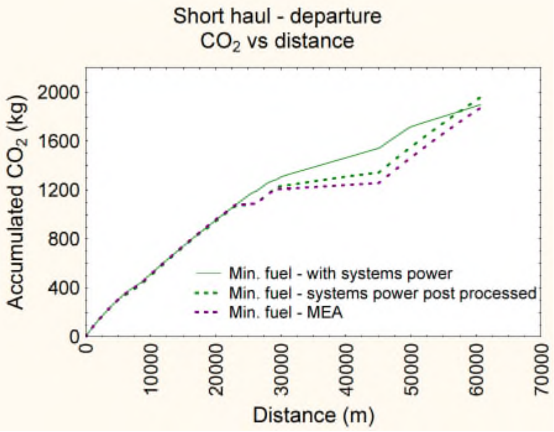


Figure 13: MEA, CO_2 vs distance

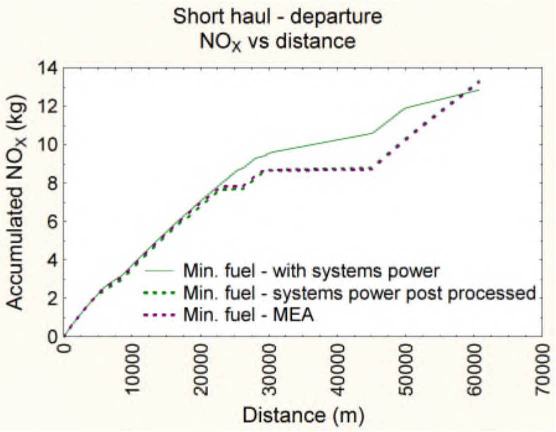


Figure 14: MEA, NO_X vs distance

The advantage of the MEA is expected to increase for a complete short haul trajectory and even more so for long haul trajectories. These preliminary results, shown in Table -5, confirms that the MEA is more fuel efficient and more importantly that the optimum method to fly a conventional aircraft and a MEA are different, thus re-stating the importance of having the airframe systems within the optimisation loop.

Table -4: Results summary of the departure segment

Trajectory definition	Fuel burn (kg)	Flight time (s)	Penalty due to systems (%)	Fuel saving due to enhanced approach
Min. fuel – zero power off-takes	582	460	-	-
Min. fuel – systems power post processed	612	460	5.15%	-
Min. fuel – with systems power	595	416	-	2.78%
Min. time – zero power off-takes	606	371	-	-
Min. time – systems power post processed	608	371	0.33%	
Min. time – with systems power	608	371	-	0.00%

Table -5: Comparison of MEA to conventional aircraft on short haul trajectory optimisation

Fuel burn			Flight time		
Conv.	MEA	%	Conv.	MEA	%
Optimised for minimum fuel burn					
595	586	1.5	416	456	-9.6
Optimised for minimum flight time					
608	608	0.0	371	371	0.0

7 Conclusion

A robust methodology to model the airframe systems penalties within the trajectory optimisation scope has been presented in this research. Moreover, the study clearly demonstrated the need for the representation of the airframe systems penalties within the optimisation loop. It established and defined the problem; “*more electric aircraft trajectory optimisation*”.

The study also established that the penalty due to the airframe systems is relative to the operating conditions of the aircraft.

Moreover, the results showed that there was a fuel penalty of 5.15% due to the airframe systems when the trajectory was optimised without accounting for the systems. It also showed that this can be reduced by 2.78% by including the systems penalty within the optimisation loop. The difference in the aircraft flight behaviour (Altitude, speed, throttle profiles) and the airframe systems behaviour (bleed air and shaft power off-take profiles) were the cause of this reduction. The environmental gains were encouraging as well. It is expected that the gains will increase for longer flight paths.

Trajectory optimisation for the MEA was achieved. The MEA, as expected, proved to have better fuel efficiency. However, the most interesting observation was the difference in the "Min. fuel" flight trajectories. This shows that the operation of the MEA should be different to the conventional aircraft in order to gain the maximum benefit out of the MEA concept. For the departure case, the "Min. fuel" for the MEA had a 1.5% lower fuel burn than the conventional aircraft.

Overall this study has focused on a single aircraft and single trajectory result. But when translated into the vast amount of flights flown everyday across distances small and large, the methodology presented here will have significant overall gains.

8 Future work

Having established the importance of representing the airframe systems within the trajectory optimisation scope, further studies will be carried out to assess the full impact on complete short haul and long haul trajectories of both more electric aircraft and aircraft with conventional secondary power systems.

Further work is planned to include more models within the optimisation scope to represent phenomena such as real-weather patterns, engine degradation and operational business aspects to enhance the optimisation approach further such that the theoretical studies will closely represent operational aircraft.

Moreover, this study has focused only on the vertical flight trajectory, but further studies will be done in optimising the 3-D space by including lateral trajectory optimisation to study the advantages of the concept of "*free flight*". Moreover, study of concepts such as "*intelligent flying with intelligent systems*" where the aircraft will change flying trajectory due to weather conditions such as icing clouds, with the minimum fuel penalty, are planned.

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Nomenclature

Units & abbreviations

°C	Celsius
ACARE	Advisory Council for Aviation Research and innovation in Europe
ADM	Aircraft Dynamics Model
AMC	Acceptable Means of Compliance
APU	Auxiliary Power Unit
ASHRAE	American Society of Heating, Refrigerating and Air conditioning Engineers
ASM	Airframe Systems Model
ASTM	American Society for Testing and Materials
ATA	Air Transport Association

BADA	Base of Aircraft DAta
CAA	Civil Aviation Authority
CO_2	Carbon Dioxide
CS	Certification Standards
ECS	Environmental Control System
ft	feet
GATAC	Green Aircraft Trajectories under ATm Constraints
IPS	Ice Protection System
ISA	International Standard Atmosphere
ID	Integrated Technology Demonstrator
K	Kelvin
Kg	Kilogram
kW	Kilo Watt
L/s	Litres per second
MEA	More Electric Aircraft
NO_X	Nitrous Oxide
NSGA	Non-dominated Sorting Genetic Algorithm
P_{net_EECS}	Net power for the electric ECS
SGO	Systems for Green Operations
WP	Way Point

Symbols

γ	ratio of specific heat of air
ε	efficiency of the heat exchanger
φ	ratio between the ambient and the aft compressor temperatures
$\dot{m}_a$	Mass flow rate of air
C_p	Specific heat capacity of air at constant pressure
T_i	Inlet temperature
T_e	Exit temperature
U	Thermal conductivity of the cabin skin
A	Wall area of cabin
T_c	Average cabin temperature
T_s	Outside skin temperature
H_P	Sensible heat for passengers and crew
H_s	Heat load due to solar radiation
H_e	Heat load from electrical equipment
T_e'	Ratio between the ambient and cabin temperatures
P_e^b	Ratio between the ambient and cabin pressures
$\dot{Q}$	Bleed air power
m	Aircraft mass
V	Aerodynamic speed
T	Thrust magnitude
h	Altitude
L	Lift magnitude
D	Drag magnitude
g	Gravitational acceleration
γ	Flight path angle
χ	Heading angle
c	Specific fuel consumption
Φ	Geodetic latitude
λ	Geodetic longitude
R_E	Earth radius
μ	Bank or roll angle