Sizing and Synthesis -
A step-by-step walk-through

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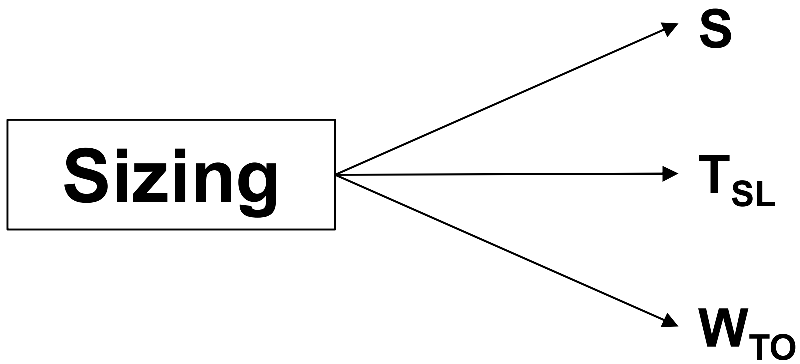
Purpose of Mission Analysis

- Constraint analysis provides a solution mapped as a point in a thrust loading, T_{SL}/W_{TO} against wing loading, W_{TO}/S diagram. But we need the actual values of these parameters and not just their ratios
- A mission analysis will yield the additional equation needed
- <u>A fuel required vs available iteration </u>is performed to determine the actual size of the aircraft required to fly the mission



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Disciplines Involved in Conceptual Design

- Propulsion
- Structures
- Aerodynamics

We need information from each of these disciplines before we proceed!

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Discipline: Propulsion

- In constraint analysis, we used lapse rate and TSFC, but going forward, more information would be needed

$$F_N = \dot{m}_a(v_j - v_0)$$

*v_j is a function of **cycle analysis***

- For our purposes, we use an engine that is in the ball park and scale it up and down (<u>rubberized engine</u>) within reason to meet our requirement (<u>fixed cycle analysis</u>)
- How can engine be <u>scaled</u>?

$$F_N \propto \dot{m}_a$$

$$\dot{m}_a = \rho\pi \frac{d_f^2}{4} v_0$$

Bigger fan produces more thrust by increasing $\dot{m}_a$

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Discipline: Propulsion

- The information about the performance of an engine on various conditions are contained in an engine deck. A typical engine deck looks like:

$\boldsymbol{h}$ (altitude)	$\boldsymbol{M}$	% $\boldsymbol{Thrust}$	$\boldsymbol{TSFC}$

- Because we are scaling the engine, instead of $\%Thrust$, we use $\frac{\%Thrust}{\dot{m}_a}$, and instead of TSFC, we use $\dot{m}_f$

$\boldsymbol{h}$ (altitude)	$\boldsymbol{M}$	% $\boldsymbol{T/\dot{m}_A}$	$\boldsymbol{\dot{m}_f}$

Discipline: Propulsion

- Importance of using $\frac{\%Thrust}{\dot{m}_a}$ over $\%Thrust$: scales the engine through $\dot{m}_a$, which can be used to calculate the diameter of the fan. This is the basis of a "rubberized" engine. Scaled up and down photographically through $\dot{m}_a$
- <u>Note</u>:
  - For cases were an existing engine is not suitable nor can easily be scaled, a new engine will need to be designed. That is accomplished through an engine cycle analysis (variation of FPR, CPR, efficiencies of stages, etc.)
  - This approach allows for a better integration of engine and airframe.

Discipline: Structures

- In the conceptual design phase, this discipline is represented by calculating the total weight and weight breakdown of the aircraft

$$W_{TO} = W_E + W_P + W_F$$

$$W_E = W_{wing} + W_{fuselage} + W_{empennage} + W_{prop} + W_{elec} + W_{hydraulic}$$

W_{TO}: Takeoff Weight
W_E: Empty Weight
W_P: Payload Weight
W_F: Fuel Weight

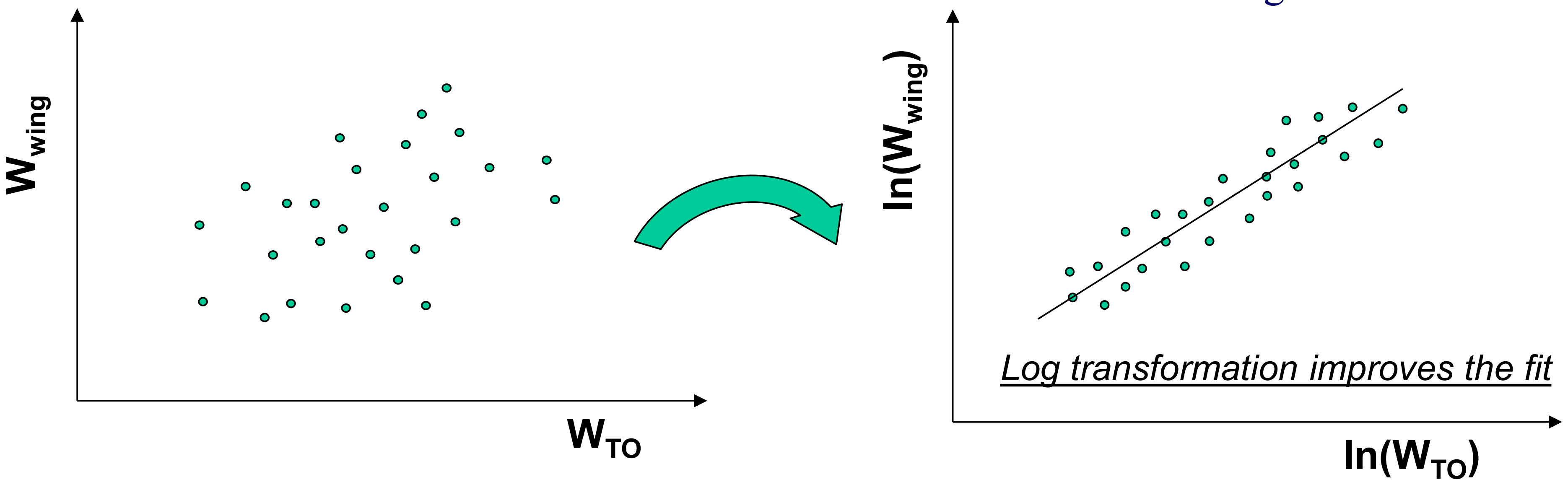
- Intuition tells us that W_E is somehow dependent on W_{TO}
  - A larger aircraft (large W_{TO}) will have a larger empty weight (W_E)
  - This implies W_{wing}, $W_{fuselage}$, $W_{empennage}$, etc. also depend on W_{TO}

Discipline: Structures

- For example, consider W_{wing}:

$$W_{wing} = f\,(span,\ chord,\ AR,\ material,\ topology)$$

Since this information is not available in conceptual design, let's look at a historical correlation between W_{wing} and W_{TO}



Notional plots

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Discipline: Structures

- Relational form for W_{wing}:

$$W_{wing} = \alpha' W_{TO}^{\beta'}$$

- Similar relations apply for the other component weights. The R^2 for such relation is very low on a component level. However, this is a useful approach when looking from an empty weight perspective. Although high, at component level, the error on the W_E using such form is very low for conceptual design level

$$W_E = W_{wing} + W_{fuselage} + \ldots = \alpha W_{TO}^{\beta}$$

  - α and β : found for a given aircraft using historical data

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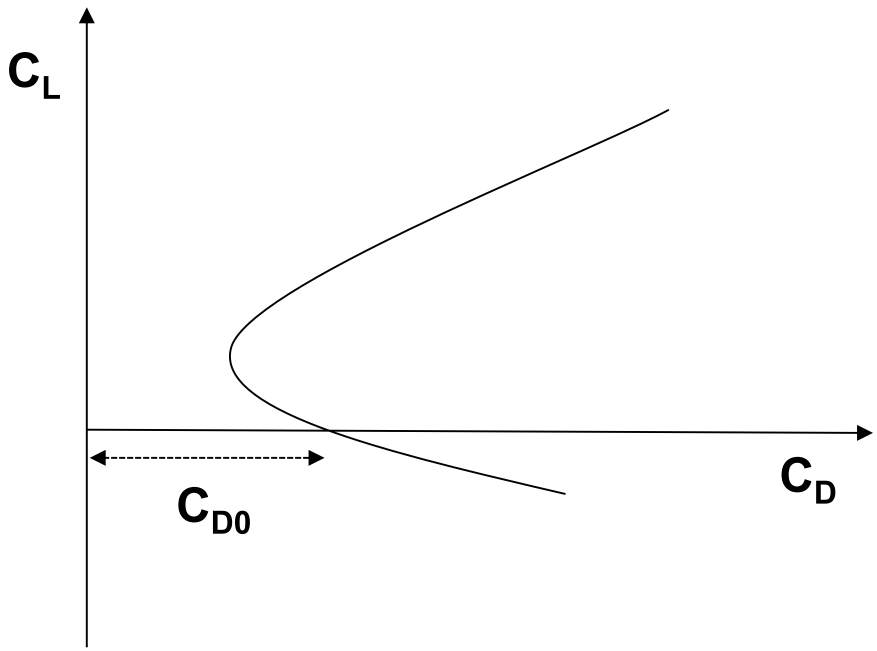
Discipline: Aerodynamics

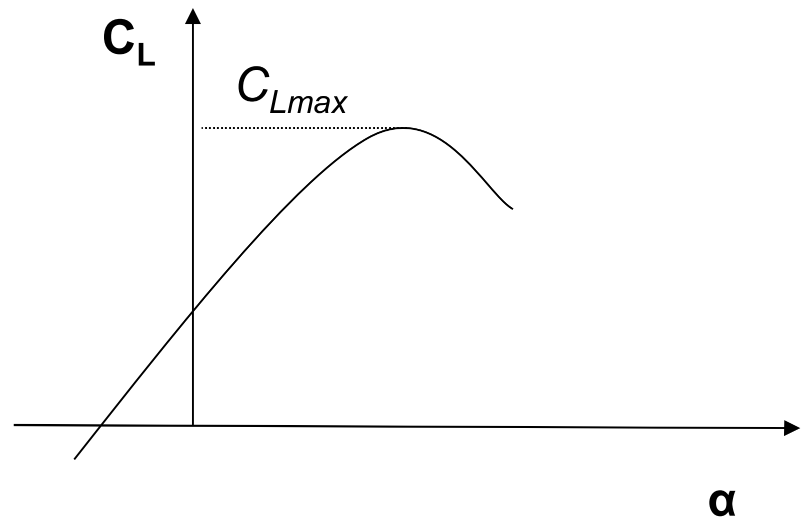
- During analysis of takeoff, landing, cruise, or any other segment, the aerodynamic characteristics of the airframe are needed
  - C_{Lmax}
  - *Lift-drag polar*
  - $C_{L\ cruise}$

- Maximum coefficient of lift (C_{Lmax}) is important in analysis during takeoff and landing

Discipline: Aerodynamics

- <u>Lift-drag polar estimation</u>
  - Lift-drag polar can be estimated for the notional design or approximated using experience or historical trends





<u>Notional plots</u>

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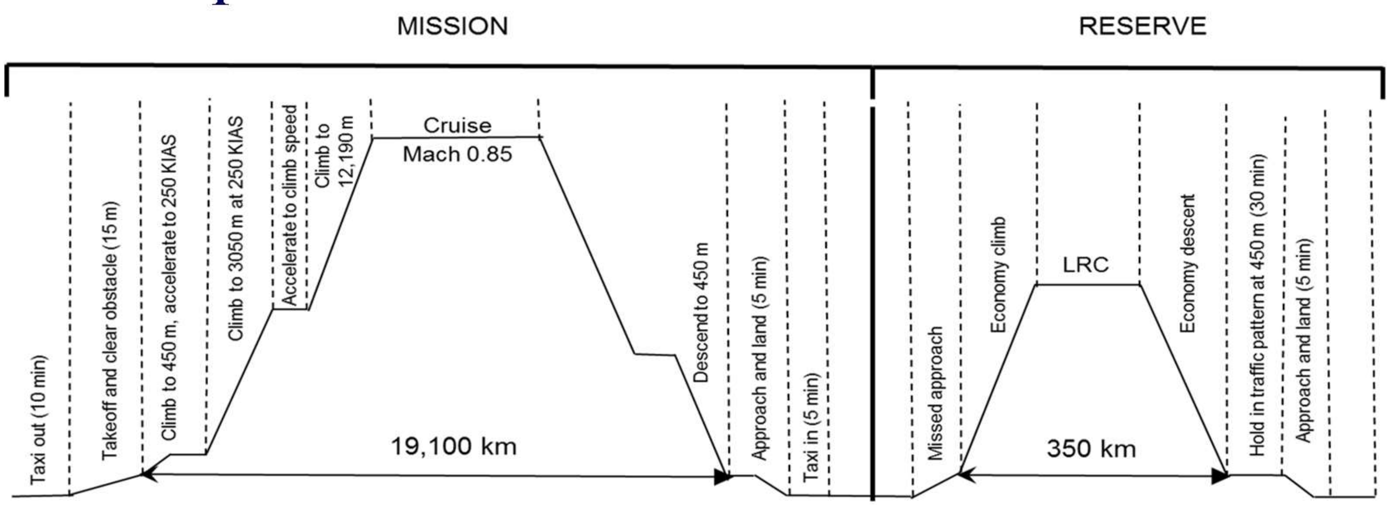
Discipline: Aerodynamics

- For sizing of horizontal tail:
  - A three Degrees of Freedom of model is needed
  - Lift, drag and pitching moment considered
  - CG calculation required
- To size the vertical tail, rudder: lateral analysis needs to be considered:
  - Need a six Degrees of Freedom depiction
  - In conceptual design, it is common to size the empennage through the use of tail volume coefficients

Sizing and Synthesis

- A mission profile is needed before we size the aircraft



Example mission profile

- Usually, we want to test our aircraft under critical conditions to ensure that it can withstand stringent conditions like one engine failure, a lifting surface not employed, etc.

Sizing and Synthesis

- Step 1:
  - It is assumed that W_P is known (from RFP)
  - Payload weight may be comprised of passengers, crew, baggage, military loads, etc.

$$W_{TO} = W_E + \mathbf{W_P} + W_F$$

- Step 2:
  - Guess a value for W_{TO}

$$\mathbf{W_{TO}} = W_E + \mathbf{W_P} + W_F$$

- Step 3:
  - Calculate S and T_{SL} using values of W_{TO} (from Step 2), T_{SL}/W_{TO} and W_{TO}/S (from constraint analysis)

Sizing and Synthesis

- Step 4:
  - Using empty weight regressions, find W_E/W_{TO} for guessed W_{TO}

$$\frac{W_E}{W_{TO}} = f(W_{TO})$$

$$\mathbf{W_{TO}} = \mathbf{W_E} + \mathbf{W_P} + W_F$$

- Step 5:
  - Calculate W_F available to fly the mission

$$W_{F,avail} = \mathbf{W_{TO}} - \mathbf{W_E} - \mathbf{W_P}$$

  - If density of fuel (ρ_F) is known, then volume available (V_F) is also known. For our purpose, V_F is not needed (for military designs, V_F is needed as such designs are limited by volume)

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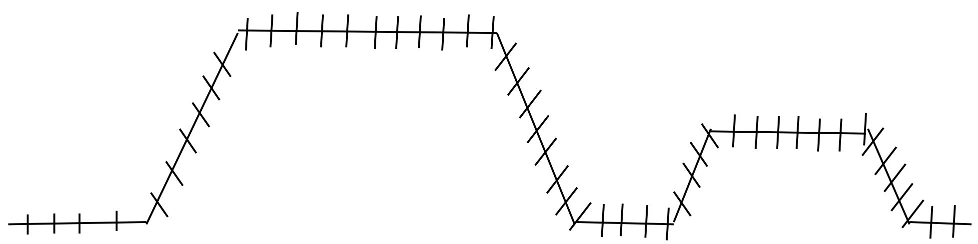
Sizing and Synthesis

- Step 6: Fuel required calculation
  - Split the mission into smaller segments and march through all segments of the mission
  - For any point in mission, *h* and *M* are known
  - Vehicle balance is done to calculate Lift (L) and Drag (D)



Mission split into smaller segments

Sizing and Synthesis

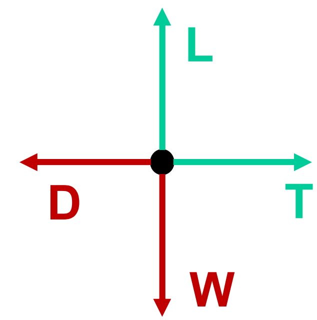
- Step 6…

Altitude *Aerodynamics*

$$L = \frac{1}{2}\rho V^2 C_L \boldsymbol{S}$$

Mach

From FBD, L balances instantaneous weight



Free Body Diagram (FBD)

  – S falls out from above. Now, Drag(D) can be calculated

$$\boldsymbol{D} = \frac{1}{2}\rho V^2 C_D S$$

  – Once drag at a point is known, part thrust can be calculated from engine deck, and if it's linked to $\dot{m}_a$, required mass flow rate of air can be obtained

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- Step 6…
  - The required fuel flow rate ($\Delta \dot{W}_f$) for this segment can also be obtained from the table. Multiply this by the time of segment 'i' to get fuel burn for that segment (ΔW_{Fi})

$$\text{Total fuel required} = W_{F,req} = \sum_i \Delta W_{Fi}$$

- Step 7:
  - Check difference between fuel available ($W_{F,avail}$) and fuel required ($W_{F,req}$)

$$\Delta F = W_{F,avail} - W_{F,req}$$

  - If the difference is within tolerance, you have a converged solution (Now you have a sized vehicle!)

Sizing and Synthesis

- Step 7…
  - If not, update W_{TO} in Step 2 as:

$$W_{TO} = W_{TO} - \Delta F$$

(or the weight difference can be split between $W_{F,avail}$ and W_{TO})

  - In the calculations, it might turn out that there was not enough area
    - You might want to update S as the largest area required or change the aerodynamics that can provide enough C_L
  - Update on the thrust would be $\dot{m}_a$ multiplier
  - Now, you have new values for T_{SL}, S, and W_{TO}.
  - Repeat Step 4 – Step 7 until $|\Delta F|$ converges to 0 or a specified tolerance

Sizing and Synthesis

Notes:

- Volume analysis can be done by converting weight of fuel required to volume required
  - The volume available calculation is not straightforward for vehicles that are volume limited
- To include horizontal and vertical tail analysis, CG needs to be determined
  - The knowledge of topology of components is needed
  - For a quick estimation, you can look at other similar aircraft and see how the components can be placed.

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