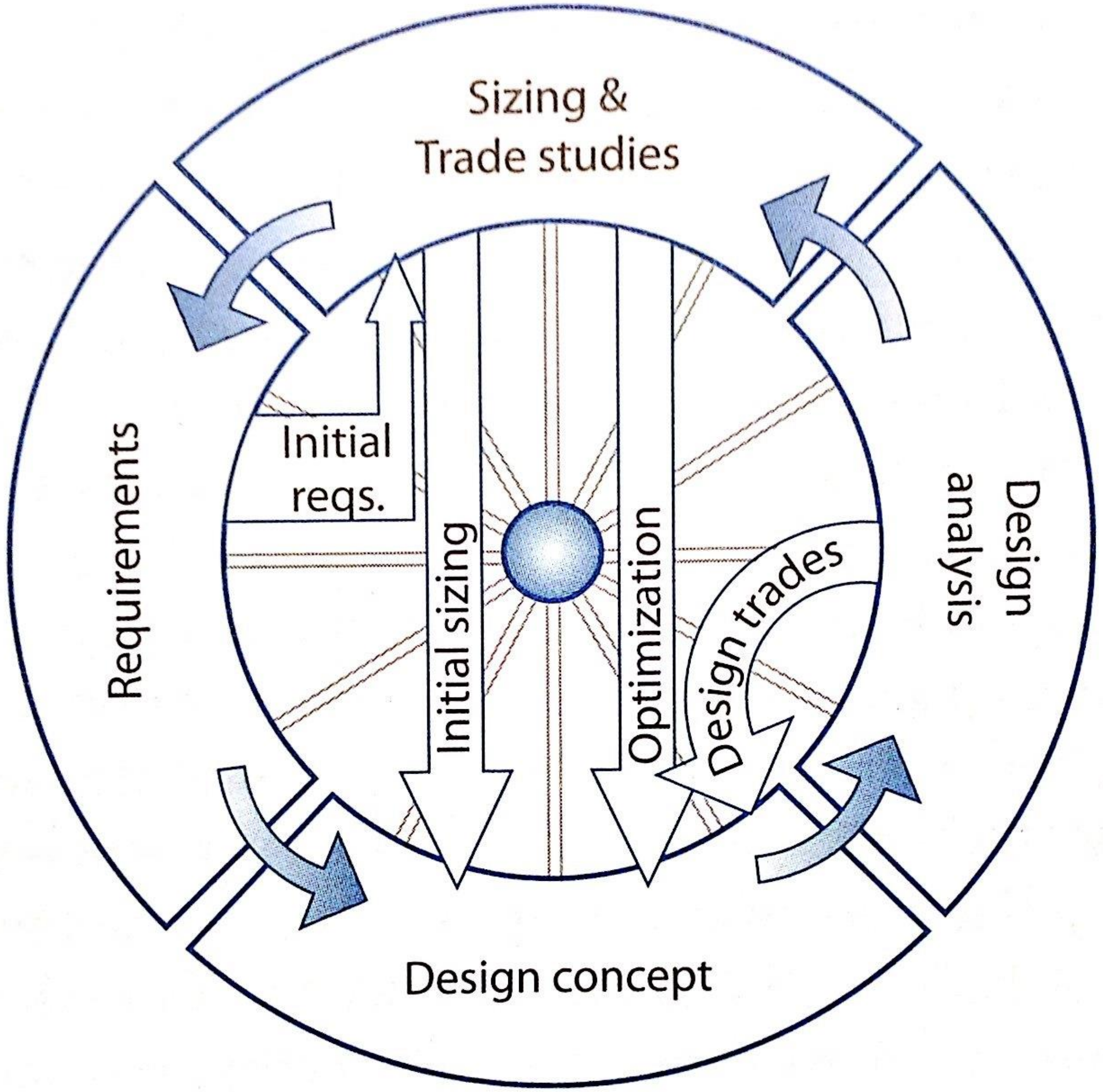
ME4932 Aircraft Performance & Design

Concept Sizing (Chapters 1,2,3)



Source: Aircraft Design by Daniel P. Raymer

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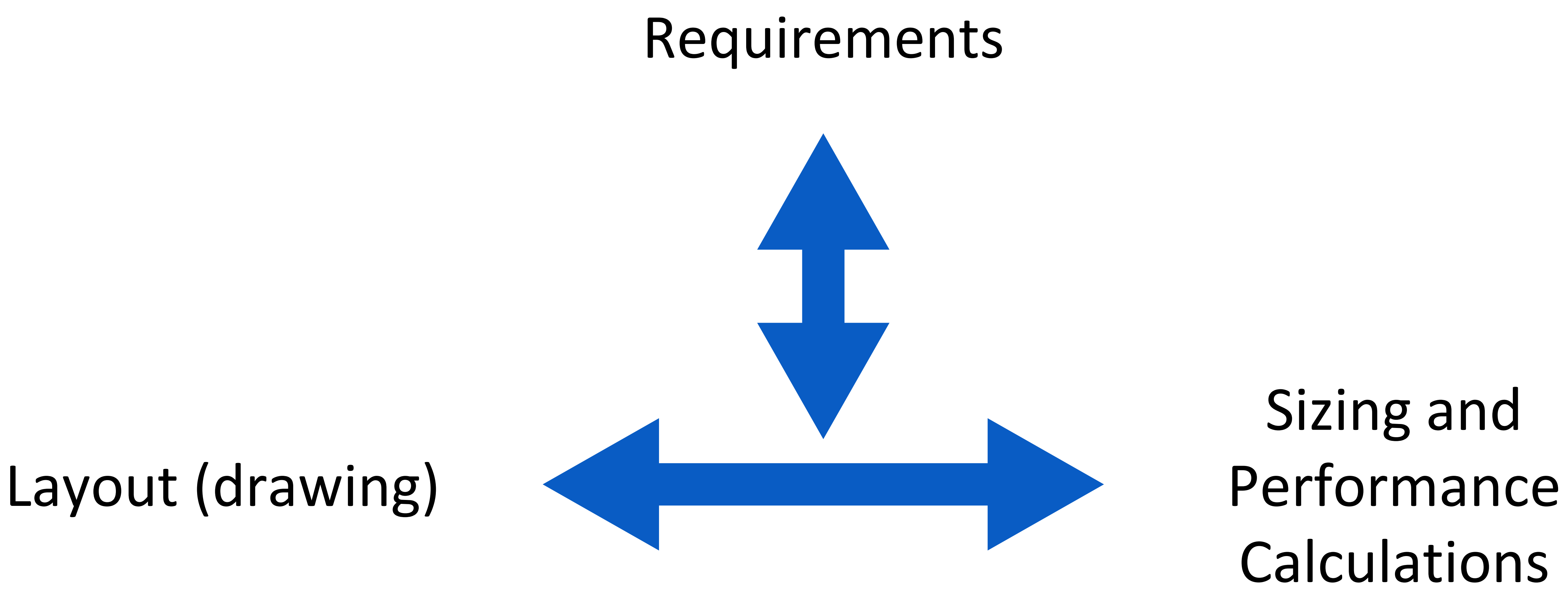
Design



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Design

- Design is a separate discipline
- Design is an iterative process
- The mind of the layout designer should work such that the layout will undergo a minimum of significant changes.
- However, changes should be considered, as the design should satisfy the requirements!
- Sometimes, the requirements should be studied to offer alternate configurations that satisfy a reduced set of requirements!
- Many times, the requirements are defined this way!
- Even when designing and A/C for a simple purpose/requirement you can find important trade-offs to consider...

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Requirements

- They change!
- Civilian world
    - By an A/C company using customer (airlines) input, market analysis....
    - FAR's
- Military world
    - Initially set by customer (Air Force, Navy, Marines...)
        - Performance
        - Cost
        - Equipment/technology to be included
        - Dimension limits

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Requirements

Table F.1 Federal Aviation Regulations (FAR)—Applicability*

Category	Various†	Normal	Transport
A) Characteristics			
Maximum takeoff weight, lb	≤12,500	≤12,500	—
Number of engines	One or more	Two or more	Two or more
Type of engine	All	Propeller engines only	All
Minimum crew			
Flight crew	One or more	Two	Two or more
Cabin attendants	None	<20 Pass.: None ≥20 Pass.: One	<10 Pass.: None ≥10 pass.: One or more
Maximum number of occupants	10	11–23	Not restricted
Maximum operating altitude, ft	25,000	25,000	Not restricted
B) FAR Applicability			
Airworthiness standards airplanes	Part 23	Part 23	Part 25
Airworthiness standards engines	Part 33	Part 33	Part 33
Airworthiness standards propellers	Part 35	Part 35	Part 35
Noise standards	Part 36: Prop-Driven, Appendix F		Part 36
General operating and flight rules	Part 91	Part 91	Part 91
Operations			
Domestic, flag and supplemental comm. operators of large aircraft	—	—	Part 121
Air travel clubs using large aircraft	—	—	Part 123
Air taxi and comm. operators	—	Part 135	—
Agricultural aircraft	Part 137	—	—

*After E. Torenbeck.[40]
†Normal, utility, aerobatic, and agricultural.

Table F.2 Takeoff Specifications*

Item	(Military) MIL-C5011A	FAR Part 23 (Civil)	FAR Part 25 (Commercial)
Velocity	$V_{TO} \geq 1.1V_s$ $V_{CL} \geq 1.2V_s$	$V_{TO} \geq 1.1V_s$ $V_{CL} \geq 1.2V_s$	$V_{TO} \geq 1.1V_s$ $V_{CL} \geq 1.2V_s$
Climb	Gear up: 500 fpm @ S.L. (AEO)† 100 fpm @ S.L. (OEI)‡	Gear up: 300 fpm @ S.L. (AEO)	Gear down: 1/2%@ V_{TO} Gear up: 3%@ V_{CL} (OEI)§
Field-length definition	Takeoff distance over 50-ft obstacle	Takeoff distance over 50-ft obstacle	115% of takeoff distance with AEO over 35 ft or balanced field length
Rolling coefficient	$\mu = 0.025$	Not defined	Not defined

*After L. Nicolai.[16]
†AEO = all engines operating.
‡OEI = one engine inoperative.
§4-engine aircraft. For 2- or 3-engine aircraft, see Table F.4.

Table F.3 Landing Specifications*

Item	MIL-C5011A	FAR Part 23	FAR Part 25
Velocity	$V_A \geq 1.2V_s$ $V_{TD} \geq 1.1V_s$	$V_A \geq 1.3V_s$ $V_{TD} \geq 1.15V_s$	$V_A \geq 1.3V_s$ $V_{TD} \geq 1.15V_s$
Field-length definition	Landing distance over 50-ft obstacle	Landing distance over 50-ft obstacle	Landing distance over 50-ft obstacle divided by 0.6
Braking coefficient	$\mu = 0.30$	Not defined	Not defined

*After L. Nicolai.[16]

Source: Aircraft Design by Daniel P. Raymer

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Requirements

Table F.4 FAR Climb Requirements for Multi-Engine Aircraft

Turbine-Engine Aircraft: FAR 25

All segments with one engine stopped, except go-around in landing configuration, which has all engines operating. Engine power or thrust set at "maximum rated," except being "maximum continuous" for third-segment climb. Maximum thrust attained after 8 s from flight idle for go-around. AEO: all engines operating. First-segment climb is up to 35 ft, second segment is up to 400 ft above ground level.

				Minimum Climb Gradient for Aircraft With n Engines, %		
Operation	**Speed**	**Flaps**	**Landing Gear**	$n = 2$	$n = 3$	$n = 4$
Takeoff climb						
First-segment	LOF*	Takeoff	Down	≥0	0.3	0.5
Second-segment	$V_2^{\dagger}$	Takeoff	Up	2.4	2.7	3.0
Third-segment Transition (or Acceleration) segment, FAA requires only positive climb gradient						
Fourth-segment	$\geq 1.25\ V_S^{\ddagger}$	Up	Up	1.2	1.5	1.7
Landing						
Go-around in approach configuration	$\leq 1.4\ V_{SR}^{\ddagger}$	Approach	Up	2.1	2.4	2.7
Go-around in landing configuration	$\leq 1.23\ V_{SR0}^{\ddagger}$ AEO	Landing	Down	3.2	3.2	3.2

*LOF = liftoff.
†Climb-out speed over 35-ft obstacle.
‡Stall speed in the pertinent condition.

Reciprocating-Engine Aircraft: FAR 25

Power or thrust for operating engines set for takeoff on first and second segments and go-around and for "maximum continuous" during cruise and third segment. One engine has a windmilling propeller for first and second segments. If plane has automatic feathering, the propeller on an inoperative engine is assumed to be feathered. One engine is stopped (may be feathered) for third segment and go-around.

Operation	**Speed**	**Flap Setting**	**Landing Gear**	**Minimum Steady-Climb Rate, ft/min**
Takeoff climb				
First-segment	V_2*	Takeoff	Down	≥50
Second-segment	V_2*	Takeoff	Up	$\geq 0.046\ V_{S_1}^{2\ \dagger}$
Third-segment	Best	Up‡	Up	$\geq \left(0.079 - \frac{0.106}{n}\right) V_{S_0}^{2}$ ¶,**
Landing go-around				
Approach configuration	$\leq 1.5\ V_{S_1}^{\dagger}$	Approach§	Up	$\geq 0.053\ V_{S_1}^{2}$ ¶

*V_2 = climb-out speed over 35-ft obstacle; out-of-ground effect.
†V_{S_1} = stall speed in a specified configuration for reciprocating-engine-powered airplanes, in knots.
‡Or most favorable.
§But $V_{S_1} \leq 1.1\ V_{S_0}$
¶V_{S_0} = stall speed in landing configuration for reciprocating-engine-powered airplanes, in knots.
**At 5000-ft altitude.

Source: Aircraft Design by Daniel P. Raymer

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Requirements

Table F.4 FAR Climb Requirements for Multi-Engine Aircraft (*Continued*)

FAR 23 (Turbine or Reciprocating)

Multi-engine power at maximum continuous except for $W < 6000$ lb.

Aircraft Status	Speed	Flaps	Landing Gear	Minimum Steady-Climb Rate, ft/min
One engine out (prop feathered)*	Most favorable	Most favorable	Up	$\geq 0.027\ V_{s_0}^{2\ddagger}$
AEO†				
$W > 6000$ lb	Most favorable	Takeoff	Up	$\geq$300-ft/min climb gradient $\geq$ 0.0833 land plane $\geq$ 0.0667 seaplane
$W < 6000$ lb	Most favorable	Takeoff	Down	$\geq$300 ft/min and $\geq 11.5\ V_{s_0}$§

*If $W < 6000$ lb and $V_{s_0} < 61$ kt, there is no engine-out climb requirement.

†AEO = all engines operating.

‡V_{s_0} = stall speed in landing configuration for reciprocating-engine-powered airplanes, in knots at 5000 ft.

§V_{s_1} = stall speed in a specified configuration for reciprocating-engine-powered airplanes, in knots.

Source: Aircraft Design by Daniel P. Raymer

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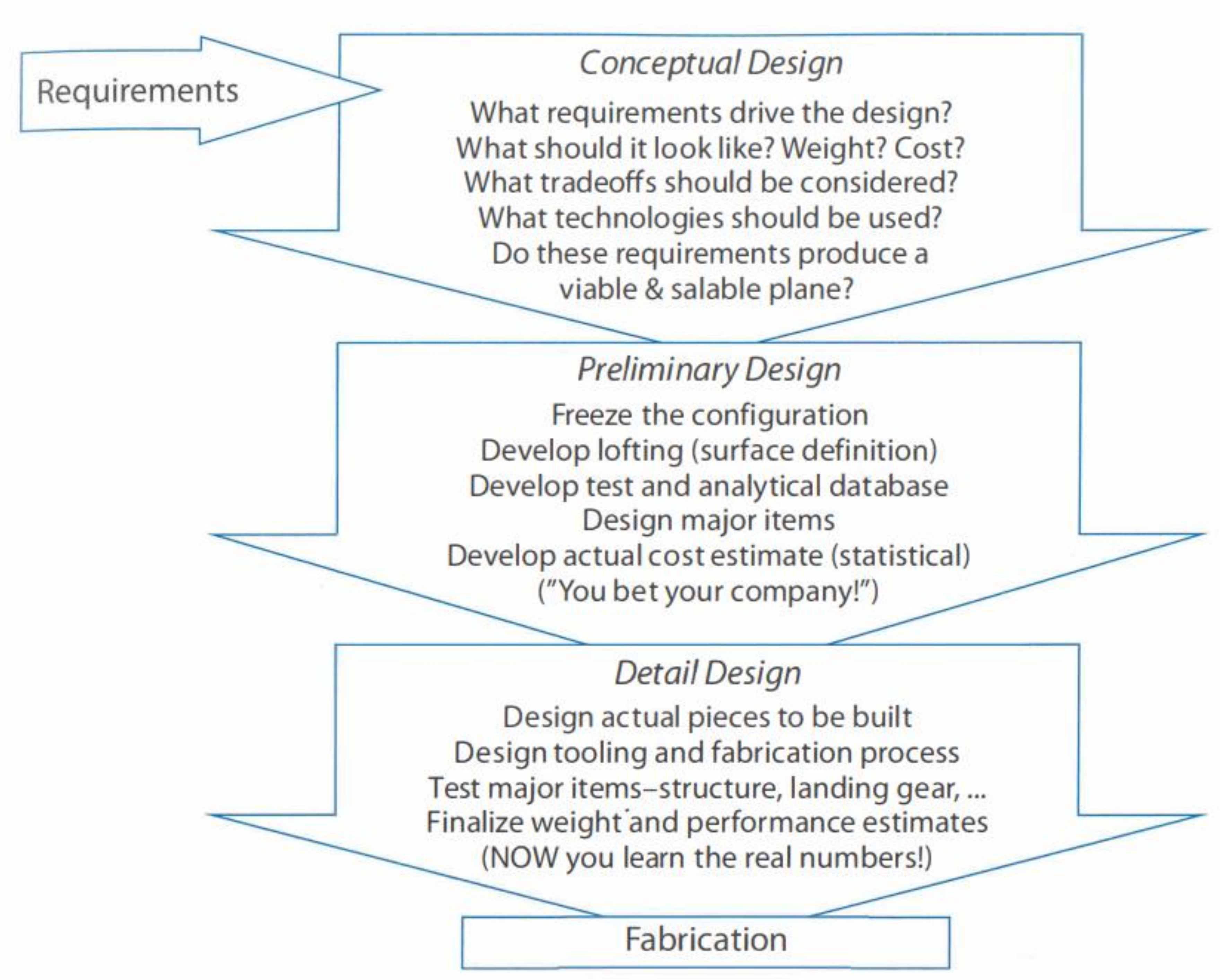
Phases of Design



Source: Aircraft Design by Daniel P. Raymer

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Phases of Design

- Conceptual (6 months?)
    - Can any A/C be built that is affordable and meets the requirements?
    - Can we come up with relaxed requirements to permit an affordable A/C?
    - It is a fluid process; the layout is constantly affected by analysis.
    - Several alternative layouts (e.g. canard v. tail v. tailless, etc.)
    - Relatively low detail.

Phases of Design

- Preliminary (2 years?)
    - Begins when major changes are over.
    - Freeze of concept
    - Increased detail of analysis
    - Wind tunnel, CFD, structures and landing gear, FCS, stability and control...
    - Lofting (mathematical modeling of outside surfaces to ensure perfect fit that will perdure)

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Phases of Design

- Detail design
    - Begins when the actual pieces to be fabricated are designed (holes, racks, ribs, rivets,....)
    - Most expensive part of design (most engineers)
    - All systems
    - Production design
    - Ends with fabrication

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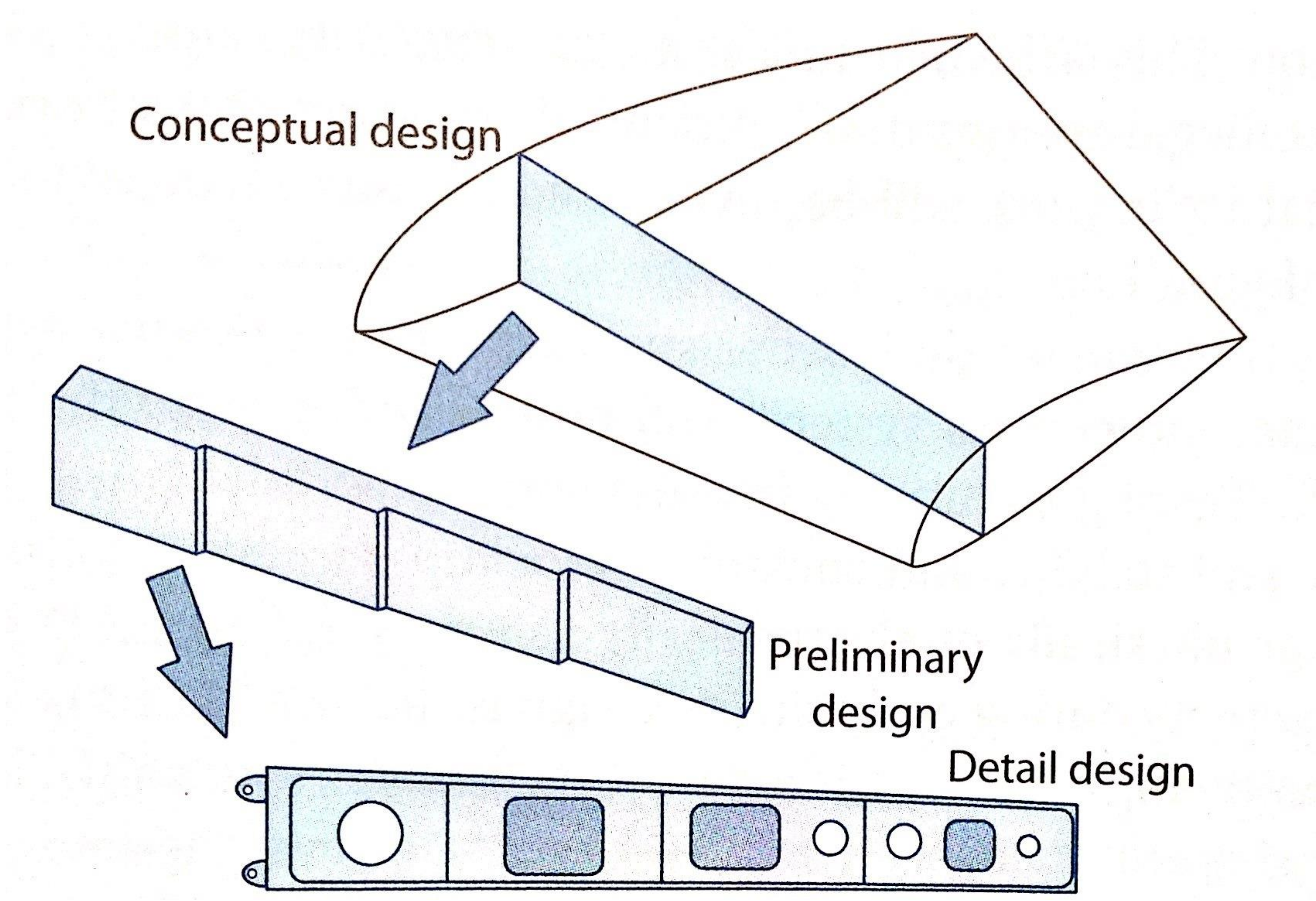
A/C Conceptual Design Process



Source: Aircraft Design by Daniel P. Raymer

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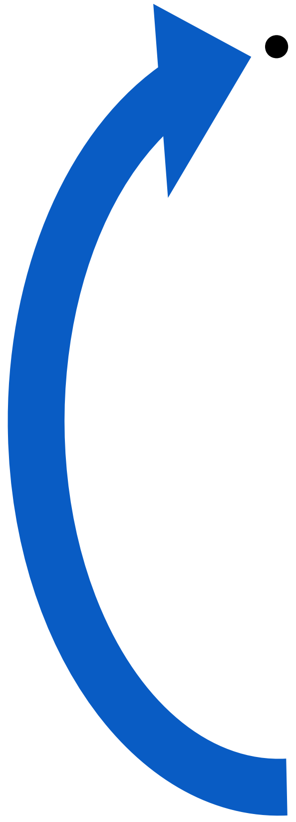
A/C Conceptual Design Process



- Begins with the requirements
- What technology level will be used (when will it fly?, TRL's)
- Initial sizing and concept sketch (Dash-1)
    - Basic aerodynamics, weight fractions, fit of major components
    - Lay-out is put through more detailed aerodynamics, weights,... analyses.
    - Performance calculated
    - Optimized to find the lightest(cheapest) A/C that satisfies requirements
    - New layout? Dash i+1?
    - Ends with design that will go into preliminary design

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A/C Conceptual Design Process

TRL 1: Basic principles observed and reported
TRL 2: Technology concept and/or application formulated
TRL 3: Analytical and experimental function or characteristic proof-of-concept
TRL 4: Component and/or breadboard validation in laboratory environment
TRL 5: Component and/or breadboard validation in relevant environment
TRL 6: Model or prototype demonstration in a relevant environment
TRL 7: System prototype demonstration in an actual environment
TRL 8: Actual system completed and qualified through test and demonstration
TRL 9: Actual system proven through successful mission operations

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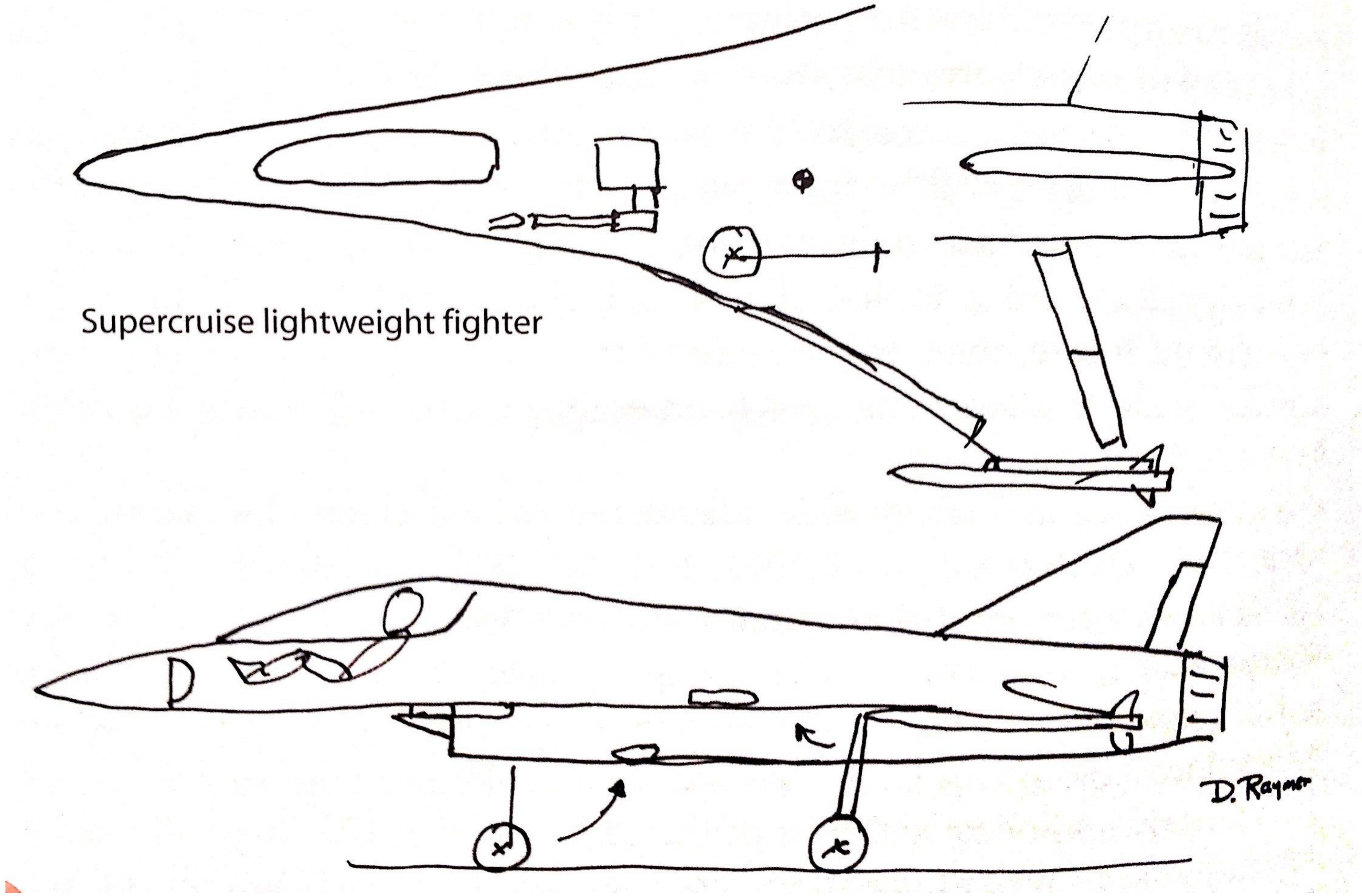
A/C Conceptual Design Process
Initial Sketch



Source: Aircraft Design by Daniel P. Raymer

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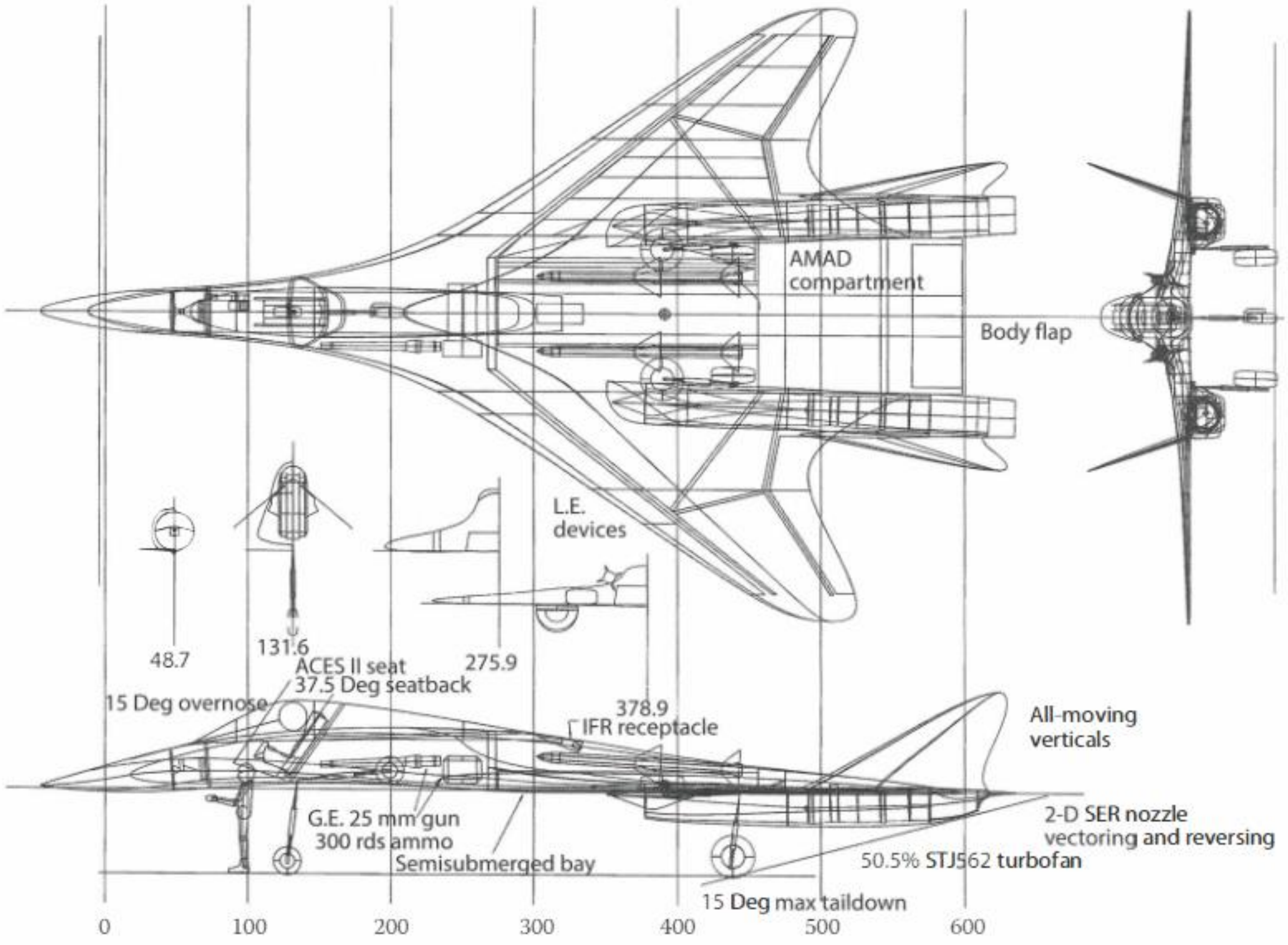
A/C Conceptual Design Process



Source: Aircraft Design by Daniel P. Raymer

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A/C Conceptual Design Process

- Sizing from a conceptual sketch:
  - Determine the initial size (weight, W_0) of the A/C in order to meet the mission (range):

$$W_0 = W_{\text{crew}} + W_{\text{payload}} + W_{\text{fuel}} + W_{\text{empty}}$$

(known) (known) (unknown) (unknown)

$$W_0 = W_{\text{crew}} + W_{\text{payload}} + \left(\frac{W_f}{W_0}\right) W_0 + \left(\frac{W_e}{W_0}\right) W_0$$

$$\boxed{W_0 = \frac{W_{\text{crew}} + W_{\text{payload}}}{1 - (W_f/W_0) - (W_e/W_0)}}$$

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A/C Conceptual Design Process

- Empty weight fraction (We/Wo)
  - 0.3 < We/Wo < 0.8
  - We/Wo decreases with Wo
  - We/Wo depends on the type of A/C

- Fuel weight fraction (Wf/Wo)
  - Depends on the mission
  - Depends on fuel consumption
  - Depends on aerodynamics

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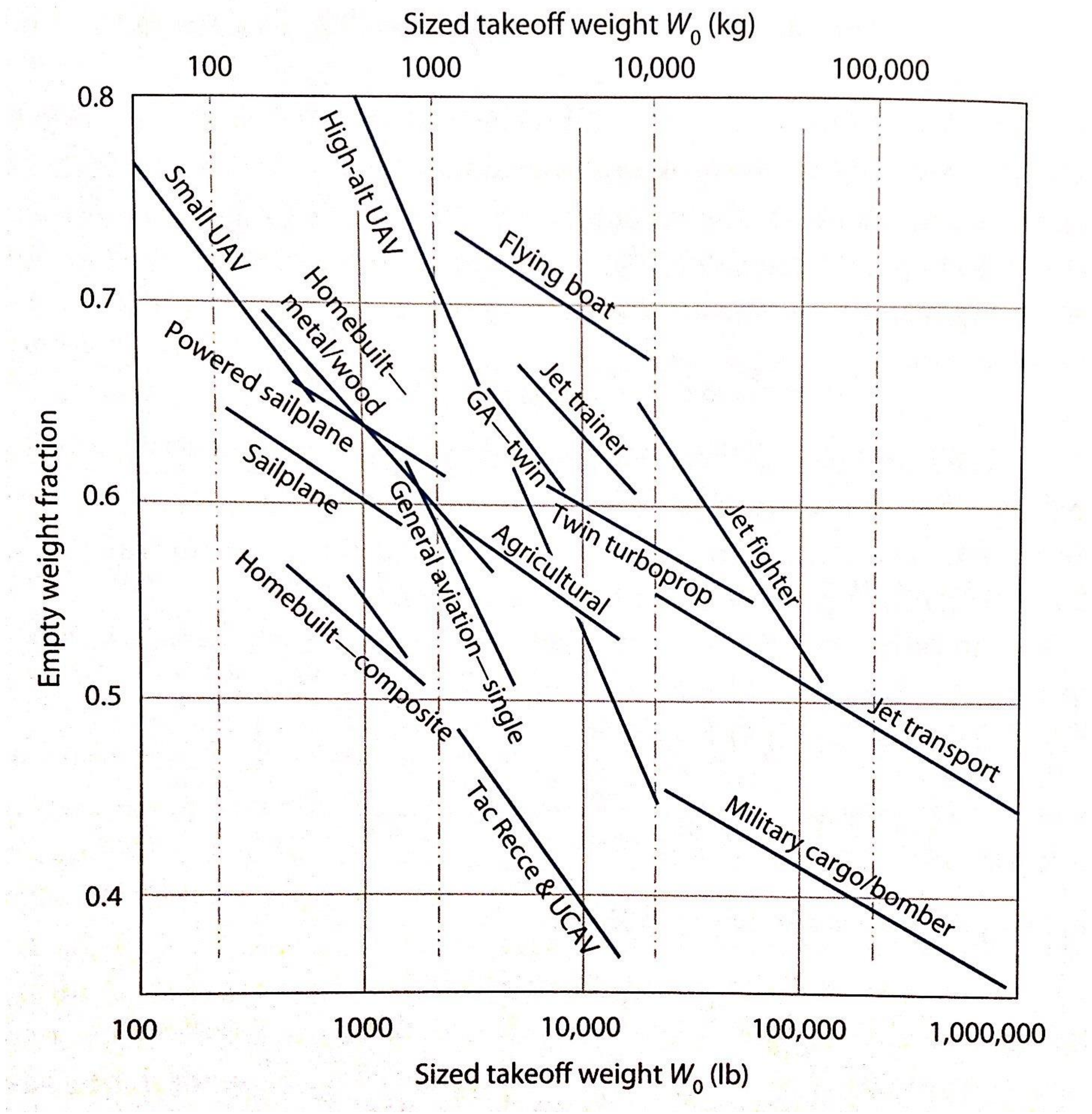
A/C Conceptual Design Process



Source: Aircraft Design by Daniel P. Raymer

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A/C Conceptual Design Process

$$\frac{W_e}{W_0} = AW_o^c K_{vs}$$

$W_e/W_0 = AW_0^C K_{vs}$	A	{A-metric}	C
Sailplane—unpowered	0.86	{0.83}	−0.05
Sailplane—powered	0.91	{0.88}	−0.05
Homebuilt—metal/wood	1.19	{1.11}	−0.09
Homebuilt—composite	1.15	{1.07}	−0.09
General aviation—single engine	2.36	{2.05}	−0.18
General aviation—twin engine	1.51	{1.4}	−0.10
Agricultural aircraft	0.74	{0.72}	−0.03
Twin turboprop	0.96	{0.92}	−0.05
Flying boat	1.09	{1.05}	−0.05
Jet trainer	1.59	{1.47}	−0.10
Jet fighter	2.34	{2.11}	−0.13
Military cargo/bomber	0.93	{0.88}	−0.07
Jet transport	1.02	{0.97}	−0.06
UAV—Tac Recce & UCAV	1.67	{1.53}	−0.16
UAV—high altitude	2.75	{2.48}	−0.18
UAV—small	0.97	{0.86}	−0.06

K_{vs} = variable sweep constant = 1.04 if variable sweep = 1.00 if fixed sweep

Source: Aircraft Design by Daniel P. Raymer

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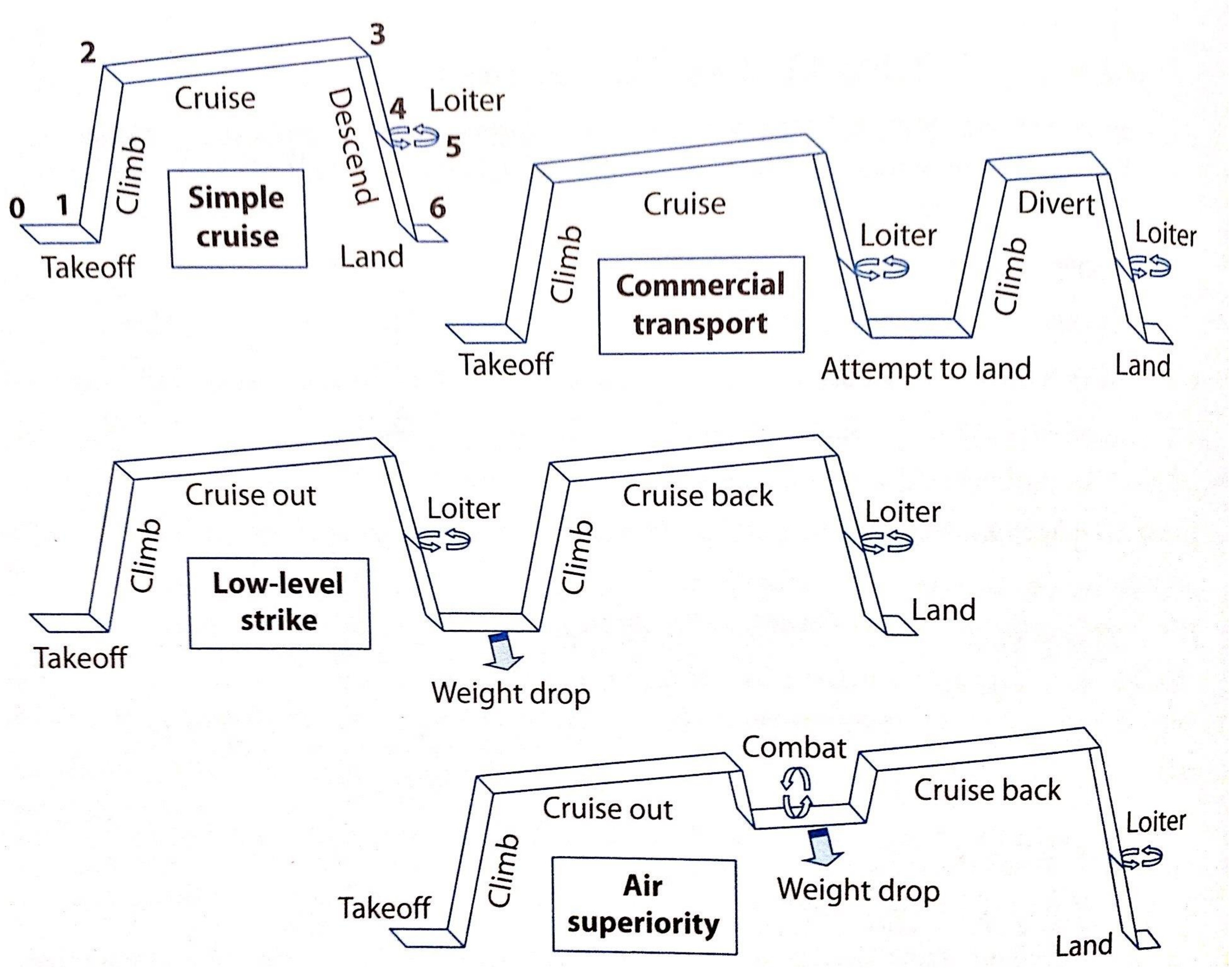
A/C Conceptual Design Process



Source: Aircraft Design by Daniel P. Raymer

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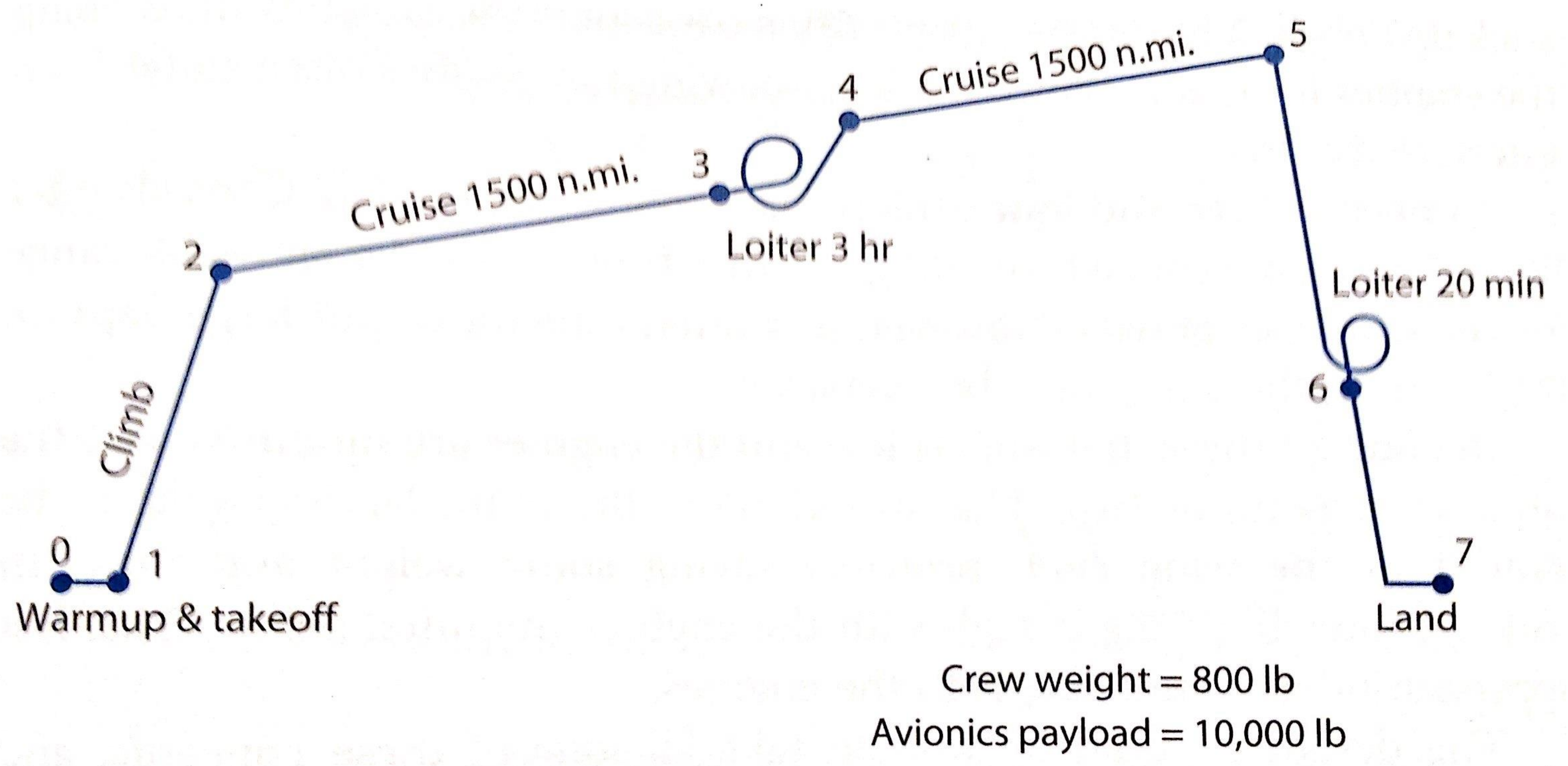
A/C Conceptual Design Process



$$\frac{W_7}{W_0} = \frac{W_1}{W_0}\frac{W_2}{W_1}\frac{W_3}{W_2}\frac{W_4}{W_3}\frac{W_5}{W_4}\frac{W_6}{W_5}\frac{W_7}{W_6}$$

$$\frac{W_f}{W_0} = 1 - \frac{W_7}{W_0}$$

Source: Aircraft Design by Daniel P. Raymer

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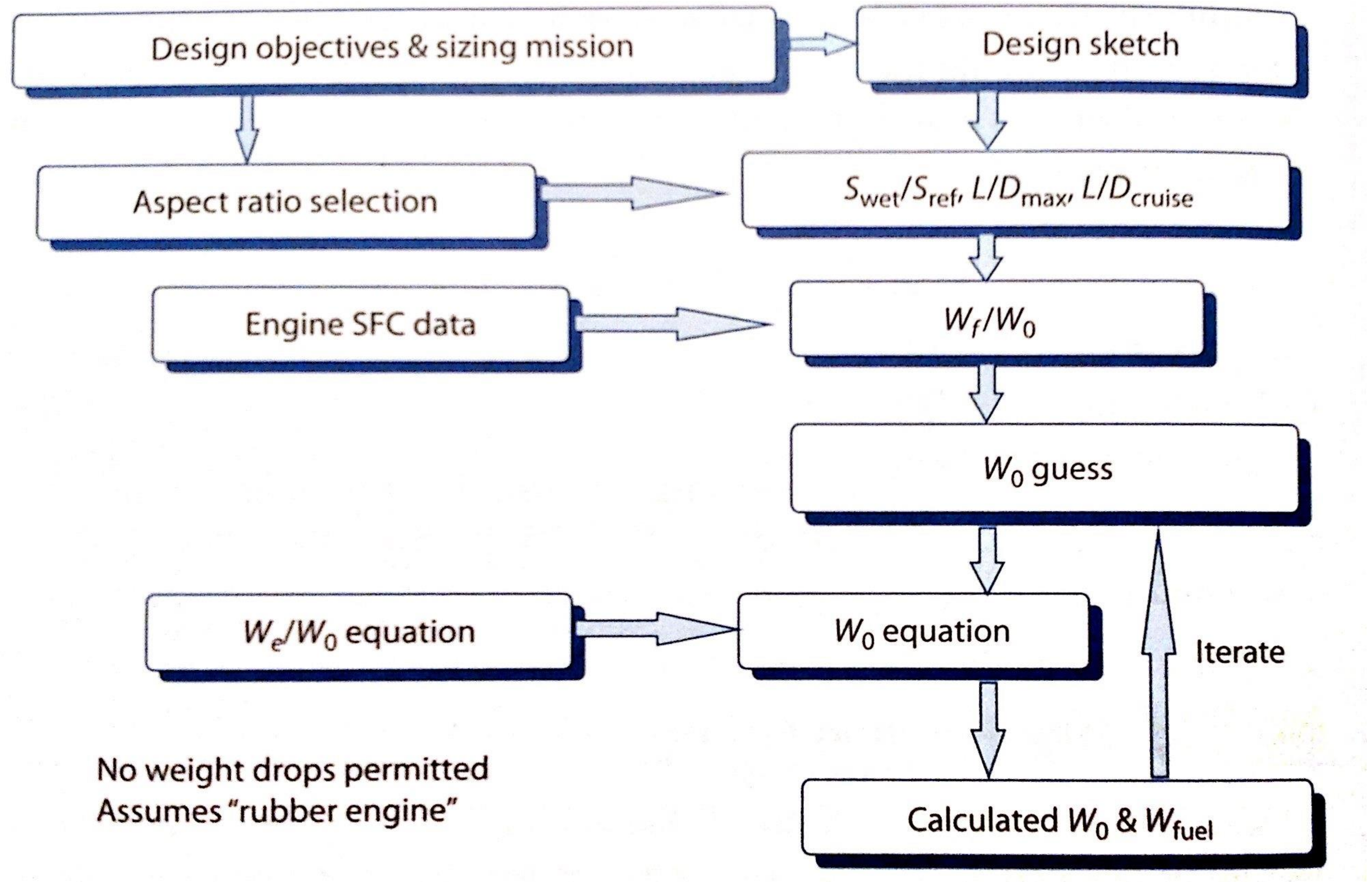
A/C Conceptual Design Process I



Source: Aircraft Design by Daniel P. Raymer

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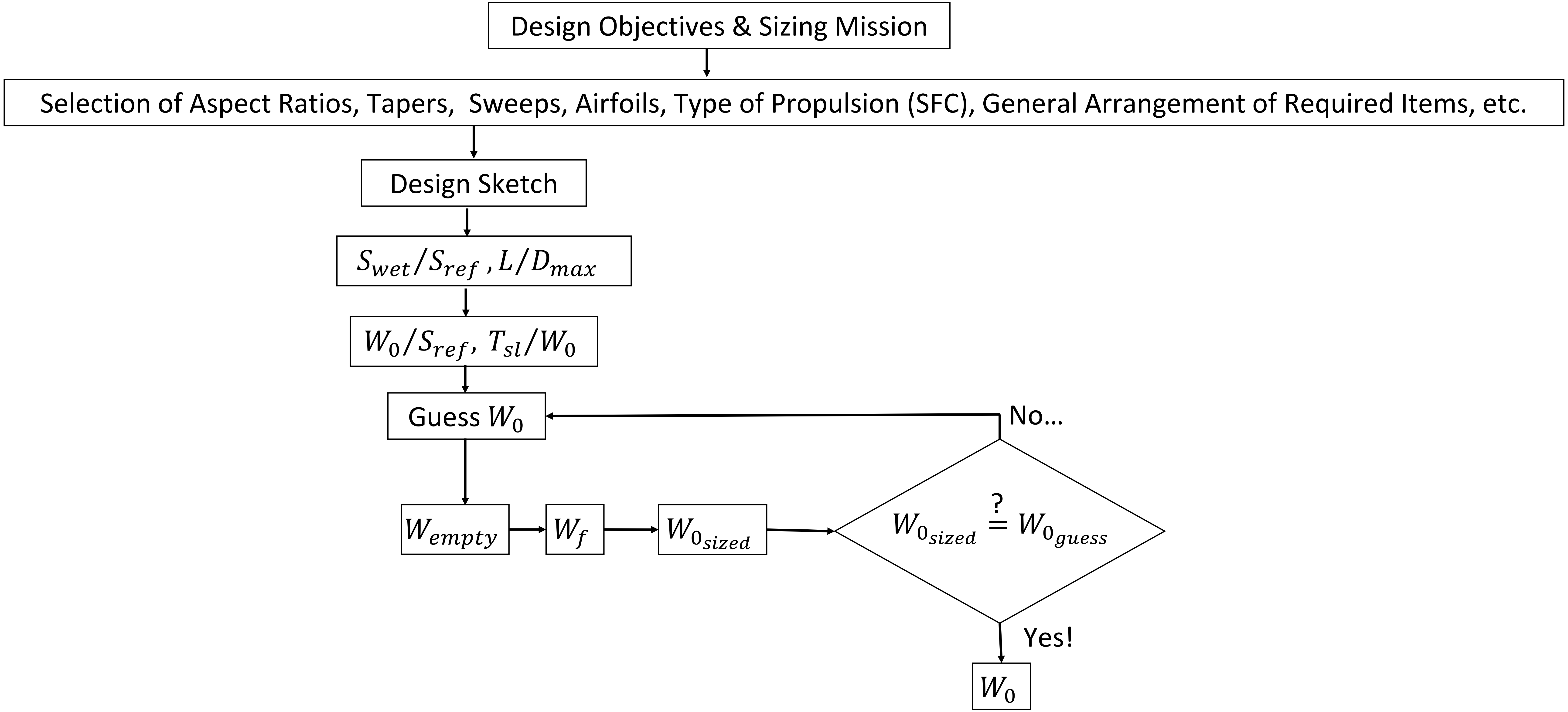
A/C Conceptual Design Process II



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A/C Conceptual Design Process

Historical Mission Segment Weight Fractions:

Mission segment	(W_i/W_{i-1})
Warmup and takeoff	0.970
Climb	0.985
Landing	0.995

For I.C.: $C = C_{bhp} \dfrac{V}{550\ \eta_p}$

Cruise/Loiter Mission Segment Weight Fractions:

$$R = \frac{V}{C}\frac{L}{D}\ell n \frac{W_{i-1}}{W_i} \quad \Rightarrow \quad \frac{W_i}{W_{i-1}} = \exp\frac{-RC}{V(L/D)}$$

$$E = \frac{L/D}{C}\ell n \frac{W_{i-1}}{W_i} \quad \Rightarrow \quad \frac{W_i}{W_{i-1}} = \exp\frac{-EC}{L/D}$$

Source: Aircraft Design by Daniel P. Raymer

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A/C Conceptual Design Process

Typical specific fuel consumptions:

Typical jet SFCs: 1/hr {mg/Ns}	Cruise	Loiter
Pure turbojet	0.9 {25.5}	0.8 {22.7}
Low-bypass turbofan	0.8 {22.7}	0.7 {19.8}
High-bypass turbofan	0.5 {14.1}	0.4 {11.3}

Propeller: $C = C_{power} V/\eta_p = C_{bhp} V/(550\eta_p)$ Typical C_{bhp}: lb/hr/bhp {mg/W-s}	Cruise	Loiter
Piston-prop (fixed pitch)	0.4 {0.068}	0.5 {0.085}
Piston-prop (variable pitch)	0.4 {0.068}	0.5 {0.085}
Turboprop	0.5 {0.085}	0.6 {0.101}

Source: Aircraft Design by Daniel P. Raymer

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A/C Conceptual Design Process

- L/D Estimation:
  - L/D is a measure of a design's overall aerodynamic efficiency.
  - For subsonic flight, it depends on span and wetted area:
    - Induced drag = f(span) = f(A=b^2/S)
    - Zero lift drag = f(wetted area)
  - Does aspect ratio predict drag???

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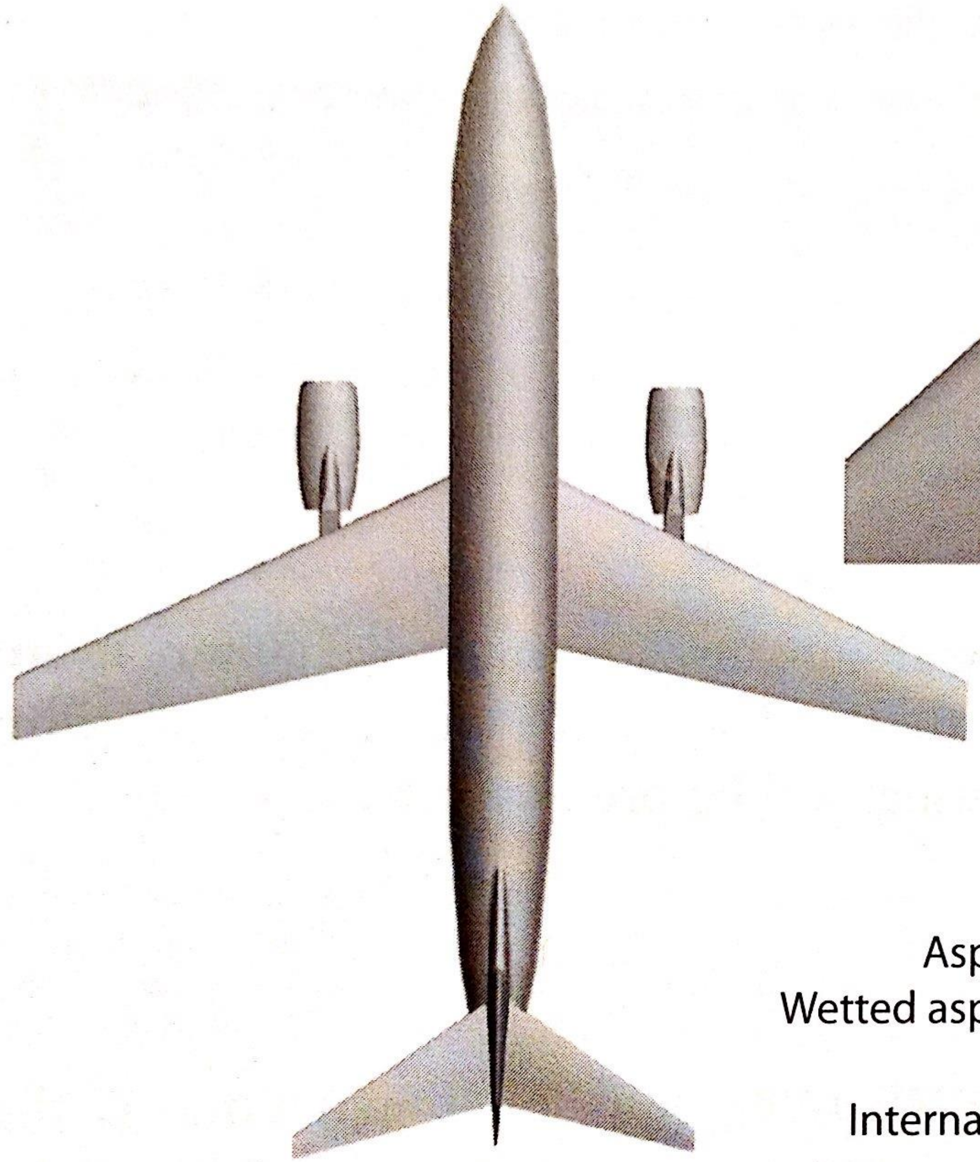
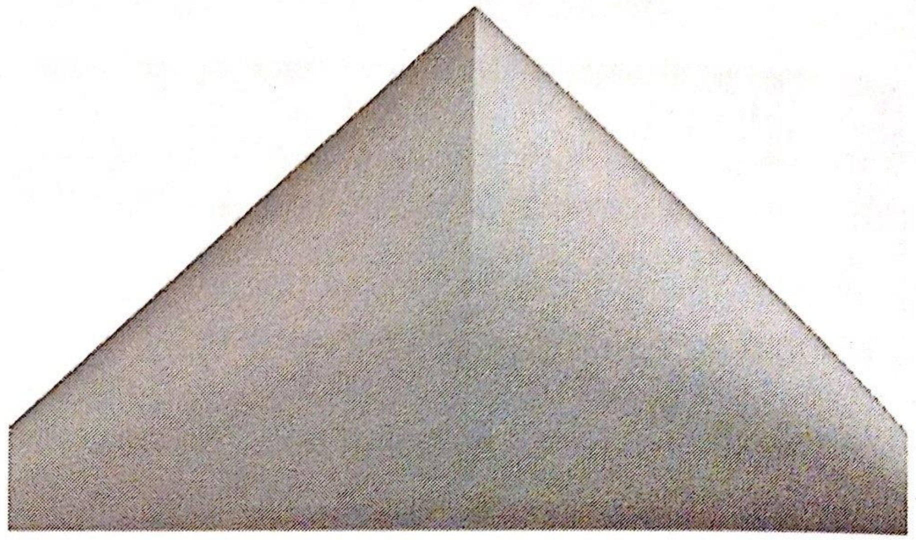
A/C Conceptual Design Process





	Conventional	Delta wing
S_{ref}	393	1000
S_{wetted}	2441	2156
Span	55	55
S_{wet}/S_{ref}	6.2	2.2
Aspect ratio	7.7	3
Wetted aspect ratio	1.2	1.4
L/D_{max}	15	16
Internal volume	2100	2100

Source: Aircraft Design by Daniel P. Raymer

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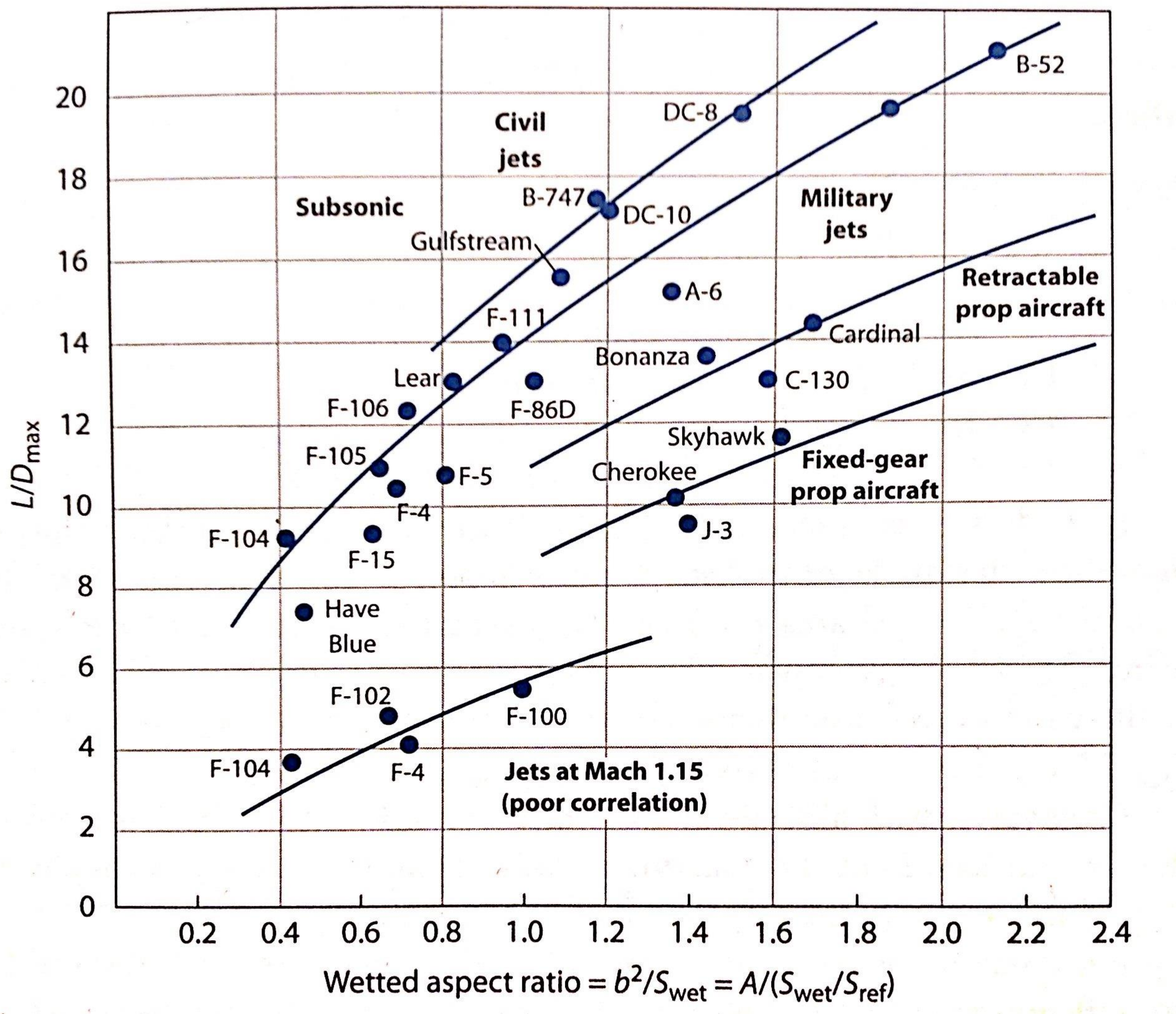
A/C Conceptual Design Process

- We define a "wetted aspect ratio" that better reflects aerodynamic efficiency by using span and wetted area to calculate it.

$$A_{\text{wetted}} = \frac{b^2}{S_{\text{wetted}}} = \frac{A}{(S_{\text{wet}}/S_{\text{ref}})}$$



Source: Aircraft Design by Daniel P. Raymer

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A/C Conceptual Design Process

$$\frac{L}{D_{max}} = K_{LD}\sqrt{A_{wetted}} = K_{LD}\sqrt{\frac{A}{(S_{wet}/S_{ref})}}$$

K_{LD} = 15.5 for civil jets
14 for military jets
11 for retractable prop aircraft
9 for nonretractable prop aircraft
13 for high-aspect-ratio aircraft
15 for sailplanes

Source: Aircraft Design by Daniel P. Raymer

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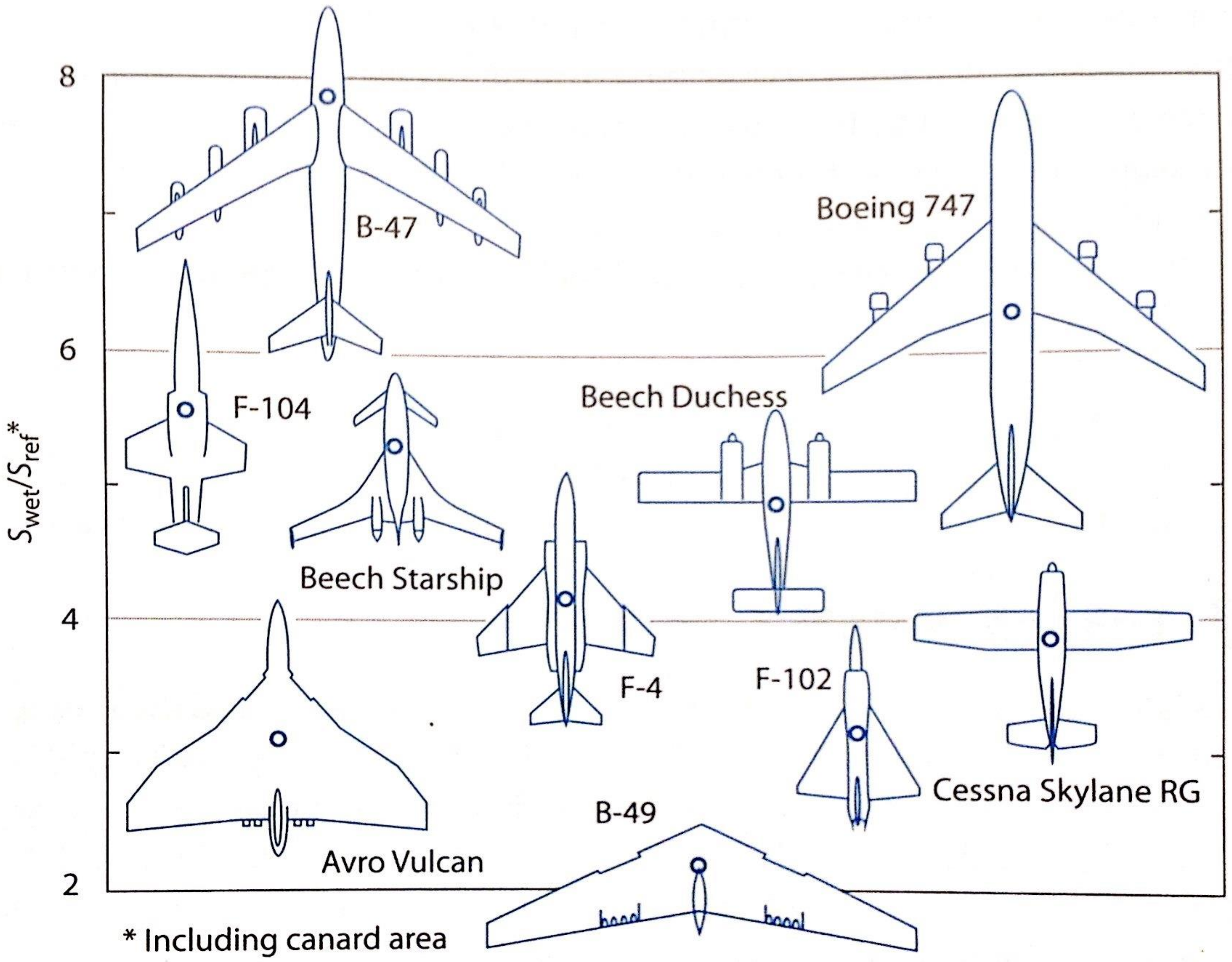
A/C Conceptual Design Process

- But at this point, we do not know S_{wet} or S_{ref}
- Since we have a sketch, we have $\frac{S_{wet}}{S_{ref}}$.



Source: Aircraft Design by Daniel P. Raymer

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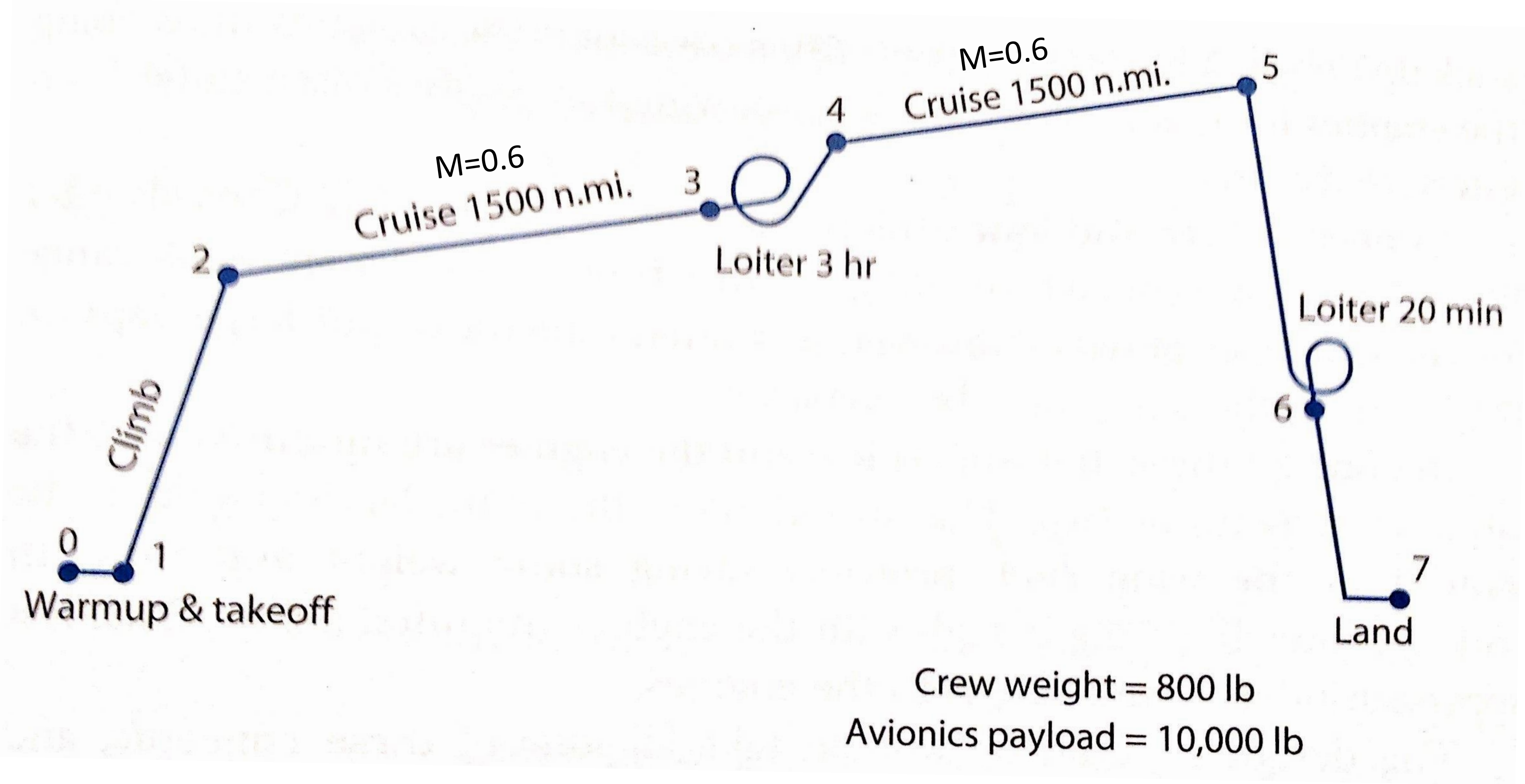
A/C Conceptual Design Example:

ASW (Antisubmarine Warfare Aircraft)



Source: Aircraft Design by Daniel P. Raymer

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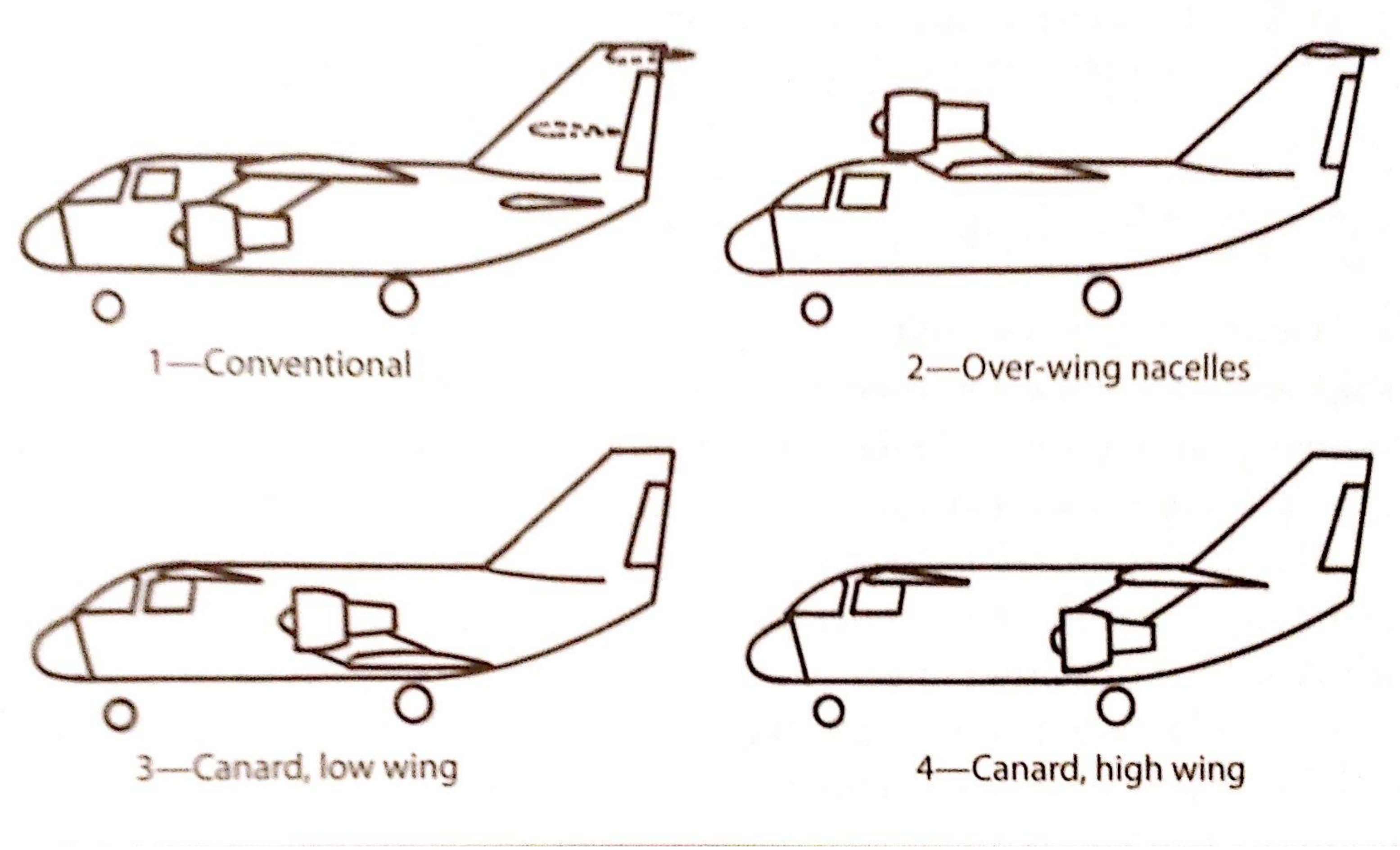
A/C Conceptual Design Example:
ASW (Antisubmarine Warfare Aircraft)

- Like S-3A
- Tail tradeoff: structural weight vs exhaust stream

- Little debris hits engine
- More lift on wing (exhaust)
- Difficult to maintain engines
- Interference (wing/engine) drag



- Reduced trim drag?
- Wider c.g. range
- Must oversize wing (small HLD)
- L.G. In wing root

- Reduced trim drag?
- Wider c.g. range
- Must oversize wing (small HLD)
- Better engine access

Source: Aircraft Design by Daniel P. Raymer

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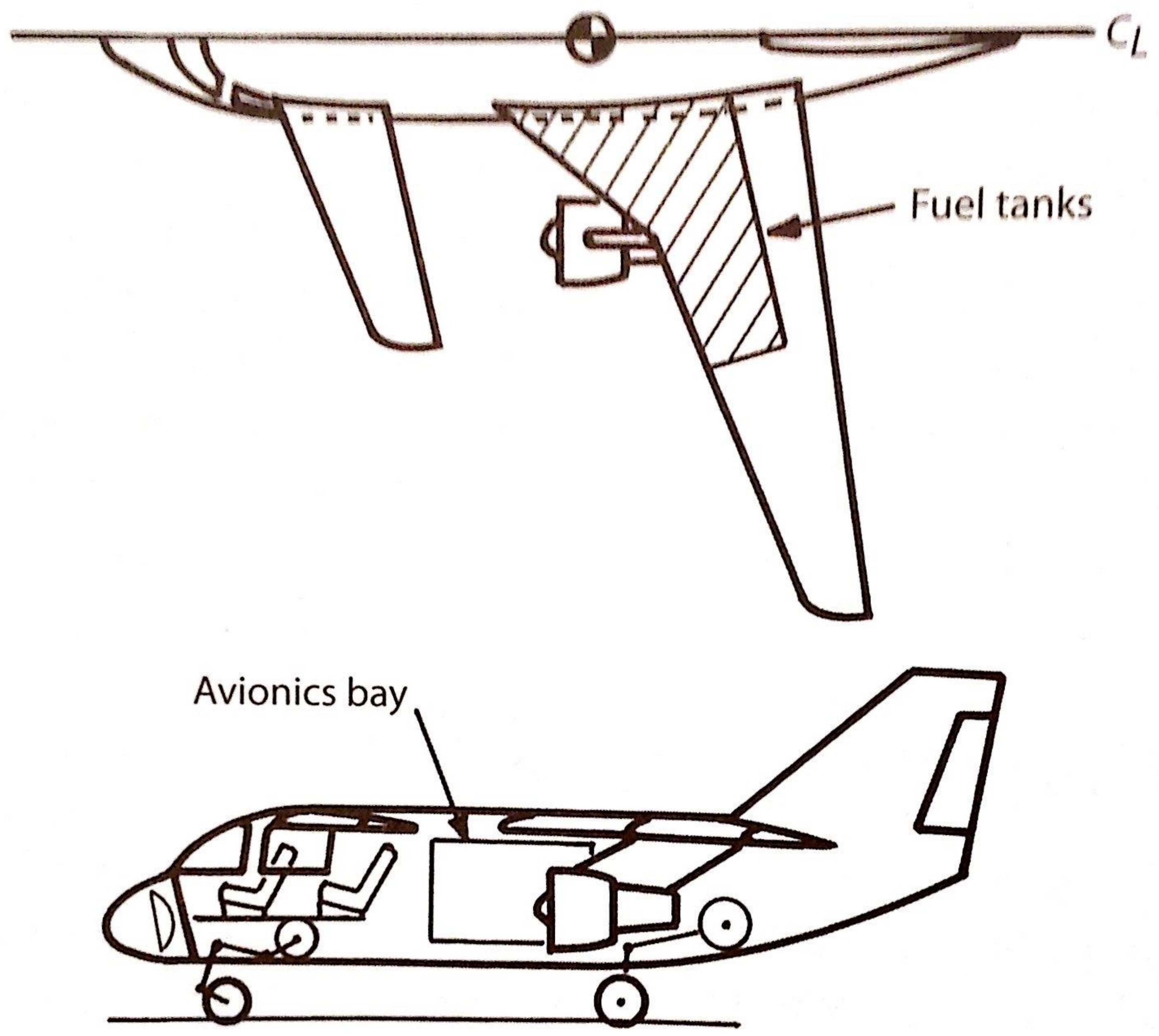
A/C Conceptual Design Example:
ASW (Antisubmarine Warfare Aircraft)



- Strake added to put fuel closer to c.g, at the cost of wetted area!
- All other concepts should be studied!
- All required volumes shown

Source: Aircraft Design by Daniel P. Raymer

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A/C Conceptual Design Example:
ASW (Antisubmarine Warfare Aircraft)

- Wing aspect ratio (concept sketch)chosen = 10
- Canards are usually bigger than tails and lift with the wing, so including the canard area equivalent aspect ratio = 7
- Looks like S_{wet}/S_{ref} = 5.5
- So wetted aspect ratio = 1.27
- Therefore, maximum L/D is about 16

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A/C Conceptual Design Example:

ASW (Antisubmarine Warfare Aircraft)

1. Warmup and takeoff $W_1/W_0 = 0.97$ (Table 3.2)
2. Climb $W_2/W_1 = 0.985$ (Table 3.2)
3. Cruise

$$R = 1500 \text{ n.mi.} = 9{,}114{,}000 \text{ ft}$$

$$C = 0.5 \text{ 1/hr} = 0.0001389 \text{ 1/s}$$

$$V = 0.6M \times (994.8 \text{ ft/s}) = 596.9 \text{ ft/s}$$

$$L/D = 16 \times 0.866 = 13.9$$

$$W_3/W_2 = e^{\{-RC/VL/D\}} = e^{-0.153} = 0.858$$

4. Loiter

$$E = 3 \text{ hr} = 10{,}800 \text{ s}$$

$$C = 0.4 \text{ 1/hr} = 0.0001111 \text{ 1/s}$$

$$L/D = 16$$

$$W_4/W_3 = e^{\{-EC/L/D\}} = e^{-0.075} = 0.9277$$

5. Cruise (same as 3) $W_5/W_4 = 0.858$
6. Loiter

$$E = \tfrac{1}{3} \text{ hr} = 1200 \text{ s}$$

$$C = 0.0001111 \text{ 1/s}$$

$$L/D = 16$$

$$W_6/W_5 = e^{-0.0083} = 0.9917$$

7. Land $W_7/W_6 = 0.995$ (Table 3.2)

Source: Aircraft Design by Daniel P. Raymer

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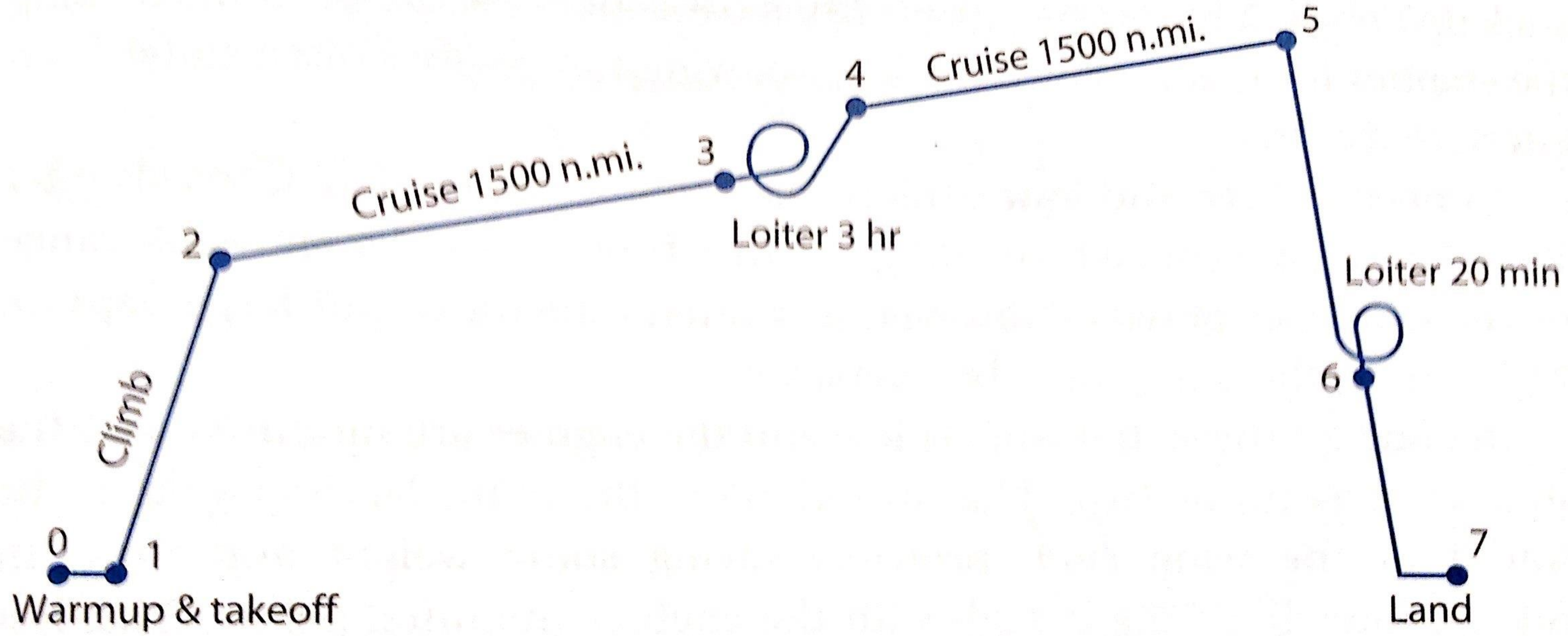
A/C Conceptual Design Example:
ASW (Antisubmarine Warfare Aircraft)



Crew weight = 800 lb

Avionics payload = 10,000 lb

$$W_7/W_0 = (0.97)(0.985)(0.858)(0.9277)(0.858)(0.9917)(0.995) = 0.6441$$

$$W_f/W_0 = 1.06(1 - 0.6441) = 0.3773$$

$$W_e/W_0 = 0.93\ W_0^{-0.07} \qquad \text{(Table 3.1)}$$

$$W_0 = \frac{10{,}800}{1 - 0.3773 - \frac{W_e}{W_0}}$$

Source: Aircraft Design by Daniel P. Raymer

ME4932 Aircraft Performance & Design

A/C Conceptual Design Example:

ASW (Antisubmarine Warfare Aircraft)

$$W_0 = \frac{10{,}800}{1 - 0.3773 - \dfrac{W_e}{W_0}}$$

W_0, guess	W_e/W_0	W_e	W_0, calculated
50,000	0.4361	21,803	57,863
60,000	0.4305	25,832	56,198
56,000	0.4326	24,227	56,814
56,500	0.4324	24,428	56,733
56,700	0.4322	24,508	56,702

Source: Aircraft Design by Daniel P. Raymer

ME4932 Aircraft Performance & Design

A/C Conceptual Design Example:
Range Trade

1000 n miles Range

$$W_3/W_2 = W_5/W_4 = e^{-0.1020} = 0.9030$$

$$W_7/W_0 = 0.7132$$

$$W_f/W_0 = 1.06(1 - 0.7132) = 0.3040$$

$$W_0 = \frac{10{,}800}{1 - 0.3040 - \dfrac{W_e}{W_0}}$$

W_0, guess	W_e/W_0	W_e	W_0, calculated
50,000	0.4361	21,803	41,544
40,000	0.4429	17,717	42,670
42,000	0.4414	18,540	42,417
42,400	0.4411	18,704	42,369
42,370	0.4412	18,692	42,372

Source: Aircraft Design by Daniel P. Raymer

ME4932 Aircraft Performance & Design

A/C Conceptual Design Example:
Range Trade

2000 n miles Range

$$W_3/W_2 = W_5/W_4 = e^{-0.2040} = 0.8154$$

$$W_7/W_0 = 0.5816$$

$$W_f/W_0 = 0.4435$$

$$W_0 = \frac{10{,}800}{1 - 0.4435 - \frac{W_e}{W_0}}$$

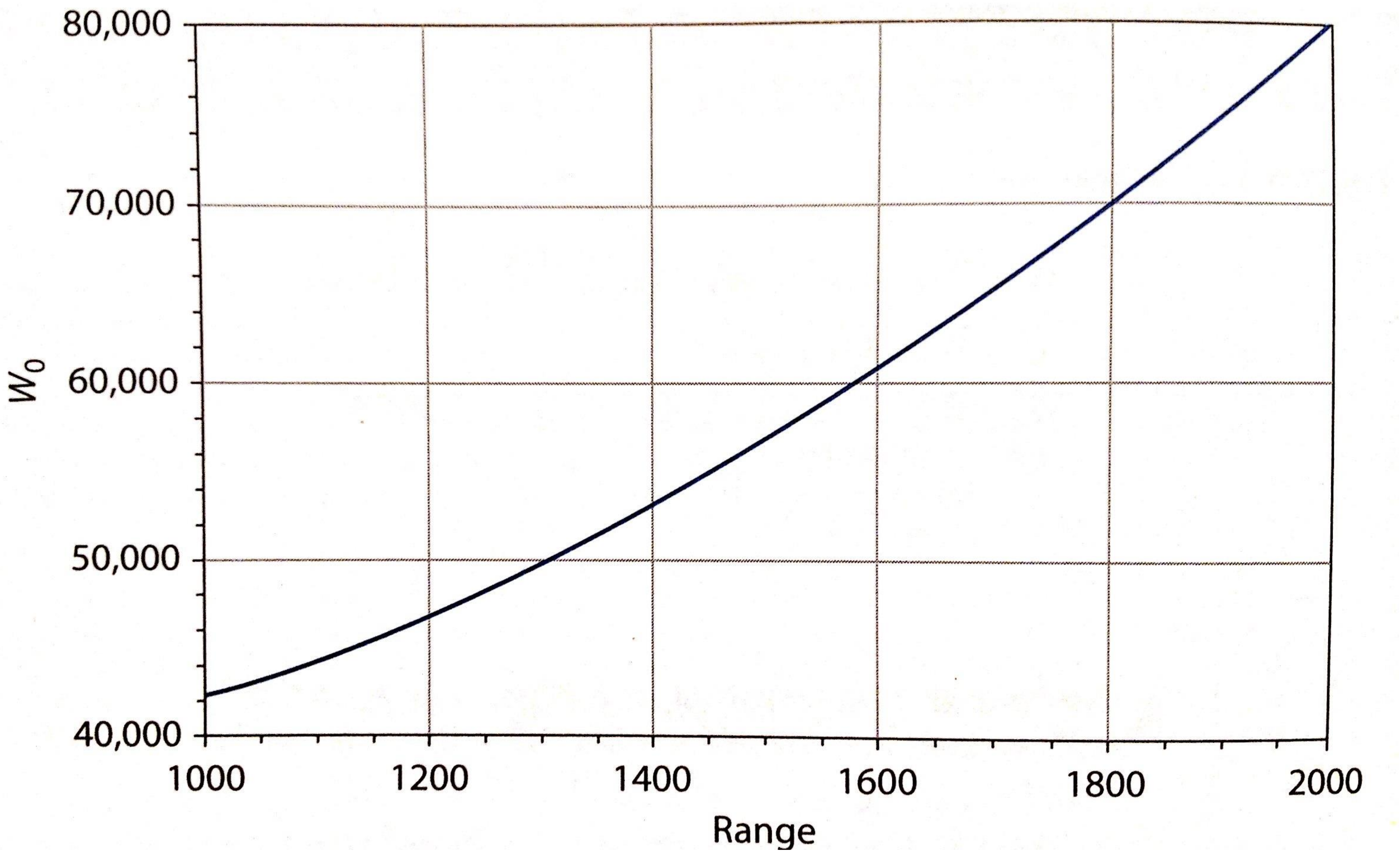
W_0, guess	W_e/W_0	W_e	W_0, calculated
50,000	0.4361	21,803	89,671
80,000	0.4220	33,756	80,265
80,200	0.4219	33,835	80,221
80,210	0.4219	33,839	80,219
80,218	0.4219	33,842	80,217

Source: Aircraft Design by Daniel P. Raymer

ME4932 Aircraft Performance & Design

A/C Conceptual Design Example:

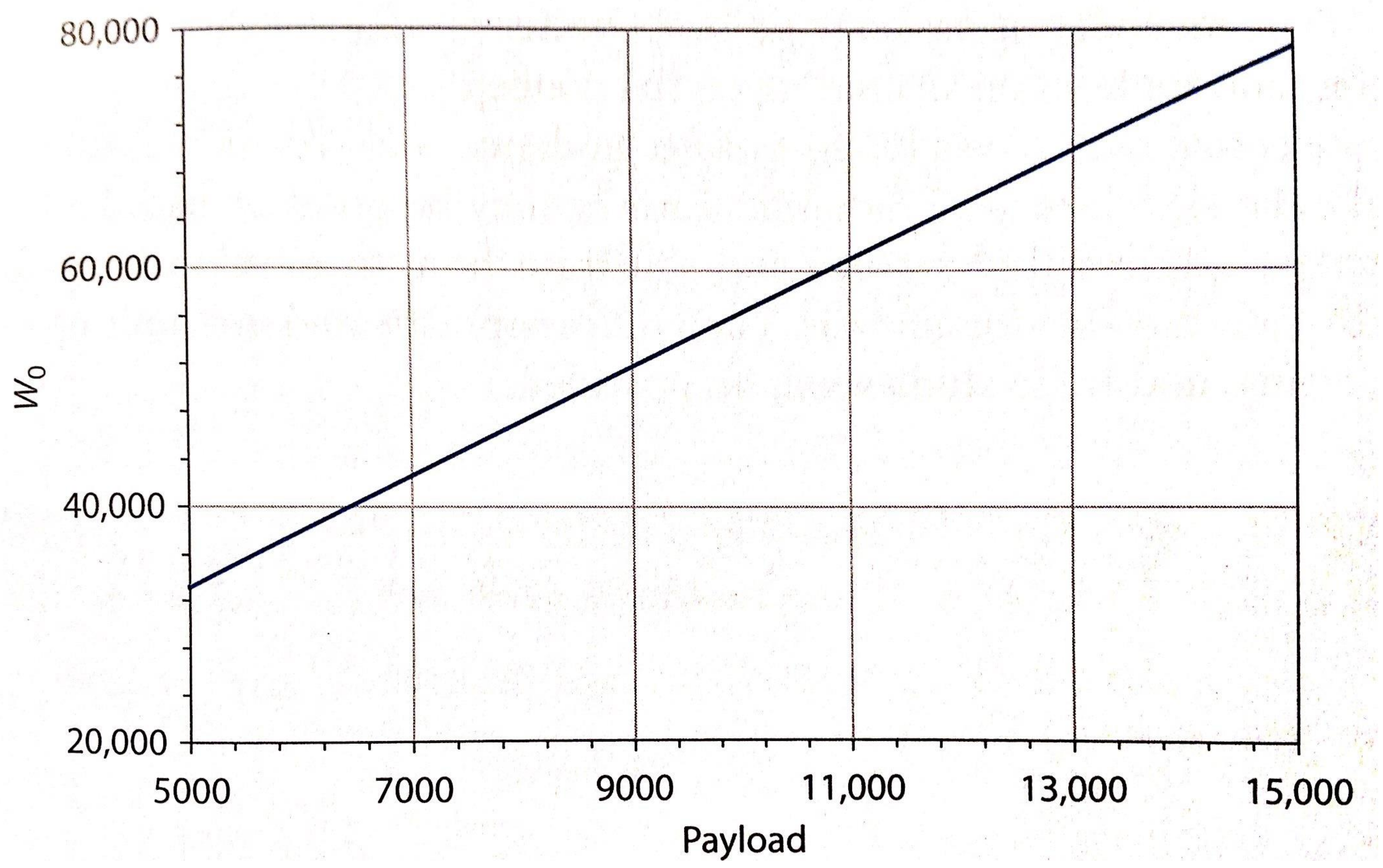
Range Trade



Source: Aircraft Design by Daniel P. Raymer

ME4932 Aircraft Performance & Design

A/C Conceptual Design Example:
Payload Trade



Source: Aircraft Design by Daniel P. Raymer

ME4932 Aircraft Performance & Design

A/C Conceptual Design Example:
Use of Composites:

- Empty weight equation used was for aluminum construction military cargo and bomber aircraft.
- The effect the use of composites can be estimated by assuming 95% of empty weight fraction.

$$W_e/W_0 = (0.95)(0.93 W_0^{-0.07}) = 0.8835\ W_0^{-0.07}$$

$$W_0 = \frac{10{,}800}{1 - 0.3773 - \dfrac{W_e}{W_0}}$$

W_0, guess	W_e/W_0	W_e	W_0, calculated
50,000	0.4143	20,713	51,810
51,000	0.4137	21,098	51,668
51,500	0.4134	21,291	51,598
51,550	0.4134	21,310	51,591
51,585	0.4134	21,323	51,587

- Reduces Wo from 56,702 to 51,585, a 9% savings by reducing We only 5%!
- Unwanted Wo growth implications!

Source: Aircraft Design by Daniel P. Raymer