Which is 1st?

You need to have a concept in mind to start

The concept will be reflected in the sizing by the choice of a few key parameters.

Then what?
- 1st estimate the TOGW of the airplane
- 2nd, estimate the W/S and T/W
- 3rd, use the mission program to evaluate the design
To Start: Define a Mission

What is this airplane supposed to do?

- How far does it go? How fast?
- What and how much does it carry?
- What are the landing and takeoff requirements?
- Are there any maneuver/accel requirements? (these are known as point performance req’ts)
- What MIL or FAR req’ts must be satisfied?

Taken together, the answers to these questions are known as the Mission Statement, and also imply that you think of concepts to do the job.

Note: the web slides contain more charts. Fill in details.

Basis for Sizing

- Many Possibilities for the Selection Criteria
- Possible Choices:
  - minimum life cycle cost
  - " flyaway cost
  - " direct operating cost
  - " fuel cost
  - " take off gross weight (TOGW)

- Cost is the real selection criteria, but hard to estimate
- For a given class of aircraft, aircraft cost/lb is similar
  . min weight is a good choice for comparing alternatives
The Importance of Weight Control

\[ \text{TOGW} = W_{TO} = W_{\text{struc}} + W_{\text{prop}} + W_{\text{fuel}} + W_{\text{payload}} + W_{\text{systems}} \]

\[ = W_{TO} \left( \frac{W_{\text{struc}}}{W_{TO}} + \frac{W_{\text{prop}}}{W_{TO}} + \frac{W_{\text{fuel}}}{W_{TO}} \right) + W_{\text{fixed}} \]

or:

\[ = \left[ 1 - \left( \frac{W_{\text{struc}}}{W_{TO}} + \frac{W_{\text{prop}}}{W_{TO}} + \frac{W_{\text{fuel}}}{W_{TO}} \right) \right] W_{TO} = W_{\text{fixed}} \]

\[ \Rightarrow W_{TO} = \frac{W_{\text{fixed}}}{1 - \left( \frac{W_{\text{struc}}}{W_{TO}} + \frac{W_{\text{prop}}}{W_{TO}} + \frac{W_{\text{fuel}}}{W_{TO}} \right)} \]

Typical:

\[ W_{TO} = \frac{W_{\text{fixed}}}{(1 - 0.75)} = 4 \cdot W_{\text{fixed}} \]

4 is the Growth Factor!

More Precise Weight Definitions

- Standard nomenclature important
- FAR, MIL STD & Technical Societies define, see Torenbeek, Chap. 8, pg 263-275 (quote at specified loading and cg)
  - eventually you will make a detailed weight statement-
- In 1st cut sizing we use Nicolai’s definitions:

\[ \text{TOGW} = W_{\text{fuel}} + W_{\text{fixed}} + W_{\text{empty}} \]

- \( W_{\text{empty}} \): basic structure and propulsion
- \( W_{\text{fixed}} \): all items that can be removed and the a/c would still be ready to fly, divided into two parts,
  a) non-expendable (crew + equipment)
  b) expendable: passengers, baggage, cargo bombs & missiles, etc.
1st Cut Sizing

Several Methods Available:

- Nicolai, Chap. 5
- Roskam, Vol. 1 (both Jets and Props)
- Raymer, Chap. 6 and 19 (Chap. 3 too crude, but read)
- Loftin, Chap. 3 and 4 (Jet) and Chap. 6 and 7 (Prop)
  (available on class web page - >400M)
- Torenbeek, pp. 144-148, 171-180

We will use Nicolai’s Method in Class Examples

Note: books on reserve in the Architecture Library: see Schetz on the Library reserve page

How to Start?

Fuel Available = Fuel Required

or, following Nicolai, With a given TOGW, subtract the fuel and payload. Is the weight left enough to build an airplane?

Available Empty Weight, \( W_{EmptyAvail} \)

= Required Empty Weight, \( W_{EmptyReqd} \)

\( W_{EmptyReqd} \) comes from statistics at 1st Iteration,

In code this is

\[ W_{EmptyReqd} = KS \times A \times TOGW^B \]

\( A,B \): come from fit of data for similar designs

\( KS \): structural technology factor
Typical Empty Weight Req’d—Takeoff Weight Correlation

Specific Example: Supersonic Transport

\[ W_{\text{empty}} = 0.500 \cdot \text{TOGW}^{0.9876} \]
To Get *WEmptyAvail*, 1st Define Mission Segments

**Altitude**
- 1
- 2
- 3 BCA, BCM
- 4
- 5
- 6+ specified M
- 5+ combat
- 6

**Radius**
- R_{subsonic}
- R_{supersonic}

---

**Mission Phase Definitions**
(follow Nicolai, except add supersonic segments)

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-2</td>
<td>engine start and takeoff</td>
</tr>
<tr>
<td>2-3</td>
<td>accelerate to subsonic cruise velocity and altitude</td>
</tr>
<tr>
<td>3-4</td>
<td>subsonic cruise out</td>
</tr>
<tr>
<td>4-5</td>
<td>accel to high speed (supersonic) dash/cruise</td>
</tr>
<tr>
<td>5-5+</td>
<td>supersonic cruise out</td>
</tr>
</tbody>
</table>

**combat (use fuel, expend weapons)**

<table>
<thead>
<tr>
<th>Phase</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>6-6+</td>
<td>supersonic cruise back</td>
</tr>
<tr>
<td>6+ -7</td>
<td>subsonic cruise back</td>
</tr>
<tr>
<td>7-8</td>
<td>loiter</td>
</tr>
<tr>
<td>8</td>
<td>land</td>
</tr>
</tbody>
</table>

Note: for Military descent:
No credit for time, fuel or distance
Mission Program

• Aircraft Companies, Gov’t., etc. have *Mission Programs*

• We have a mission program written for MATLAB
  - based on Sid Powers’ *BASIC Aircraft Performance*
  - originally by Mike Morrow
  - then further developed by Dzelal Mujezinovic
  - currently Chris Cotting

• You need detailed propulsion data (and aerodynamics), well as weight, etc. to “fly” the mission.

Now to Get *WEmptyAvail*

• Compute fuel fraction for each segment of mission

• For Range segments:

  \[ R_{i+1} = \frac{V}{sfc} \left( \frac{L}{D} \right) \ln \frac{W_i}{W_{i+1}} \]

  or

  \[ \frac{W_{i+1}}{W_i} = e^{\frac{R_{sfc}}{V(L/D)}} \]

For Loiter Segments:

  \[ E = \frac{1}{sfc} \left( \frac{L}{D} \right) \ln \frac{W_i}{W_{i+1}} \]

  or

  \[ \frac{W_{i+1}}{W_i} = e^{\frac{E_{sfc}}{(L/D)}} \]

Note: Watch Units!
Where to get values to put in formulas?

With your vehicle concept in mind:

- use historical data for $L/D_{\text{max}}$, requires $C_{D0}$, $E$, $AR$
- $sfc$: use engine spec. or see propulsion text
- Velocity: fly just before drag rise (0.7 to 0.8 Mach)
- Following charts provide some info

(or see Raymer, Torenbeek, Nicolai, Roskam, etc. for summaries and statistics)

Typical Zero Lift Drag Values for Transports

![Graph showing typical zero lift drag values for transports from Nicolai, Fundamentals of Aircraft Design, METS, Inc., 1975]
**L/D\textsubscript{max} data correlation by Raymer**


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**Speed and Altitude: Review of Best Range**

(consider specific range, SR)

- Drag Rise Not Included
- Drag Rise Included

*Note: Study of impact of technology integration requires operation at BCA/BCM*

Based on a figure in Shevell, *Fundamentals of Flight*
For other parts of the Mission:

- Startup, Takeoff: estimate 2 1/2 to 3 % of TOGW
- Climb and Accel: Use correlation chart or Raymer Eqn.
- Accel to High Speed, Use Chart Again
- Combat: # of minutes max power, or # of turns:
  \[ \text{Combat Fuel} = \text{sfc} \times \text{Thrust} \times \text{Time} \]
  and:
  \[ \dot{\psi} = \frac{g \sqrt{n^2 - 1}}{V}, \text{ in radians per sec.} \]
  \[ \text{Time} = \frac{(\text{no. of turns})(360^\circ)}{\dot{\psi}}, \text{(in degrees per sec)} \]
  - Watch units: Degrees and Radians
- Reserve and trapped fuel must be accounted for

Weight fraction for climb-accel phases

from Nicolai, Fundamentals of Aircraft Design, METS, Inc., 1975

See also: Raymer, 4th Ed, page 115, eqns. 6.9 and 6.10, and page 582, eqns. 19.8 and 19.9
Actual Computation: Perform an Iteration

1. Assume TOGW
2. Compute $W_{EmptyReqd}$
3. Compute $W_{EmptyAvail}$
4. Estimate a new TOGW

$$W_{TO}^{j+1} = W_{TO}^j + \Delta (W_{EmptyReqd} - W_{EmptyAvail})$$

- where $\Delta$ is a relaxation factor to speed convergence (2 for the examples)
5. Go to step 2, and repeat until

$$|W_{EmptyReqd} - W_{EmptyAvail}| < \varepsilon$$

Example & Use of Fuel Fractions

$$\frac{W_{final}}{TOGW} = \frac{W_{final}}{W_{TO}} = \frac{W_8}{W_1} = \frac{W_2}{W_1} \frac{W_4}{W_2} \cdots \frac{W_8}{W_7}$$

fuel fraction for each segment
(must include a step change if you drop something)

$$W_{fuel} = \left(1 + \frac{W_{reserve\ fuel}}{W_{TO}} + \frac{W_{trapped\ fuel}}{W_{TO}}\right) \left(1 - \frac{W_8}{W_1}\right) W_{TO}$$

$$W_{EmptyAvail} = W_{TO} - W_{fuel} - W_{fixed}$$

see extra notes on web for extension to include bombs dropped, etc.
Our example sizing code acsize.QB

- Originally we had an implementation of this scheme in QuickBASIC (still available on the software page): acsize.QB
- We also have acsweep.QB. It computes lines of WemptyReqd and WemptyAvail
- Now a REALbasic code (Mac counterpart of VisualBASIC?) version of acsize
Example: Nicolai’s Lightweight Fighter

- 250 nm mission radius
- 4 minutes of max $a/b$ at $M = 0.9$, 30K ft
- one accel from $M = 0.9$ to $M = 1.6$ at 30K ft
- 5% reserve fuel
- Crew of One
- Two AIM 9 missiles, one M-61 cannon
- One F100 afterburning turbofan engine

Implies:
- $L/D$ cruise = 9
- $sfc = 0.93$
Sensitivity of TOGW to Change in Payload, the Growth Factor


TOGW Sensitivity to Radius (or Range) Requirement

Valid assessment of technology or multidisciplinary optimization requires keeping the range fixed

Large Transport Aircraft Example

- the Range-Payload diagram
- comparison with C-5A
  - 6000 nm range
  - 100,000 lb payload
  - $sfc = .6 @ M=.8, 36,000$ ft alt.
  - $L/D = 17$
- examples for increasing range, holding the technology level constant

Range-Payload Diagram

- Max payload increasing fuel wt. TOGW changing
- TOGW at max value
- Max fuel reduced payload
- Full fuel tanks Reduce payload wt. TOGW changing
Effect of Range Requirement on Weights for a C-5A Class Aircraft

- all for fixed technology, holding payload constant
- baseline: range = 6000nm
- range = 8000nm: solution obtained
- range = 10,000nm: appears solution would converge (unbelievable weight)
- range = 12,000nm: no solution at any TOGW!

Note: Nicolai, in *Fundamentals of Aircraft Design*, shows that a range-payload diagram which matches the actual C-5A can be developed using our methods.
Range = 8,000 nm case

Required and Available Curves slopes start to be parallel, small errors lead to large errors in TOGW

note scale!

Range = 10,000 nm case

Converged solution may occur at TOGW approaching infinity!
Range = 12,000 nm case

No solution for this technology level at any size

TOGW Weight Growth:
for a specified technology level
the range cannot be increased without limit

Payload = 600,000 lb
L/D = 21
sfc = .55
KS = .85
M = .77

Using Idealized (Optimistic) Single Segment Analysis

Note: this case does not correspond to the technology levels used in the previous charts, which are for something close to a C-5. This example was developed for the 1992-93 AIAA Contest Payload, with advanced technology.
Parametric studies provide insight

You can investigate how the key technology parameters affect the TOGW for a given mission:

- $L/D$
- $sfc$
- $K_s$

It’s worth studying and pondering

To Conclude:

- This method is the 1st cut back of the envelope method for sizing: it works.
- Note: The example codes available on the software link on our web page are for jet propulsion
- Your skill: Develop confidence by “predicting” the size of existing airplanes
- You will use a sizing program and practice
- Next sizing class will look at sizing a little more deeply for wing and engine size selection.
  - Constraints on takeoff and landing, etc. become critically important