# OpenConcept Aircraft Sizing

# Optimization Implementation and Validation


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# Contents

# 1 Acknowledgements

This project was an intellectual challenge and a passionate endeavour that has driven a large portion of my graduate curriculum. I was able to explore topics of interested and grow my intuition for aircraft design and optimization beyond what I thought was achievable while in a one-year master's program. For allowing me to do this under his mentorship, I express sincere gratitude to Professor Joaquim R. R. A. Martins. In addition to being his student in the senior aircraft design class, my exposure to his research lab and optimization has given me newfound confidence in my ability to learn aircraft design and optimization techniquies, which I hope to put to use at full-time position in aircraft design.

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## 2 Executive Summary

This report details the theory, methods, implementation and validation of aircraft sizing studies using the OpenConcept [1] conceptual design toolkit, which is built on the OpenMDAO design optimization framework. At the start of this project, OpenConcept was capable of performing mission analyses for a fixed aircraft model to compute key mission requirements such as fuel burn. This project implemented design methods for conventional aircraft to to enable optimization studies for a specified mission to be performed using wing area, wing parameters, and engine thrust rating. For jet transport aircraft, such as the Boeing 737-8, the the optimizer can use either the mission's cash operating cost or total fuel burn as objective functions. For single engine turboprop-powered aircraft, the optimizer can use only the mission's fuel burn. For each design the optimizer chooses, it computes the fuel burn and cash operating cost for a specified mission range and altitude. The mission also includes a balanced field length takeoff segment, and reserve segments to meet FAA Part 25 reserve fuel requirements. The optimizer has been validated and produces a reasonable result for aircraft sizing for two test aircraft: the Boeing 737-800 and the Socata TBM-850.

# 3 Project Introduction and Justification

This project adds aircraft wing and thrust sizing functionality to OpenConcept, which enables preliminary aircraft design sizing for a given fuselage and payload requirement. It allows for single mission optimizaiton of an aircraft, which outputs the optimized wing shape parameters and engine thrust rating that minimizes an objective function. This project required that I implement methods that estimate drag, component weights, tail geometry, and operating costs. Together, the new functions can take a fuselage design, compute the weights for key components of the aircraft, and check if the design is feasible. The optimizer repeats this until it finds a solution that is optimal. Jet transport aircraft can use block fuel burn or cash operating costs as objective function. Turboprop aircraft can only use block fuel burn. This report will cover the methods implemented and sizing methodology used to achieve optmial design.

# 4 Aircraft Sizing Methodology

The aircraft sizing methodology implement the constraint based approach defined in the Aircraft Design Metabook [2]. This approach defines the constraints for thrust and wing area over all the flight segments, including engine inoperative conditions. The constraints are used to determine the feasible design point for wing area and engine thrust. A design point inside this design space is chosen such that an objective function is minimized. Common objective functions are total fuel burn and the operational cost of the aircraft.

# 5 New OpenConcept Functions and Components

The following subsections discuss the theory and implementation regarding new OpenConcept functions[1]. For each component, I defined partial derivatives along all possible input variables to unlock design variables, such as wing sweep and aspect ratio, as optimization design variables.

## 5.1 Weights Buildup for Jet Transport

This set of components are implemented as OpenMDAO explicit components in the `weights_jettransport.py` file. They compute and estimate of a jet transport's empty weight considering major design parameters for the wing, empennage, fuselage, landing gear, and thrust.

[1] New OpenConcept functions can be found at https://github.com/vrsub/openconcept/tree/sizing

### 5.1.1 Wing Weight

The component to calculate wing weight uses Equation 15.25 from Raymer [3], which is as follows

$$W_{wing} = 0.0051(W_{MTOW} * N_z)^{0.557} S_{ref}^{0.649} AR^{0.5} (t/c)_{root}^{-0.4} (1+\lambda)^{0.1} cos(\Lambda_{c/4})^{-1} S_{csw}^{0.1} \quad (1)$$

where $\Lambda_{c/4}$ is the quarter-chord sweep of the aircraft, and $S_{csw}$ is the area of the control surfaces, and $N_z$ is the ultimate load factor of the aircraft. For the purposes of this study, $S_{csw}$ is assumed to be 20% of the total wing area. This component's inputs are the aircraft maximum takeoff weight, and all wing parameters, and analytical partial derivatives are defined for all six input variables.

### 5.1.2 Horizontal Stabilizer Weight

This component implements Equation 15.26 from Raymer [3], which is

$$W_{hstab} = 0.0379 K_{uht} * C_1^{-0.25} * W_{MTOW}^{0.639} * N_z^{0.10} S_h^{0.75} * L_t^{-1.0} K_y^{0.704} \times cos\Lambda^{-1} AR_h^{0.166} (1 + \frac{S_{elev}}{S_h})^{0.1}$$

where $S_h$, $\Lambda$, $AR_h$ are design parameters of the horizontal stabilizer. $L_t$ is the distance between the quarter chord line of the wing root to the quarter chord line of the horizontal stabilizer. $K_{uht}$ is a scale fact or used for a full-moving stabilizer, set to 1.143. $S_{elev}$ is the area of the elevons, which is assumed to by 20% of the horizontal stabilizer reference area. $K_y$ is the fuselage radius of gyration, which is approximated as 30% of $L_t$ according to Raymer. Lastly, constant $C_1$ is defined as $1 + \frac{F_w}{b_h}$, where $F_w$ is the fuselage width at the tail intersection (assumed to be 60% of the total fuselage width) and $b_h$ is the horizontal tail span. This constant and its partial derivatives are expressed in a separate component to simplify partial derivatives in the main weight component.

### 5.1.3 Vertical Stabilizer Weight

This component implements Equation 15.27 from Raymer [3] for a tradition tail configuration. The equation is

$$W_v stab = 0.0026 W_{MTOW}^{0.556} N_z^{0.536} L_t^{-0.5} S_v^{0.5} K_z^{0.875} cos(\Lambda_v) AR_v^{0.166} (t/c_{root})^{-0.5} \quad (2)$$

where the inputs are the design parameters of the vertical stabilizer and wing. $K_z$ is the fuselage yawing radius, which is approximated as $L_t$, previously defined as the distance between wing and tail quarter-chord lines.

#### 5.1.4 Fuselage Weight

The equation to estimate fuselage comes from Equation 15.28 of Raymer [3]. Its inputs are fuselage geometric parameters and the constant $K_{ws}$ defined by wing parameters. This constant and its constants are computed in a separate component and used as inputs for the main fuselage weight computation. $K_{door}$ and $K_{lg}$ are constants set depending on the number of cargo doors and other unique features of the aircraft. For this study, the values were set to match balues for a traditional commercial passenger aircraft. The fuselage weight is defined as

$$K_{ws} = 0.75(1 + \frac{2\lambda}{1+\lambda})(B_w tan(\Lambda_{c/4}) L^{-1})$$

$$W_{fuselage} = 0.3280 K_{door} K_{lg} (W_{MTOW} N_z)^{0.5} L_f^{0.25} S_{f,wet}^{0.302} (1 + K_{ws})^{0.04} (L/D)^{0.10} \tag{3}$$

#### 5.1.5 Other weight estimations

The weight estimation for main and nose landing gear comes from Equation 15.29 and 15.30 in the Raymer textbook [3]. These are implemented into separate component and used in the total weight buildup. They use the piublished maximum landing weight of the aircraft, along with notional values for landing gear length. To be fully accurate, the landing gear length can only be found by assigning the landing gear position and sizing the gear length to meet rotation angle requirements.

The aircraft single engine weight is computed using the method outlined in Section 7.3.3 of the Metabook [2]. This uses the design point maximum thrust rating in pounds-force to compute engine dry weight, oil weight, reverser weight, and control systems. Additionally, it computes the weight for the engine starting system. These component weights are summed to calculate the total single engine weight.

### 5.2 Empennage Sizing

One main piece of added functionality is empennage sizing based on wing design parameters and the volume coefficient method. The tail volume coefficient method uses the available configuration moment arm and historical volume coefficients to estimate the reference area required for the horizontal and vertical tails. It is defined as

$$S_v = \frac{c_v b_W S_{ref}}{L_t} \tag{4}$$

$$S_h = \frac{c_h \bar{c}_w S_r e f}{L_t} \tag{5}$$

where $S_{ref}$ is the main wing area, $b_w$ is the wing span, $\bar{c}_w$ is the wing mean aerodynamic chord, and $L_t$ is the distance between wing and horizontal tail quarter chord lines. For the case of jet transport aircraft, $c_v = 0.09$ and $c_h = 1$ [2]. For a regional turboprop, $c_v = 0.08$ and $c_h = 0.9$. The tail volume coefficients are implemented as user options, and can be changed in the function call depending on the type of aircraft being studied. The wing mean aerodynamic chord is computed in a separate component and used as an input to the tail sizing components.

### 5.3 Cash Operating Cost Buildup for Jet Transports

An mentioned in the Metabook [2], airlines divide the total operating cost of an aircraft into direct operating cost (DOC) and indirect operating cost (IOC). DOC can serve as an objective function function because it takes into account fuel price and maintenance labor cost for a given mission. I have created a set of OpenMDAO components that compute the cash operating cost (COC) of a jet transport, which is a large component of total DOC. This unlocks a new objective function that did not previously exist for jet transport analysis. There are 7 major components to COC, and they are defined as:

- Crew: This is the cost incurred through flight crew staffing expenses and other compensations. This was calculated using Eq 3.11 in the Aircraft Design Metabook [2] with a cost escalation factor based off a base year of 1999.

- Attendants: This is the cost associated with flight attendant staffing fees and is given compensation. This cost was calculated using Equation 3.15 in the metabook [2].

- Fuel: The fuel weight was computed by calculating the fuel fraction using a weight convergence algorithm, and the cost of fuel was computed using Equation 3.16 in the metabook [2].

- Oil: The cost of oil and lubricants is computed based off the weight of oil, which is computed using the weight of the fuel. We used Equation 3.18 and 3.19 in the metabook [2].

- Landing Fees: The landing fees represent the cost of landing at an airport and paying for gate fees and other services. This was computed using Equation 3.21 in the metabook [2].
- Navigation Fees: The navigation fees describe the cost related to flight planning and the use of air traffic control systems. These costs were computed using Equation 3.22 in the metabook [2].
- Airframe Maintenance: This component represents all the costs relevant to the maintenance of the airframe, and is based on the maintenance labor hours, the cost of labor, and material cost. It is a function of airframe cost, which was estimated using the procedure detailed in Section 3.3 of the metabook [2]. The cost of airframe maintenance was calculated using Equations 3.23, 3.24, and 3.26 in the metabook [2].
- Engine Maintenance: The engine maintenance cost is computed in the same way as the airframe maintenance cost, and uses correlations involving the maximum thrust of the engines. The total cost of engine maintenance was computed using Equations 3.27, 3.28. and 3.31 in the metabook [2].

The inputs for these equations are the mission block time, aircraft weight, and maximum rated thrust of a single engine. Each of these components and their partial derivatives are implemented as individual components in OpenConcept can be called individually, or summed together using the `JetTransportCOC` group.

### 5.4 Parasitic Drag Buildup

The parasitic drag build up computes a basic estimation of the total skin friction drag coefficient non-wing aircraft using aircraft geometry parameters.

The first component comptues the total wetted area of the aircraft, currently defined as

$$S_{wet} = 2S_h + 2S_v + 2S_{fuselage} \tag{6}$$

where the fuselage wetted area is modeled from a cylinder with length and width of the fuselage. The total wetted area is then passed to a component that estimates the non-wing parasitic drag coefficient based off the formula

$$C_{d_{0,non-wing}} = C_{fe}\frac{S_{wet,non-wing}}{S_{ref}} \tag{7}$$

where $C_{fe} = 0.003$. This implementation of a wetted area computation will underestimate the the wetted area of the tail due to its assumption that they are paper thin. A better approximation for wetted area can be found in Raymer, and can be implemented in the future.

### 5.5 Wing Stall Computation

I computed the maximum $C_L$ based on Raymer's estimate [3], which uses the wing quareter-chord sweep angle and the airfoil maximum $C_l$. I used notional values for the wing maximum lift coefficient found in the Airfoil Tools[2] database. This estimation is expressed as

$$C_{L_{max}} = 0.9 * C_{l_{max}} * cos(\Lambda_{c/4}) \tag{8}$$

### 5.6 Mission with Reserve and Takeoff Segments

I created a new mission that can be used in the mission simulation portion of the analysis for each design point the optimizer chooses. This mission combines the existing full mission analysis which includes balanced field length takeoff segments, with the reserve segments rquired by FAR Part 25. It does not account for 5% block fuel. This new mission allows for sizing using total fuel requirements while using block fuel mass as an objective function. Additionally, it unlocks balanced field length parameters as constraints, so the user can limit takeoff distance within an optimization. Each flight segment uses a force-balance component to determine the forces required to maintain mission parameters for the duration of the segment. Its input is the aircraft model, which contains the aircraft design and capabilities, such as thrust and weight models. These are used by the solver to compute flight conditions at all points of the mission.

### 5.7 OpenAeroStruct Drag Polar Integration

The aircraft model incorporates a drag polar estimation using OpenAeroStruct[3] [4] to create an improved drag estimation. The OpenAeroStruct model uses the aircraft's design properties and required flight conditions to compute an estimate of the wing total drag, which includes components from parasitic, lift-induced, and transsonic wave drag.

[2]http://airfoiltools.com

[3]OpenAeroStuct documentation can be found at https://github.com/mdolab/OpenAeroStruct

OpenAeroStruct generates a discretized panel model for the given wing, and generates drag polar data across various Mach numbers, angles of attack, and altitudes. These conditions area varied depending on the operating conditions of the aircraft. I also used the span efficieny estimation from OpenAeroStruct instead of a static variable. The OpenAeroStruct implementation allowed me to use wing design parameters, such as aspect ratio and taper ratio, as design variables in the final optimization.

## 6 Optimization Model Setup

I made the optimization model setup based on existing OpenConcept models, which were capable of performing a full mission simulation for a static aircraft design. The setup for optimization is segmented into 3 distinct components: the aircraft model, the analysis model, and optimization model. Each of these component defines a distinct portion of full optimization run-script[4].

- Aircraft Model: This portion of the optimization model defines the full aircraft model, defines the propulsion system, and computes the fuel weight over time for each flight segment. It incorporates the OpenAeroStruct drag polar to estimate drag. The propulsion model outputs are doubled for a twin engined aircraft, which gives the total fuel used and thrust.. The OEI flight segments are defined in the mission analysis section of OpenConcept and can ”turn off” and engine to simulate and OEI acase.. Once the required thrust and fuel burn are computed, they are passed to the weight model and force balance components to compute the aircraft weights over the course of the mission.

- Analysis Model: This level of the model is where all design parameters and constraints are calculated. First, all necessary design parameters are initialized into an aircraft data dictionary. This dictionary contains the following

  1. Wing, tail, fuselage, and landing gear parameters
  2. Payload and landing weights
  3. Aerodynamic characteristics
  4. Propulsion system characteristics

  Once all necessary values are initialized, the analysis model computes the following design parameters, which are stored in the aircraft data dictionary:

[4] Run script published to https://github.com/vrsub/openconcept/blob/sizing/examples/B738_sizing.py

1. Wing Root Chord and Mean Aerodynamic Chord, assuming linear taper
2. Horizontal and vertical stabilizer reference area using the volume coefficient method components
3. Non-wing skin friction drag coefficient using implemented component
4. Operating empty weight estimate using weights build-up method
5. Maximum takeoff weight for defined mission using payload weight, empty weight, and fuel weight. Fuel weight is solved for implicitly using the mission analysis
6. Wing $C_{L_{max}}$ assuming a constant airfoil $C_{l_{max}}$

Once these values are computed, the analysis model runs the selected mission with the stored aircraft model, which computes total fuel burn and mission block time. The mission outputs are then passed to the COC evaluation subsystem, which computes an estimate of total cash operating cost of the mission.

- Mission and Optimization Configuration: This component sets values for the mission, such as range, cruise altitude, cruise speed, etc. It also initializes the implicit solver, optimization driver, optimization design variables, constraints, and objective functions.

# 7 Optimization Results for Boeing 737-800

The optimization setup described in Section 6 was used optimize the wing area, thrust, and wing parameters of the Boeing 737-800 aircraft model, with the goal of attempting to recreate the published design parameters

## 7.1 Mission Description

I selected a mission with a 2050 nautical mile distance at an altitude of 33,000 feet. The aircraft cruises at an average of 260 knots. The mission requires the aircraft be capable of of reserve cruise for 30 minutes at an altitude of 15,000 ft at 250 knots. The payload weight is configured to be a fully loaded passenger mission, with 180 passengers, 6 crew, and their respective luggage. The fuselage size is kept constant due to it being sized for the passenger requirements. The 737-800 currently design is shown in Table 1. The fuel burn and cash operating costs for the mission were computed using the newly implemented Raymer weight buildup, OpenAeroStruct drag computation, and Roskam cash operating cost method. This was done to estimate the objective functions using the methods the analysis model uses to optimize the results.

| Parameter | Value |
|---|---|
| $S_{ref}$ | 124.6 $m^2$ |
| $AR$ | 9.45 |
| Taper Ratio | 0.159 |
| $\Lambda_{c/4}$ | 25.0° |
| $t/c_{root}$ | 0.12 |
| $S_v$ | 26.44 $m^2$ |
| $S_h$ | 32.78 $m^2$ |
| OEW | 41,871 kg |
| MTOW | 79,002 kg |
| Single Engine Rating | 27,000 lbf |
| Mission Block Fuel Burn | 16,983.6 kg |
| Cash Operating Cost | $35,361 |

**Table 1:** Known 737-800 Design Parameters

### 7.2 Optimization Problem Setup

There were two objective functions used to optimize the design of the Boeing 737-800; pure fuel burn and cash operating cost. The optimization was run with each objective function, and the results are shown in the following sections.

### 7.3 Design Variables and Constraints

The added functionality to OpenConcept allowed for more design variables to be used in the optimization. For the Boeing 737-800 case, the design variables and their limits are shown in Table 2. Tip twist is constrained to 0 degrees to accurately model the wing as a twisted rigid body. The constraints[5] for the optimization are shown in Table 3

[5]Wingspan limitation set for Group III airport gates, Takeoff distance constraints from published Boeing Airport Planning handbook

| Design Variable | Min Value | Max Value | Unit |
|---|---|---|---|
| $S_{ref}$ | 100 | 150 | $m^2$ |
| Engine Thrust Rating | 20,000 | 30,000 | lbf |
| $\Lambda_{c/4}$ | -2 | 50 | degrees |
| Wing tip twist | 0 | 0 | degrees |
| Wing twist (other spanwise locations) | -5 | 5 | degrees |
| Taper Ratio | 0 | 1 | |
| Wing $AR$ | 5 | 15 | |

**Table 2:** Boeing 737-800 Design Variables

| Design Variable | Upper Limit | Unit |
|---|---|---|
| Engine Throttle | 1 | |
| Flight Condition $C_L$ | $C_{L_{max}}$ | |
| Wing Span | 36 | meters |
| Takeoff Distance | 7,000 | feet |

**Table 3:** Boeing 737-800 Constraints

### 7.4 Results and Analysis

Both optimizations result in reasonable design variables that are not at the design variable bounds and are relatively close to the original 737-800 design point. There was one case where the design variable for wing root twist converged to the upper limit, which is discuss later. Compared to the original design case, both optimizations resulted in design variables close to the design point with objective function evaluations that are better than original results.

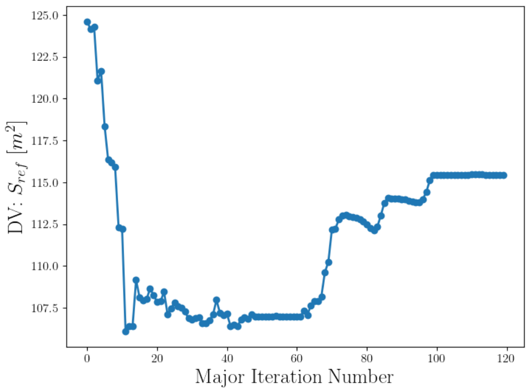
#### 7.4.1 Objective: Minimize Block Fuel Burn

Table 4 shows the design variables and evaluation of the fuel burn objective function chosen by the optimizer. The block fuel burn is is a few hundred kilograms less than the initial design, with COC also about $1,000 lower. The original design point of the 737-800 has a wing area of 124.6 $m^2$ and maximum engine thrust of 27,000 lbf. The optimized values show a slightly smaller wing with high thrust, which aligns with the expectation of how the optimizer choeses the wing size. A larger wing area increases the weight enough such that it requires more fuel to lift. However, the results also show that there is a bottom limit to how small the wing can be and how large the engine. If the engine is too large, the fuel burn would be too high to maintain the thrust required for lift. The active constraint is the wing span, which is exactly 36 meters for our aircraft. This behavior is validated by our knowledge that high aspect ratio wings are more efficient, and the optimization model attempts to maximize wing span to achieve higher efficiency. A note of concern in the results is that the root twist is at its maximum value, indicating that the true optimal solution maybe be outside the assigned design space.

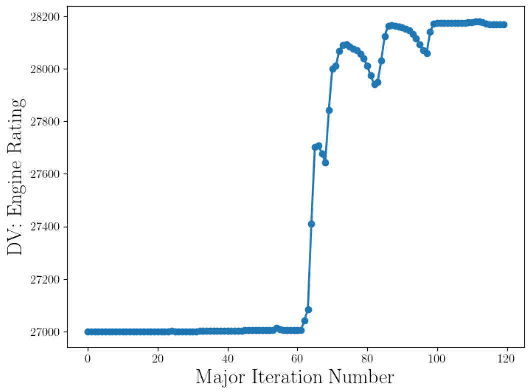
| Design Variable | Value | Unit |
|---|---:|---:|
| $S_{ref}$ | 115.4 | $m^2$ |
| Engine Thrust Rating | 28,169 | lbf |
| $\Lambda_{c/4}$ | 24.1 | degrees |
| Wing tip twist | 0 | degrees |
| Station 1 twist | 3.18 | degrees |
| Midpoint twist | 3.96 | degrees |
| Station 3 twist | 3.01 | degrees |
| Wing root twist | 5 | degrees |
| Taper Ratio | 0.46 | |
| Wing $AR$ | 11.22 | |
| Obj: Fuel Burn | 16,121.1 | kg |
| COC | $34,286.1 | |

**Table 4:** Boeing 737-800 Optimized Design for Fuel Burn

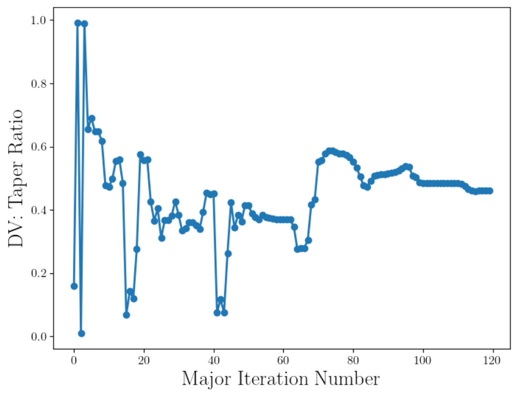
The following plots show the history of all design variables and the objective function evaluation over optimization iterations.



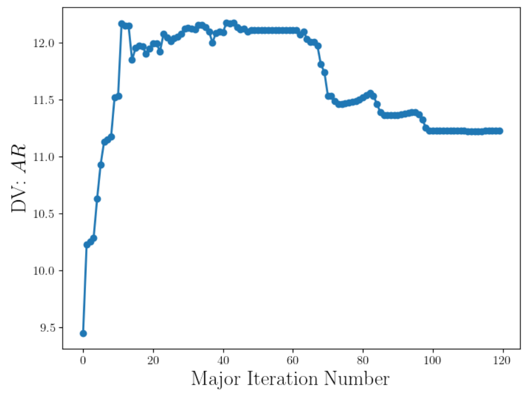

**(a)** $S_{ref}$ vs Iteration



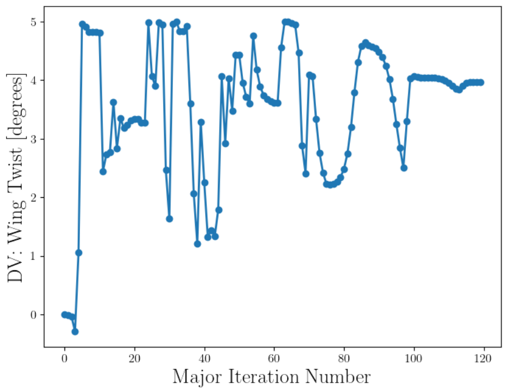

**(b)** Engine rating vs Iteration



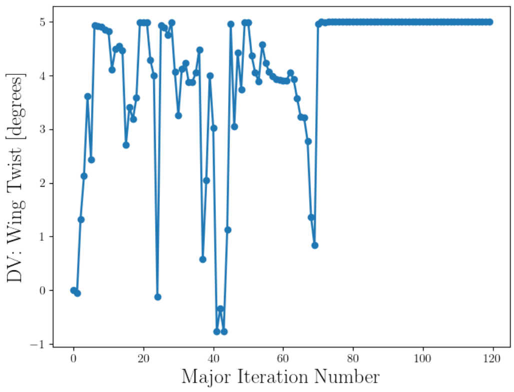

**(a)** Taper ratio vs Iteration



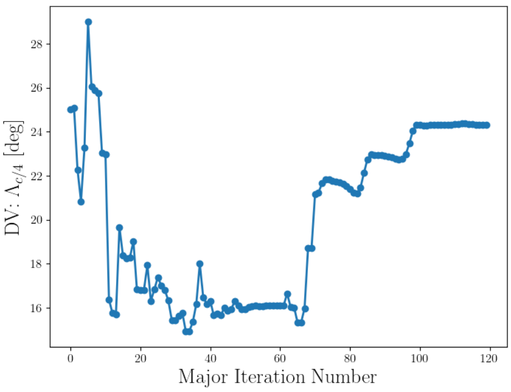

**(b)** Aspect Ratio vs Iteration



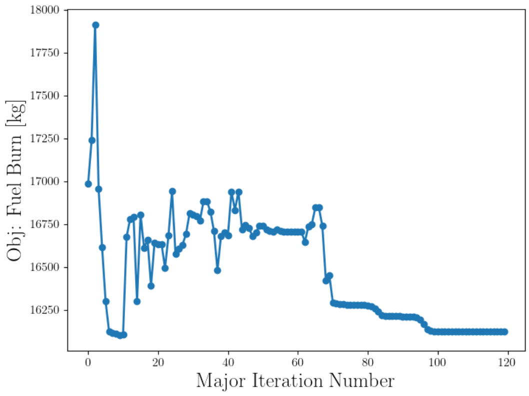

**(a)** Midspan Twist vs Iteration




**(b)** Root twist vs Iteration




**(a)** $\Lambda_{c/4}$ vs Iteration




**(b)** Fuel Burn vs Iteration

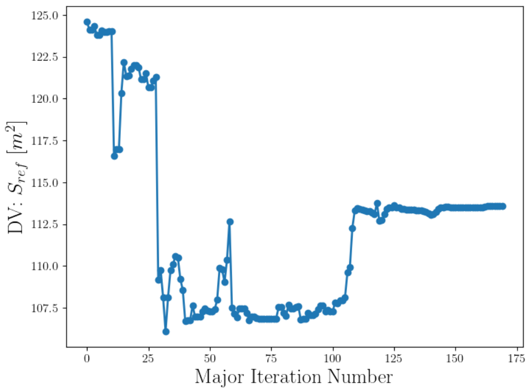
#### 7.4.2 Objective: Minimize Cash Operating Cost

Table 5 shows the optimizer's chosen design point considering cash operating cost as the objective function. Compared to the fuel burn optimization, the COC optimization has a slightly higher fuel burn, but ultimately a lower cash operating cost. This optimization used the same constraints and design space as the fuel burn optimization. These results show a slightly different wing area and shape, with slightly lower thrust compared to the fuel burn optimization. However, the design point is still very close to the original 737-800 design and shows that cash operating cost accounts for slightly different objectives. For example, the main wing sweep angle is slightly lower than the fuel burn optimization. It is well established that larger sweep reduces wave drag, but increases the structural weight of the aircraft. My hypothesis is that the optimizer chose to lower sweep angle to lower the aircraft's weight, which would contribute to lower fuel burn. This will slightly increase wave drag induced fuel burn, but the trade-off seems to favor reducing wing sweep and weight.

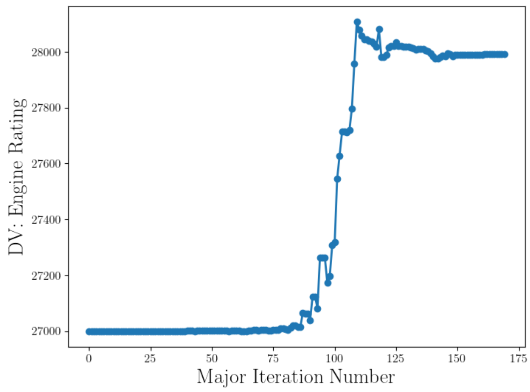
| Design Variable | Value | Unit |
|---|---:|---:|
| $S_{ref}$ | 113.56 | $m^2$ |
| Engine Thrust Rating | 27,993 | lbf |
| $\Lambda_{c/4}$ | 22.84 | degrees |
| Wing tip twist | 0 | degrees |
| Station 1 twist | 3.55 | degrees |
| Midpoint twist | 3.73 | degrees |
| Station 3 twist | 2.60 | degrees |
| Wing root twist | 4.58 | degrees |
| Taper Ratio | 0.397 | |
| Wing $AR$ | 11.41 | |
| Fuel Burn | 16,144.9 | kg |
| Obj: COC | $3,4254.2 | |

**Table 5:** Boeing 737-800 Optimized Design for Cash Operating Cost

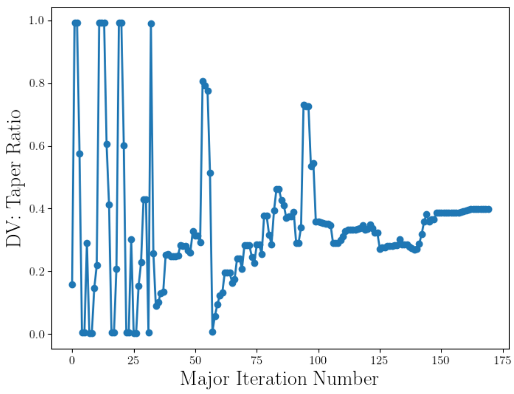
The following plots show the history of all design variables and the objective function evaluation over optimization iterations.



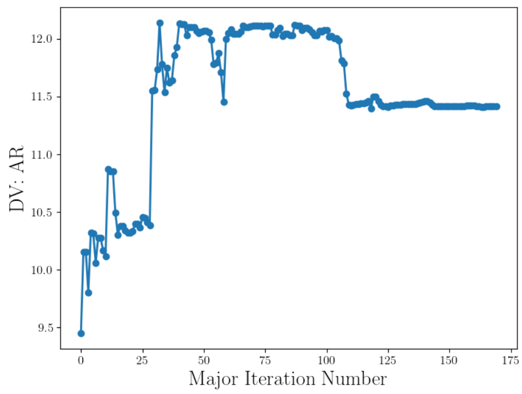

**(a)** $S_{ref}$ vs Iteration



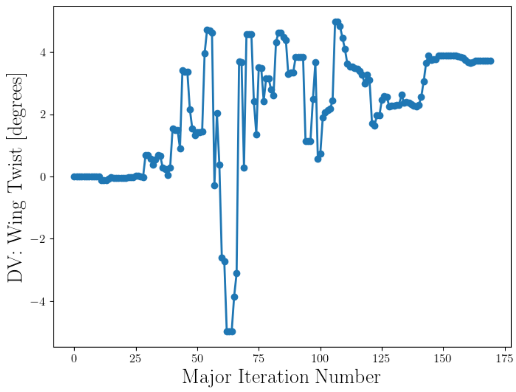

**(b)** Engine rating vs Iteration



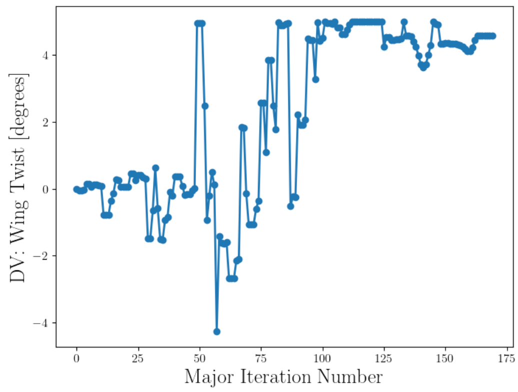

**(a)** Taper ratio vs Iteration



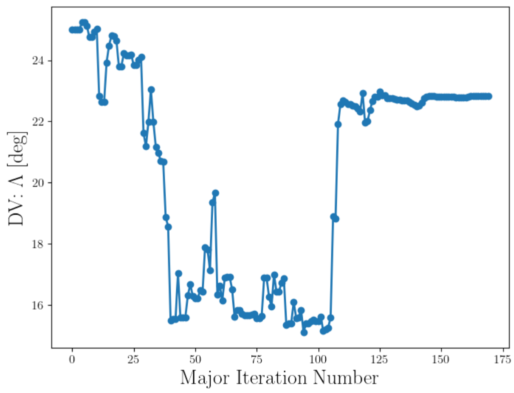

**(b)** Aspect Ratio vs Iteration



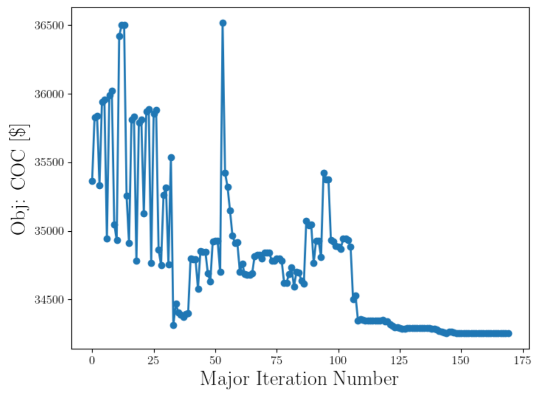

**(a)** Midspan Twist vs Iteration




**(b)** Root twist vs Iteration




**(a)** $\Lambda_{c/4}$ vs Iteration




**(b)** Cash Operating Cost vs Iteration

# 8 Optimization Results for Socata TBM-850

The optimization setup described in Section 6 was used optimize the wing area, thrust, and wing parameters of the Socata TBM-850 aircraft model, with the goal of attempting to recreate the published design parameters.

## 8.1 Mission Description

I selected a mission with a 1250 nautical mile distance at an altitude of 28,000 feet. The aircraft cruises at an average of 200 knots. The mission requires the aircraft be capable of of reserve cruise for 30 minutes at an altitude of 15,000 ft at 200 knots. The payload weight is configured to be a fully loaded passenger mission of 850 pounds. The fuselage size is kept constant due to it being sized for the passenger requirements. The TBM-850 current design is shown in Table 6. The fuel burn estimation for the original design was computed using an existing component weights method, the OpenAeroStruct drag polar, and all new the new functions that will be used in the optimization. This was done to estimate the objective functions using the equations the analysis model uses to optimize the results.

| Parameter | Value |
|---|---|
| $S_{ref}$ | 18 $m^2$ |
| $AR$ | 8.95 |
| Taper Ratio | 0.622 |
| $\Lambda_{c/4}$ | 1° |
| $t/c_{root}$ | 0.16 |
| $S_v$ | 47.5 $ft^2$ |
| $S_h$ | 31.4 $ft^2$ |
| OEW | 4685 lb |
| MTOW | 7027 lb |
| Engine Rating | 850 hp |
| Mission Block Fuel Burn | 1492 lb |

**Table 6:** Known TBM-850 Design Parameters

### 8.2 Optimization Setup, Design Variables and Constraints

Since there was no cost build up method for turboprop aircraft, I chose to only use fuel burn as the objective function. As with the Boeing 737 model, the added functionality to OpenConcept allowed for more design variables to be used in the optimization. For the TBM-850 case, the design variables and their limits are shown in Table 7. Tip twist is constrained to 0 degrees to accurately model the wing as a twisted rigid body. For this case, I did not include a wing span constraint to study how wing aspect ratio behaves with no constraint. The other constraints for the optimization are shown in Table 8

| Design Variable | Min Value | Max Value | Unit |
|---|---|---|---|
| $S_{ref}$ | 10 | 30 | $m^2$ |
| Engine Thrust Rating | 500 | 1,00 | hp |
| $\Lambda_{c/4}$ | -2 | 15 | degrees |
| Wing tip twist | 0 | 0 | degrees |
| Wing twist (other spanwise locations) | -5 | 5 | degrees |
| Taper Ratio | 0 | 1 | |
| Wing $AR$ | 8 | 20 | |

**Table 7:** TBM-850 Design Variables

| Design Variable | Upper Limit | Unit |
|---|---|---|
| Engine Throttle | 1 | |
| Flight Condition $C_L$ | $C_{L_{max}}$ | |
| Takeoff Distance | 1000 | meters |

**Table 8:** TBM-850 Constraints

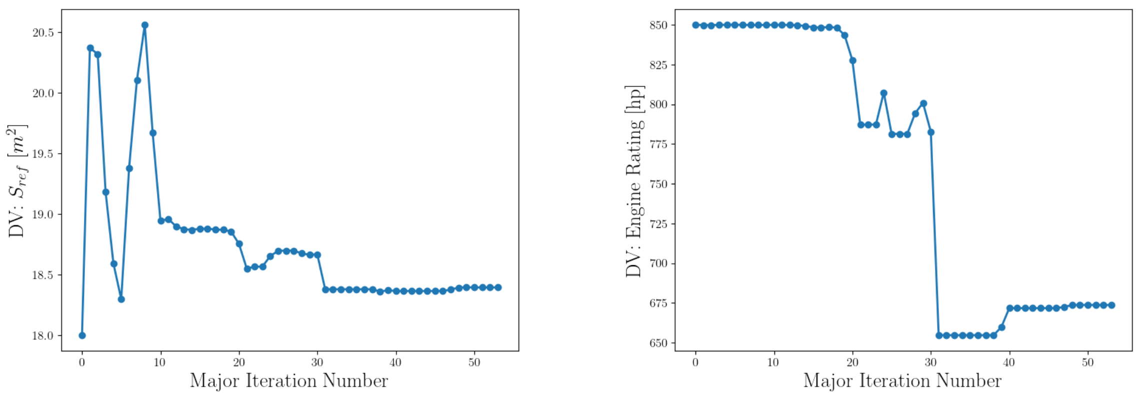
### 8.3 Results and Analysis

Table 5 shows the optimizer's chosen design point considering block fuel burn as the objective function. These results show a slightly different wing area and shape with a much lower thrust requirement. Fuel burn is also considerably lower for the optimized design. However, the design point is still very close to the original TBM-850 design. An observation from these results is that the wing aspect ratio is smaller in the optimized design. This could be due to higher wing structural weight for higher aspect ratio wings not providing a sizable efficiency improvement to justify the long wing. Another observation is the much lower engine thrust required for the mission. This can be attributed to the TBM-850 being the same airframe of the TBM-700, just with a higher power engine. The optimization results align more closely with the TBM-700 aircraft, which has as 700 hp engine.

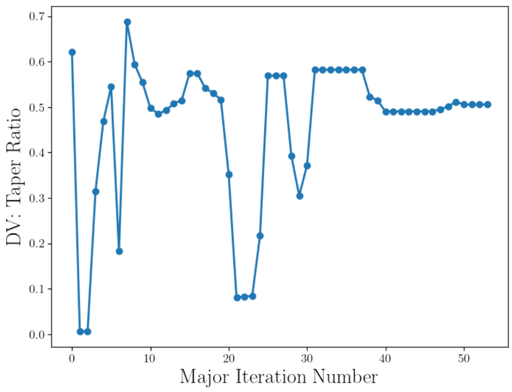
| Design Variable | Value | Unit |
|---|---|---|
| $S_{ref}$ | 18.4 | $m^2$ |
| Engine Thrust Rating | 673.7 | hp |
| $\Lambda_{c/4}$ | 0.63 | degrees |
| Wing tip twist | 0 | degrees |
| Station 1 twist | 0.87 | degrees |
| Midpoint twist | 1.047 | degrees |
| Station 3 twist | 0.73 | degrees |
| Wing root twist | 0.61 | degrees |
| Taper Ratio | 0.51 | |
| Wing $AR$ | 8 | |
| Fuel Burn | 1308.2 | lb |

**Table 9:** Socata TBM-850 Optimized Design for Fuel Burn

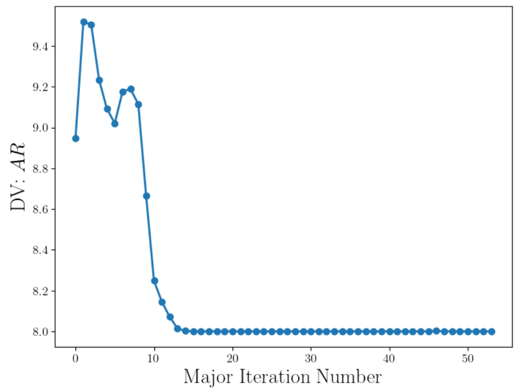
The following plots show the history of all design variables and the objective function evaluation over optimization iterations.



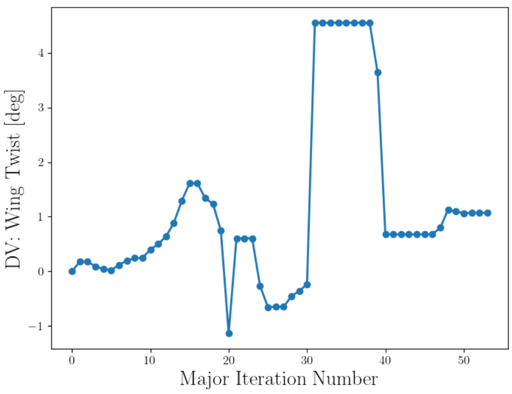

**(a)** $S_{ref}$ vs Iteration  **(b)** Engine rating vs Iteration



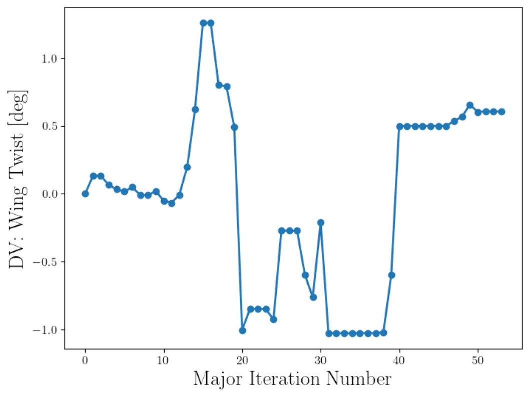

**(a)** Taper ratio vs Iteration



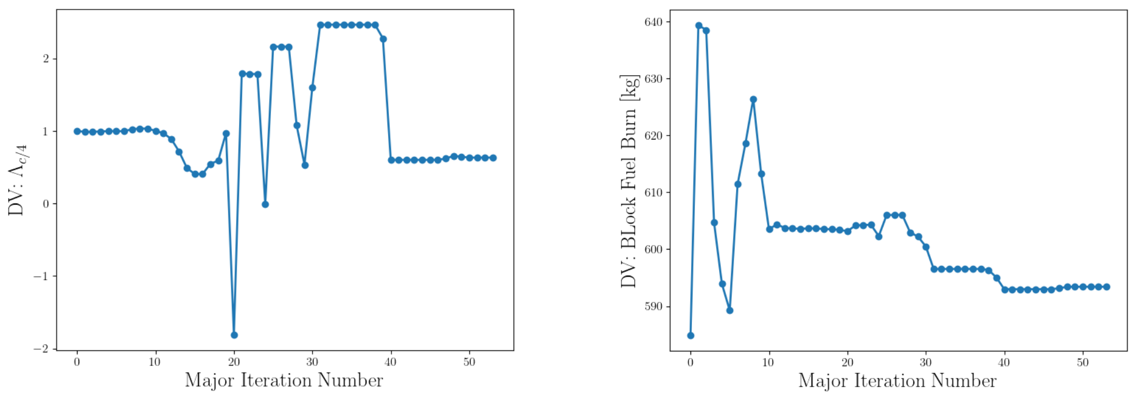

**(b)** Aspect Ratio vs Iteration




**(a)** Midspan Twist vs Iteration




**(b)** Root twist vs Iteration




**(a)** $\Lambda_{c/4}$ vs Iteration

**(b)** Block Fuel Burn vs Iteration

# 9 Conclusion and Future Work

This report outlined the methods implemented into OpenConcept to allow for preliminary aircraft sizing optimization using the OpenMDAO framework. I added multiple functions and components to assist in estimating the aircraft's characteristics and implemented them into an optimization model. This optimizer was validated against two existing aircraft models and shows that the optimizer is able to converge to a solution close to the original design of the aircraft. In the near future, these new components and methods will be merged with the public OpenConcept repository to enable public access. Additionally, future mission sizing can be performed where the aircraft is sized for a design mission with max payload, but optimized around an economy mission. The optimization can also incorporate landing stall speed as a constraint to calculate the maximum lift coefficient of the main wing in a clean configuration.

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