Aircaft Design Project Part 1 - Report

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I. Introduction

This report presents the development and testing of a Sizing and Synthesis Tool designed for the preliminary design of a fixed-wing commercial aircraft, with the Airbus A320neo as a case study. The goal of this tool is to compute key characteristics such as takeoff weight, wing surface area, and static thrust at sea level, based on a user-defined mission profile and additional performance constraints.

The tool iteratively performs mission and constraint analyses, where the output of one analysis serves as input to the other, ensuring consistency throughout the design process. The mission analysis includes evaluating fuel, empty weight fractions and the takeoff weight, while the constraint analysis identifies the design point on a thrust-loading versus wing-loading plot. The tool's main features include the ability to customize mission phases and to adjust various inputs such as payload and crew weights.

Results from applying this tool to the A320neo benchmark showed non-negligible deviations from actual values, in thrust loading and wing loading. The calculated thrust loading was approximately 35% higher than the actual value, while the wing loading was off by around 10.5%. These discrepancies likely stem from simplifying assumptions made during mission analysis and constraint formulation. Despite this, the tool successfully converged on a design point that satisfies the various operational constraints, demonstrating its utility for early-stage aircraft design.

In conclusion, while the tool provides valuable insights into aircraft sizing, further refinements are necessary to improve accuracy. The assumptions used in the weight fraction determination and constraint analysis The analysis of the mission and constraints was based mainly on analytical formulas and historical data was poorly used. Incorporating more real-world data could enhance its predictive capabilities.

II. General description of the Sizing and Synthesis Tool

As mentionned in the introduction, this tool enables to traduce the requirements of a commercial aircraft to its key characteristics. The current section explains more in detail the inputs and the outputs of this tool. Additionally, it would also describe its general data-flow, providing insights on the interaction between its main parts.

A. Inputs

Mission Profile

The most important input of this tool is the mission profile. The user first specify the total number of phases, then the type of each phases by order and finally the values of the parameters of each phase (fig.1). Therefore, this tool is able to flexibly analyze various types of mission phase, in a different order.

Additional constraints

Secondly, the additional constraints has to be specified in the safe way than for the mission profile.

Other parameters

Thirdly, the values of other inputs parameters have to be specified. These parameters are the initial guesses of takeoff

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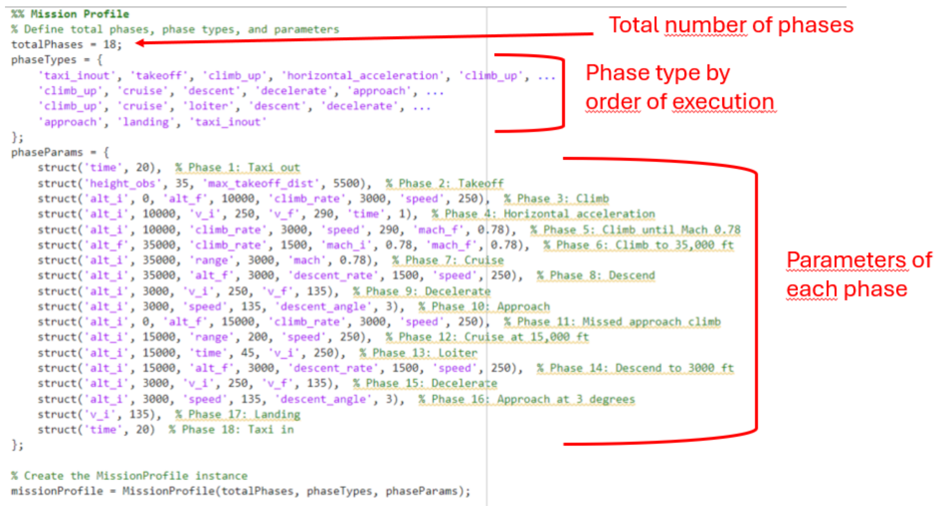
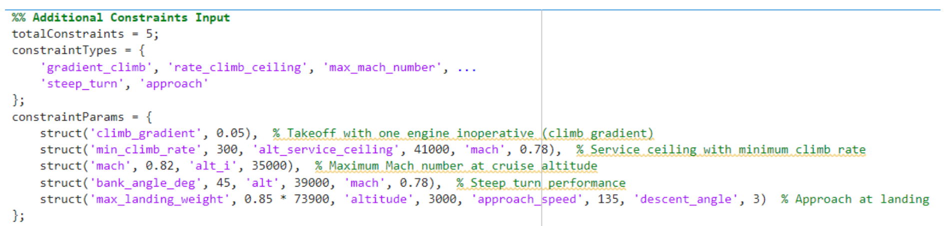



```
%% Mission Profile
% Define total phases, phase types, and parameters
totalPhases = 18;
phaseTypes = {
    'taxi_inout', 'takeoff', 'climb_up', 'horizontal_acceleration', 'climb_up', ...
    'climb_up', 'cruise', 'descent', 'decelerate', 'approach', ...
    'climb_up', 'cruise', 'loiter', 'descent', 'decelerate', ...
    'approach', 'landing', 'taxi_inout'
};
phaseParams = {
    struct('time', 20),  % Phase 1: Taxi out
    struct('height_obs', 35, 'max_takeoff_dist', 5500),  % Phase 2: Takeoff
    struct('alt_i', 0, 'alt_f', 10000, 'climb_rate', 3000, 'speed', 250),  % Phase 3: Climb
    struct('alt_i', 10000, 'v_i', 250, 'v_f', 290, 'time', 1),  % Phase 4: Horizontal acceleration
    struct('alt_i', 10000, 'climb_rate', 3000, 'speed', 290, 'mach_f', 0.78),  % Phase 5: Climb until Mach 0.78
    struct('alt_f', 35000, 'climb_rate', 1500, 'mach_i', 0.78, 'mach_f', 0.78),  % Phase 6: Climb to 35,000 ft
    struct('alt_i', 35000, 'range', 3000, 'mach', 0.78),  % Phase 7: Cruise
    struct('alt_i', 35000, 'alt_f', 3000, 'descent_rate', 1500, 'speed', 250),  % Phase 8: Descend
    struct('alt_i', 3000, 'v_i', 250, 'v_f', 135),  % Phase 9: Decelerate
    struct('alt_i', 3000, 'speed', 135, 'descent_angle', 3),  % Phase 10: Approach
    struct('alt_i', 0, 'alt_f', 15000, 'climb_rate', 3000, 'speed', 250),  % Phase 11: Missed approach climb
    struct('alt_i', 15000, 'range', 200, 'speed', 250),  % Phase 12: Cruise at 15,000 ft
    struct('alt_i', 15000, 'time', 45, 'v_i', 250),  % Phase 13: Loiter
    struct('alt_i', 15000, 'alt_f', 3000, 'descent_rate', 1500, 'speed', 250),  % Phase 14: Descend to 3000 ft
    struct('alt_i', 3000, 'v_i', 250, 'v_f', 135),  % Phase 15: Decelerate
    struct('alt_i', 3000, 'speed', 135, 'descent_angle', 3),  % Phase 16: Approach at 3 degrees
    struct('v_i', 135),  % Phase 17: Landing
    struct('time', 20)  % Phase 18: Taxi in
};

% Create the MissionProfile instance
missionProfile = MissionProfile(totalPhases, phaseTypes, phaseParams);
```

Fig. 1 Input for the mission profile



```
%% Additional Constraints Input
totalConstraints = 5;
constraintTypes = {
    'gradient_climb', 'rate_climb_ceiling', 'max_mach_number', ...
    'steep_turn', 'approach'
};
constraintParams = {
    struct('climb_gradient', 0.05),  % Takeoff with one engine inoperative (climb gradient)
    struct('min_climb_rate', 300, 'alt_service_ceiling', 41000, 'mach', 0.78),  % Service ceiling with minimum climb rate
    struct('mach', 0.82, 'alt_i', 35000),  % Maximum Mach number at cruise altitude
    struct('bank_angle_deg', 45, 'alt', 39000, 'mach', 0.78),  % Steep turn performance
    struct('max_landing_weight', 0.85 * 73900, 'altitude', 3000, 'approach_speed', 135, 'descent_angle', 3)  % Approach at landing
};
```

Fig. 2 Enter Caption

weight, wing surface, static thrust at sea-level, and the payload and crew weights of the aircraft.

Maximum Iteration

Finally, the user has to specify the maximum number of iteration done by the tool. 10 iterations are generally sufficient to converge the results.

B. Output

After the maximum number of iteration, the tool outputs the following parameters:

- the design point expressed by thrust loading and wing loading
- Thrust at sea-level
- Wing surface
- Takeoff weight
- Fuel weight
- Empty weight

Additionally, the following plots are displayed:

- The evolution of the weight fraction W/W_{TO} during the mission
- The weight breakdown between empty, fuel, payload and crew weights
- The constraints plots, indicating the design point and the design space

```
%% Other parameters
% Define induced drag coefficient, payload/crew weights, initial guess for
% takeoff weight, wing surface and sea-level thrust

payload_weight = (190 + 30) * 150;
crew_weight = 1050;

% initial guess
W_to_guess = 160000;   % takeoff weight
S_guess = 1300; % wing surface
T_sl_guess = 24700*2; % static thrust at sea level

% Create an instance of other_input_parameters
otherParameters = other_input_parameters(payload_weight, crew_weight, W_to_guess, S_guess, T_sl_guess);
```

Specify payload / crew weights

Specify initial gueses of takeoff weight, wing surface, static thrust at sea-level

Fig. 3 Input of the initial guesses of takeoff weight, wing surface, static thrust at sea-level, and the payload and crew weights of the aircraft

C. General data-flow of the tool

The general data-flow of the tool is illustrated by the figure 4. It is important to note that the inidividual analysis of mission phase, of constraints and of different weights are coupled - the outputs of mission and constraints analysis are input in the mission phase analysis of the next iteration and the output of the mission analysis are inputs of the mission and constraint analysis. On the other side, the inputs of the tool (e.g. the mission profile, the additional constraints and the assumptions on some parameters) are also used by different parts of the tool for each iteration.

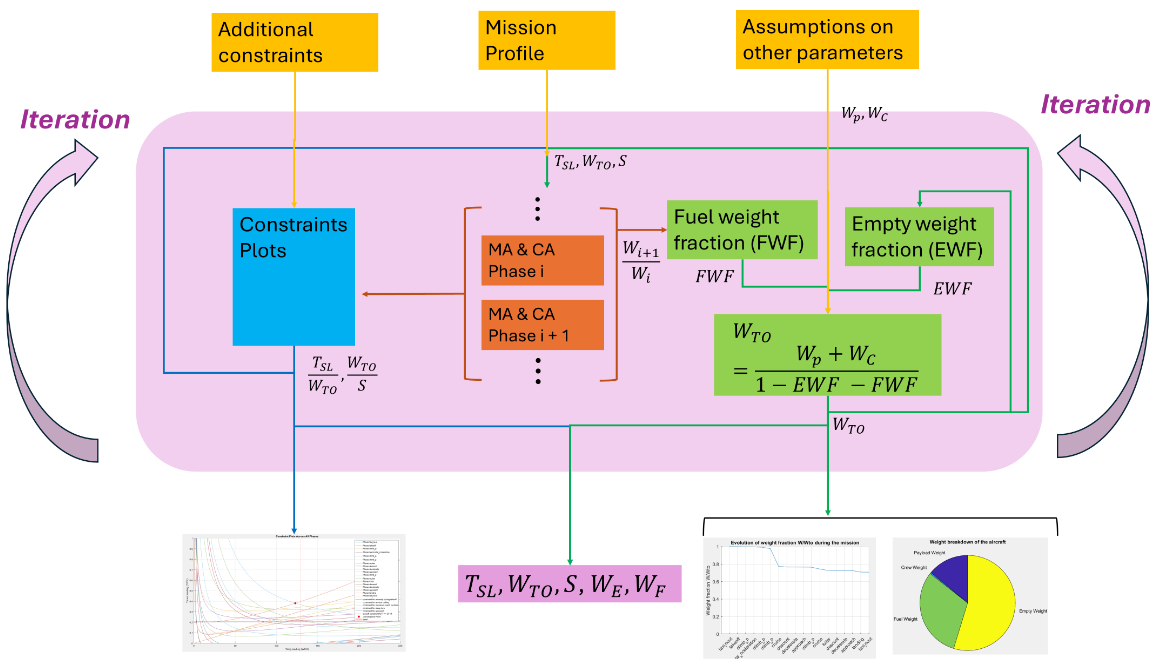


Fig. 4 Data-flow diagram of the tool

III. Mission Analysis

A. Methodology

The workflow for the mission analysis was as follow.

- First the fraction between the initial and final weights for each mission phase was individually analyzed.
- Secondly, these separate analysis were used for the iteration between the takeoff weight, the fuel weight fraction and the empty weight fraction.

For the determination of weight fractions, different methods, including Breguet's endurance or range formulas or the integration of generic fuel burn were used depending on the phase. Moreover, the determination of the thrust specific fuel consumption (TSFC) was completed using Mattingly Equation[1]. Regarding atmospheric parameters which have influence on the final result of the weight fraction, they were determined using the AIAA 'altitude tables' [2]. It was decided to use the table instead of a simplified model as the atmospheric parameters were influencing almost all the parameters. Thus, accurately determining them would enable to reduce the errors.

Different assumptions were used for the individual analysis of the mission phases. These differences are described below:

- **Takeoff**:
  The weight fraction for takeoff is calculated assuming constant fuel consumption, with the maximum thrust capacity. The lift coefficient is also assumed to be at its maximum value (i.e. $CL_{max} = 2.56$). Finally, by assuming constant the derivative of the weight over the time during the takeoff, the integration of generic fuel burn was used to compute the weight fraction.
- **Climb Phases**:
  Climb rates and speeds are assumed to be constant during each climb phase. Thus, the thrust specific fuel consumption were evaluatated at the mean altitude of the phase. The weight fractions are calculated using the Breguet range equation, accounting for altitude and velocity profiles.
- **Cruise**:
  Cruise is assumed to be a steady, level flight. Therefore, the lift-drag ratio was evaluated at its maximum value : $(\frac{L}{D})_{max} = \sqrt{\frac{1}{4K_1 CD_0}}$. The weight fraction is computed using the Breguet range equation.
- **Descent**:
  Descent phase was considered as a constant speed climb up with negative climb up rate. Therefore, the assumption and the method were similar to the climb phase.
- **Horizontal Acceleration**:
  The aircraft accelerates over a fixed time or distance with constant acceleration. Therefore, the mach number to determine the TSFC was evaluated at its mean value.
- **Loiter**:
  The loiter phase assumes the aircraft flies at the endurance speed to maximize fuel efficiency. The weight fraction is determined using the Breguet endurance equation.
- **Deceleration**
  The deceleration is assumed completed only by the effect of drag. There is not fuel consumption during this phase.
- **Approach**:
  A constant descent angle is assumed during approach, and fuel consumption is minimal.The fuel flow were assumed to be 20% of the one for the takeoff. Therefore, the integration of generic fuel burn, taking into account the previous assumption was used for the determination of weight fraction.
- **Landing**:
  The weight fraction for landing is calculated using Breguet's endurance equation. The time of this operation were assumed to be 30 min. It is the endurance capacity imposed by the regulation before starting a landing operation.

After the determination of weight fraction for each phase, the takeoff weight, and the fuel and empty weight fractions were determined by iteration and an initial guess of the takeoff weight. The empty weight were expressed by the takeoff weight using the formula:

$$EWF = k_{WE} W_{TO}^{-0.06} \tag{1}$$

with $k_{WE} = 1.15$ The fuel weight fraction was determined by multiplying the weight fractions of all the phases and applying the formula:

$$FWF = 1.05 * (1 - \frac{W_n}{W_{TO}} \tag{2}$$

The factor 1.05 was set to keep a margin of 5% additional fuel, to comply to the requirement 'land to the alternate airport [...] with a 5% fuel reserve.

Finally, the takeoff weight was expressed by the two weights fraction and the crew and payload weight using the formula :

$$W_{TO} = \frac{W_c + W_p}{1 - EWF - FWF} \tag{3}$$

B. Results

The results of the mission analysis for the A320 neo benchmark aircraft is presented in the table 1. The figures 5 and 6 show the weight breakdown of the aircraft and the evolution of the weight fraction across the mission, respectively.

Table 1 Results of the mission analysis for A320 neo benchmark

Parameter	Results of A320 neo Benchmark	Real values from A320-200[3]	Relative error
Takeoff weight	235,640 lb	/	/
Fuel weight	72,585 lb	/	/
Empty weight	12,901 lb	/	/
Fuel weight fraction	0.3080	0.256	20%
Empty weight fraction	0.5475	0.562	2%

The empty weigh fraction shows a satisfactory result compared to the real value of A320-200. However, the fuel weight fraction results in a relative error of 20%. The possible explanation of this difference is provided in the last section.

IV. Constraint Analysis

A. Methods

Similarly to the mission analysis, the constraint analysis encompasses first the separate analysis of mission phases and of additional constraints and then a constraint plots in which the design space as well as the design point were determined, using some criteria. // Except the case of takeoff and landing, each mission phase was studied to obtain the paramaters of the master equation, which are $V, dV/dt, dh/dt, q, R, CD_0, \alpha, \beta$. As the scope of the tool was limite to the case of commercial aircrafts, the drag in specific configuration, R, was assumed equal to zero, except for the case of takeoff with thrust similar to drag. The weight fraction, β, was obtained by the mission analysis.

In order to obtain these parameters, the following methods and assumptions were taken.

- **Takeoff (case $T >> D + R$):** The thrust was assumed to be at its value at sea-level and the lift coefficient at its maximum value. The value of friction coefficient of the runaway was taken at its worst condition, which is on

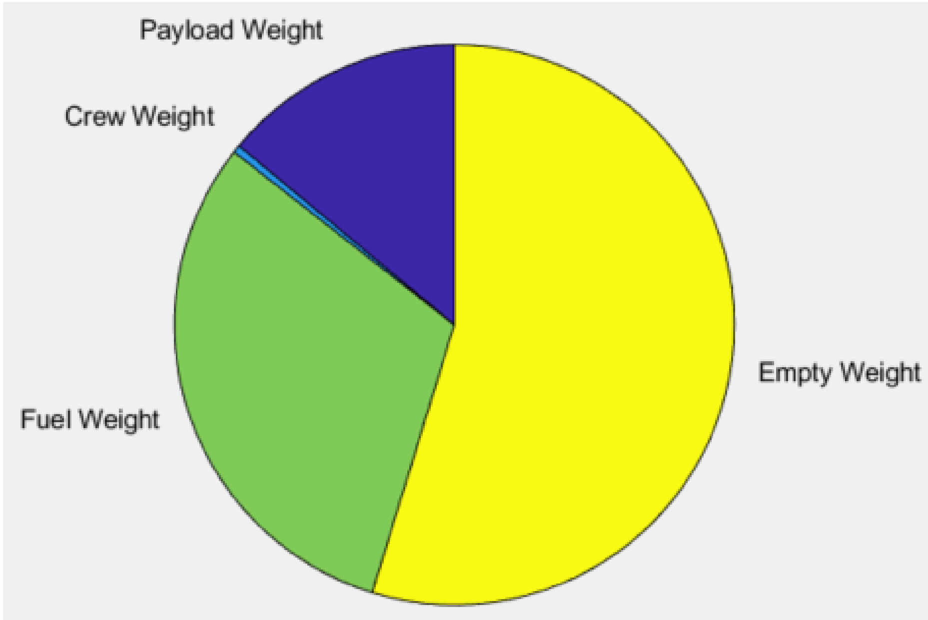


Fig. 5 Weight breakdown of the aircraft

wet and hard runaway (μ_{TO} = 0.05)[1]. The thrust-to-weight ratio is calculated to ensure the aircraft can lift off within the defined takeoff distance and clear a defined obstacle height.

- **Constant speed climb**:
  The climb rate and speed were assumed constant, even though when the speed where given in KEAS, the change in altitude implied a change in true speed. The velocity, as well as the atmospheric parmaters were evaluated at their values at the mean altitude.
- **Cruise**:
  In the cruise phase, the constraint ensures the aircraft can maintain steady level flight at a constant altitude and Mach number. The range speed was used, which required to take the drag and lift such that their ratio was at its maximum.
- **Descent**:
  As mentioned in the previous section, the descent is considered as a constant speed climb with negative climb rate. The speed is thus assumed constant and is evaluated at the mean altitude.
- **Horizontal Acceleration**:
  The aircraft accelerates over a fixed time or distance with constant acceleration. Therefore, the mach number to determine the TSFC was evaluated at its mean value
- **Loiter**:
  The loiter phase requires to maximize endurance. As the engine is jet-propelled, the endurance speed is obtained with the maximum lift-drag ratio.
- **Deceleration**
  The deceleration is assumed completed only by the effect of drag. There is not fuel consumption during this phase. By assuming that the lift fully compensate the weight, the drag is express as the function of weight and lift coefficient such that the lift-drag ratio is maximized.
- **Approach**:

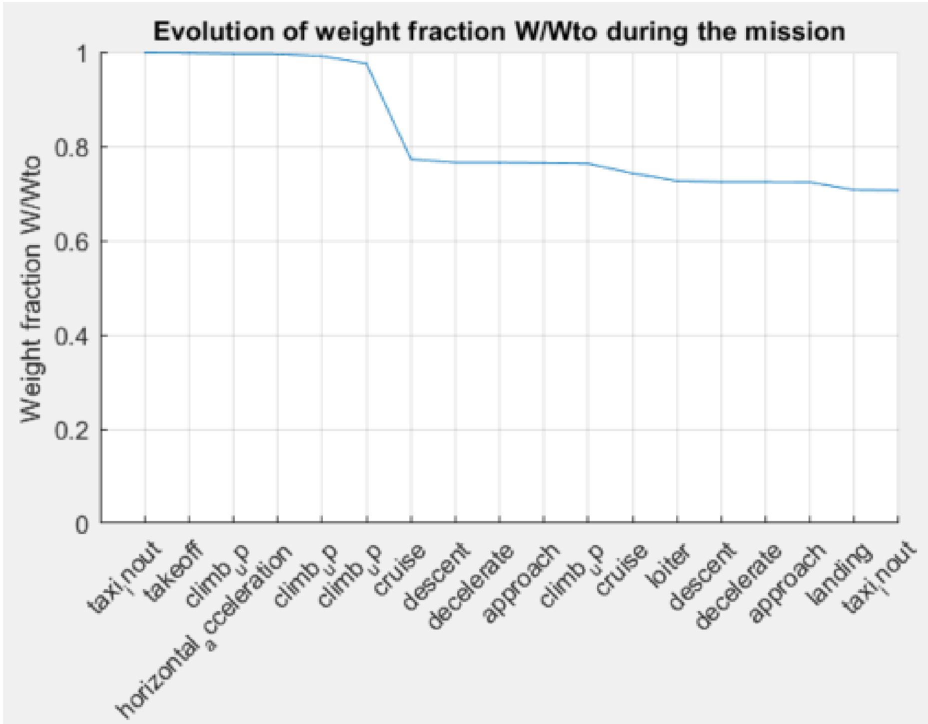


Fig. 6 Evolution of the weight fraction W_i/W_{TO} accross the mission

The constraint is designed to ensure safe approach of the aircraft. The lift coefficient is taken at its maximum.

- **Landing**:

  The stall coefficient is assumed equal to 1.15, as stated in Mattingly[1].

Finally, the constraint plots are obtained. The design space corresponds the zone above all the curves and on the left of the 'landing' constraint plot.

Regarding the chosen design point, it was decided to choose the point which minimize the thrust loading. Indeed, a low value of thrust loading is generally correlated with fuel efficiency and thus lower operating cost. Moreover, requiring a higher thrust increases the size of the engine, so the weight.

B. Results

The design point for the Airbus A320neo was determined using the constraint plots (fig.7) generated from the Sizing and Synthesis Tool. These plots illustrate the relationship between thrust loading (T/W) and wing loading (W/S) for various phases of flight, including takeoff, climb, cruise, and landing. The design point was selected at the intersection of the 'landing' and 'climb' constraints, as these represent the most demanding phases in terms of thrust requirements.

V. Conceptual Design Point

The tool's predicted design point yielded a thrust loading of 0.4164 and a wing loading of 110.1 lb/ft². When compared to the actual A320-200 values—0.3084 for thrust loading and 123.04 lb/ft² for wing loading—the tool's results showed a relative error of 35% in thrust loading and 10.5% in wing loading (ref.2)

These differences are likely due to several simplified assumption.

- During the climb phase the speed was assumed constant. However,a speed value in KEAS can significantly vary

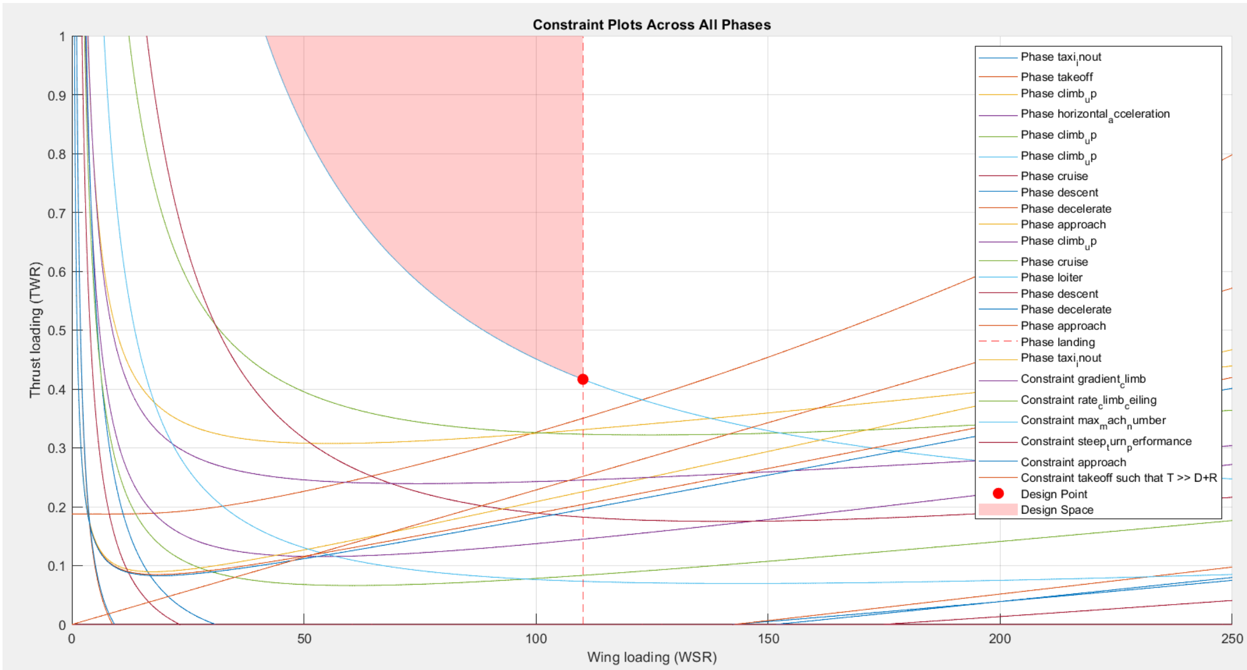


Fig. 7 Constraints plots of A320 neo benchmark aircraft

Table 2 Design points for A320 neo benchmark aircraft and of A320-200, as well as the relative error between them

Parameters	Results of the tool on A320 neo Benchmark	Real values from A320-200	Relative error
Thrust loading $\frac{T_{SL}}{W_{TO}}$	0.4164	0.3084[3]	35%
Wing loading $\frac{W_{TO}}{S}$	$110.1000 lbf/ft_2$	$123.0372 lbf/ft_2$[3]	10.5%

with altitude when expressed as a true speed. For instance, for a speed of 250 KEAS, the true speed at the altitude of 0 ft is 250 ft/sec, while at the altitude of 10000 ft, it is 291 ft/sec. The error resulting from this assumption can be thus significant when it is applied for the 3 climb phases which starts from the takeoff until reaching the cruise altitude (i.e. 35000 ft).

- Parameters relative to drag and lift, such as drag for 0 lift or the maximum lift-drag ratio, were constantly using the formulas with very few use historical data. A better mix of the two approaches could result to results that are closer to the real-world data.
- The empty weight fraction was expressed by a formula using the takeoff weight. However, the structural correlation between these two parameters are complex and a more accurate model can be used for better estimation of weight fractions.

Despite these differences, the tool provides results that are acceptable for early-stage design, where rough estimations are sufficient to guide the conceptual design. To take into account the uncertainty created by these assumptions, engineers using this tool can put in place a margin on the design point. This margin can be determined by comparing the tool's outputs with the data of existing aircrafts.

In order to improve accuracy of the tool, more advanced methods, such as detailed fuel consumption models or refined aerodynamic performance models, can be used. Moreover, the integration of generic fuel to obtain the weight fraction of the phase can also be done numerically, without assuming that it is constant as it was done for this tool.

Given the assumption made such as the values of the coefficients of the induced drag or the drag of non-clean configuration, the tool is best suited for a medium-range commercial aircraft using jet-propelled engines. Using this tool for significantly larger or smaller aircraft, or for aircraft with unconventional configurations, would require careful reconsideration of the assumptions and methodologies used.

These reflections provide insights into the strengths and limitations of the Sizing and Synthesis Tool, highlighting the importance of validating its outputs against real-world data.

References

[1] Mattingly, J. D., Heiser, W. H., and Pratt, D. T., *Aircraft Engine Design*, American Institute of Aeronautics and Astronautics, Reston, UNITED STATES, 2000.

[2] Mattingly, J. D., *Altitude Tables*, AIAA Education Series, Schetz, Joseph D., 2024. URL `https://arc.aiaa.org/doi/10.2514/5.9781624105173.0615.0622`, retrieved 20 October 2024.

[3] Jenkinson, L., Simpkin, P., and Rhode, D., "Butterworth-Heinemann - Civil Jet Aircraft Design - Aircraft Data File - Airbus Aircraft," `https://booksite.elsevier.com/9780340741528/appendices/data-a/table-1/table.htm`, 2024. Retrieved 20 October 2024.