Politecnico di Torino

Progettazione di veicoli aerospaziali (AA-LZ)

E1. Conceptual Design of subsonic commercial aircraft

2. TAKE-OFF WEIGHT

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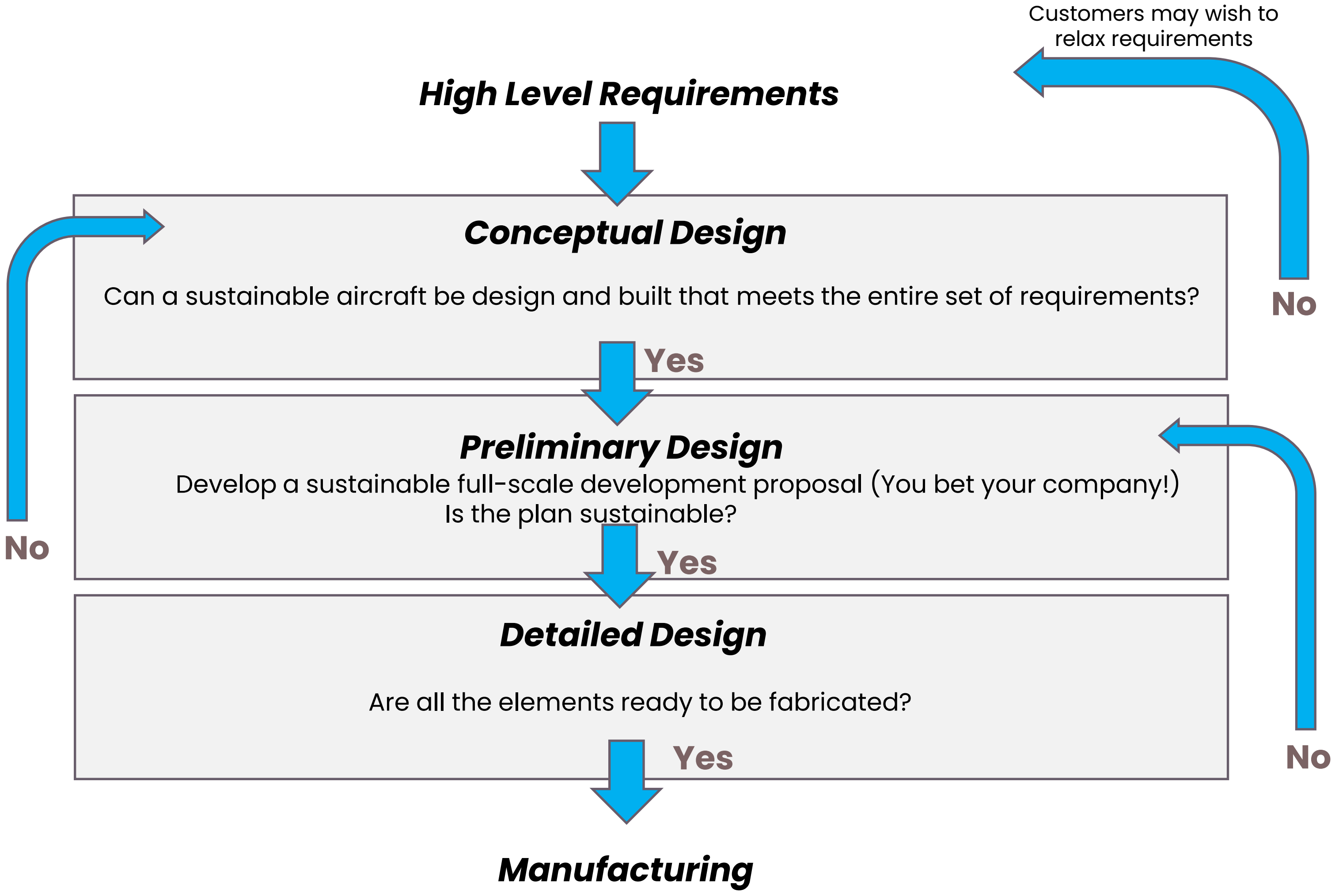
Introduction

A brief recap…

Main Goals

1. To understand the importance of Conceptual Design among the design and development phases of an aircraft.
2. To acquire knowledge about the most up-to-date methodologies for Conceptual Design of aircraft
3. To understand the most influential factors on the Conceptual Design of a modern commercial aircraft
4. To be able to perform a Conceptual Design of a modern commercial aircraft

Aircraft Design Phases



<u>Aircraft design results to be iterative and highly multidisciplinary process!</u>

High Level Requirements

$$HR = (x_{j_1}) \cup (p_{j_2}) \cup (q_{j_3}) \cup (r_{j_4})$$

Where

- ✓ HR is the entire set of Design Specifications;
- ✓ x_{j_1} (j_1 = 1:n_1) is the set of target performance to be reached
- ✓ p_{j_2} (j_2 = 1:n_2) is the set of design parameters initially set by customers
- ✓ q_{j_3} (j_3 = 1:n_3) is the set of operational requirements
- ✓ q_{j_4} (j_3 = 1:n_4) is the set of constraints superimposed by the applicable regulatory framework

Set of Performance
$$\begin{cases} Cruise\ Mach\ Number:\ x_1 \geq 0.85 \\ Range: x_2 \geq 5000\ km \\ \dots \end{cases}$$

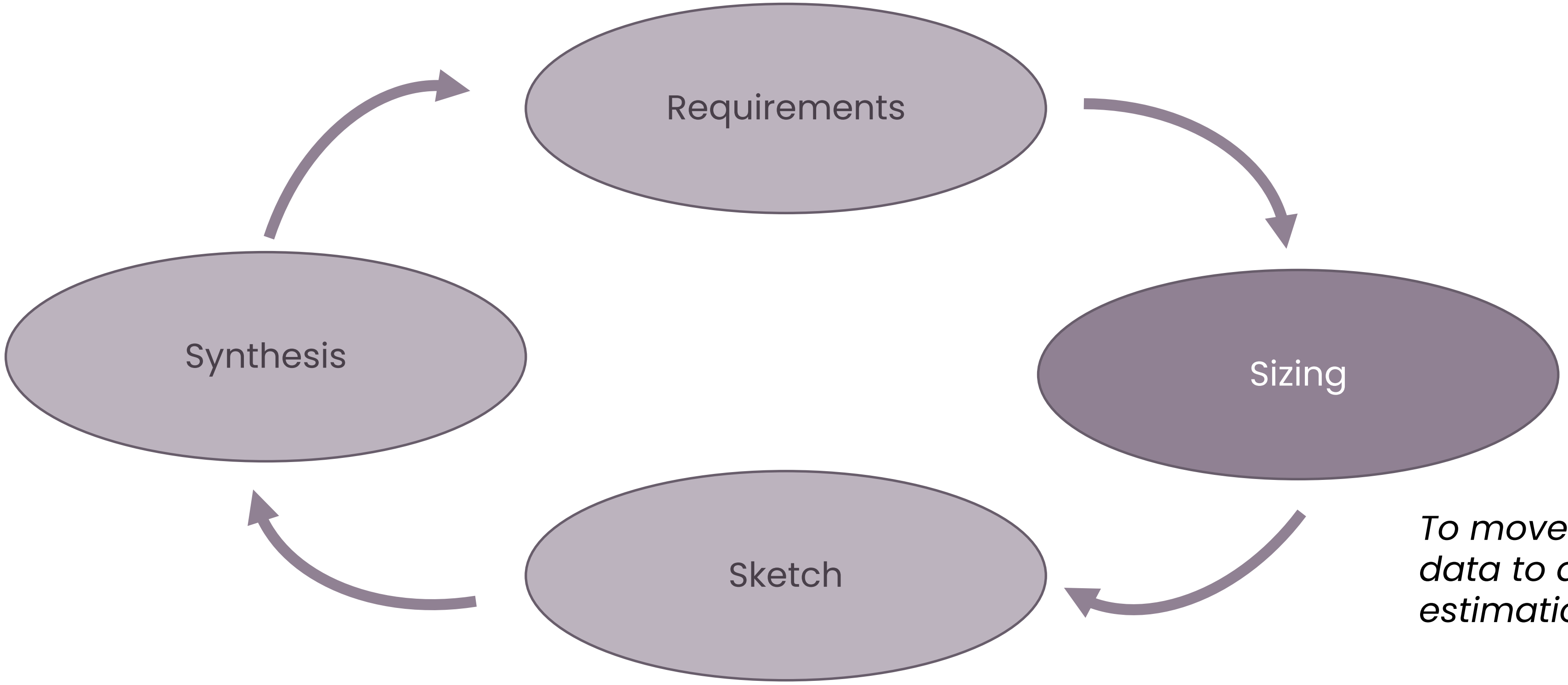
Set of Design Parameters
$$\begin{cases} Payload\ Mass: p_1 \geq 10\ t \\ Fuselage\ Length: p_2 \leq 40\ m \\ Wing\ span: p_3 \leq 35\ m \\ \dots \end{cases}$$

Set of Operational Requirements
$$\begin{cases} Cruise\ Altitude: 11\ k \leq q_1 \leq 12\ km \\ Turn\ Around\ Time\ q_2 \leq 2h \\ \dots \end{cases}$$

Set of Constraints from Regulatory Framework
$$\begin{cases} n_{exits} = f(n_{pax} g[m_{pay}]) \\ Balance\ Field\ Length \\ \dots \end{cases}$$

New Requirements for new aircraft configurations

Design Problem



To move from qualitative data to quantitative estimations

Conceptual Design Process

Highly Iterative
Highly Multidisciplinary

The Aircraft Design process

Multi-Stage

Initial Sizing

Conceptual Design

Preliminary Design

Detailed Design

Production

Testing

..Fly!

The Aircraft Design process

Multi-Stage

Requirements

Initial Sizing

Conceptual Design

Thousands of configurations

Preliminary Design

Layout fixed

Detailed Design

Production

Testing

..Fly!

The Aircraft Design process

Multi-Stage

Requirements
Initial Sizing

Conceptual Design

Preliminary Design

Detailed Design

Production

Testing

..Fly!

Multi-Disciplinary

Aerodynamics

Structures

Flight mechanics

Propulsion

On-board systems

Weights optimization

Payload

Performance

Control systems

The Aircraft Design process

Multi-Stage

Requirements
Initial Sizing

Conceptual Design

Preliminary Design

Detailed Design

Production
Testing
..Fly!

Multi-Disciplinary

Aerodynamics
Structures
Flight mechanics
Propulsion
On-board sys.
Weights opt.
Payload
Performance
Control systems

AEROELASTICITY

The Aircraft Design process

Multi-Stage

Requirements
Initial Sizing

Conceptual Design

Preliminary Design

Detailed Design

Production

Testing

..Fly!

Multi-Disciplinary

Aerodynamics

Structures

Flight mechanics

Propulsion

On-board systems

Weights optimization

Payload

Performance

Control systems

Multi-Fidelity

Textbook methods

Statistics/empirical data

Analytical methods

Numerical simulations

- Level 1
- Level 2
- Level 3

Experimental

Flight test

The Aircraft Design process

Multi-Stage

Requirements
Initial Sizing

Conceptual Design

Preliminary Design

Detailed Design

Production
Testing
..Fly!

Multi-Disciplinary

- Aerodynamics
- Structures
- Flight mechanics
- Propulsion
- On-board systems
- Weights optimization
- Payload
- Performance
- Control systems

Multi-Fidelity

- Textbook methods
- Statistics/empirical data
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  - Level 1
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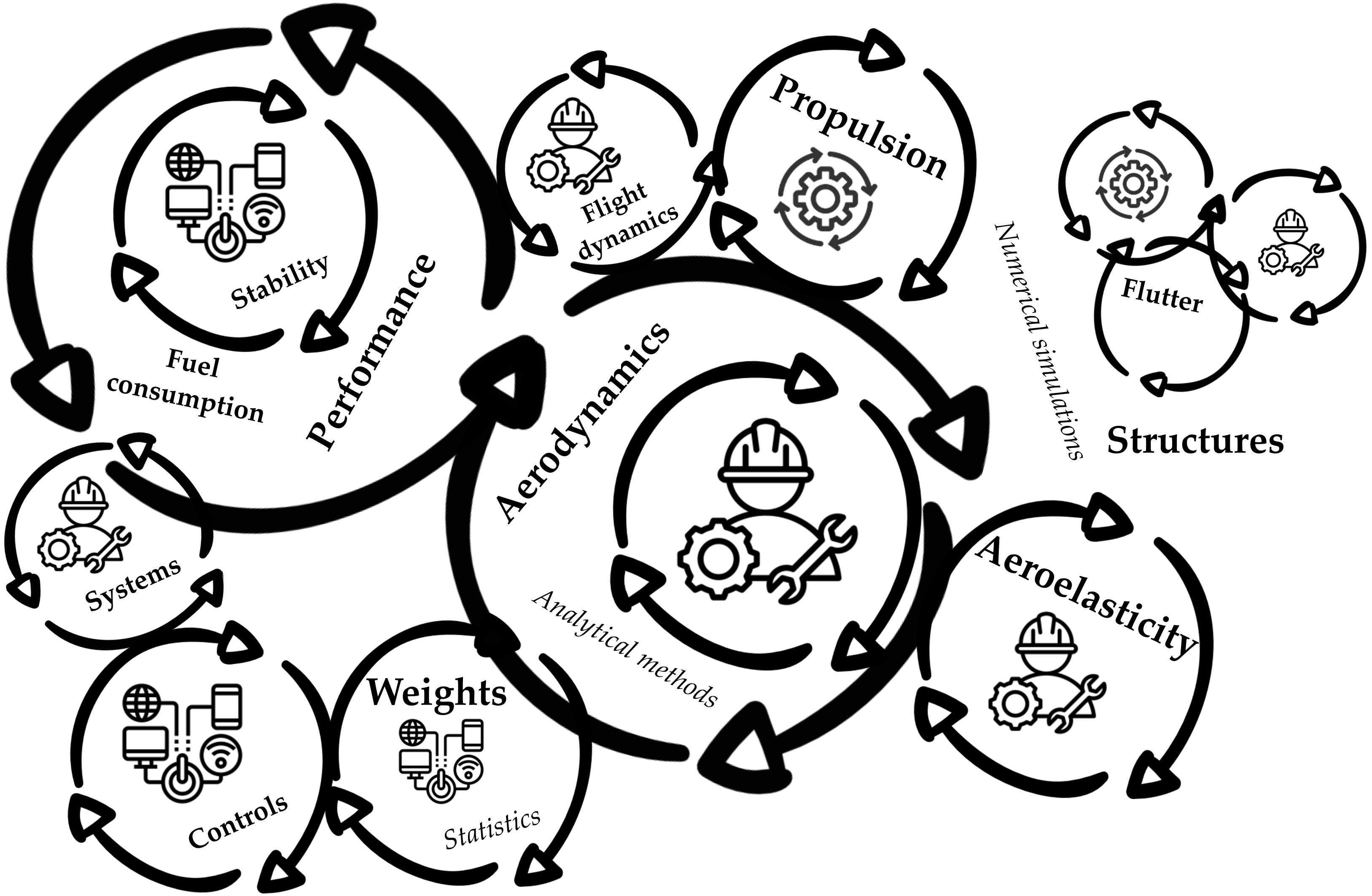
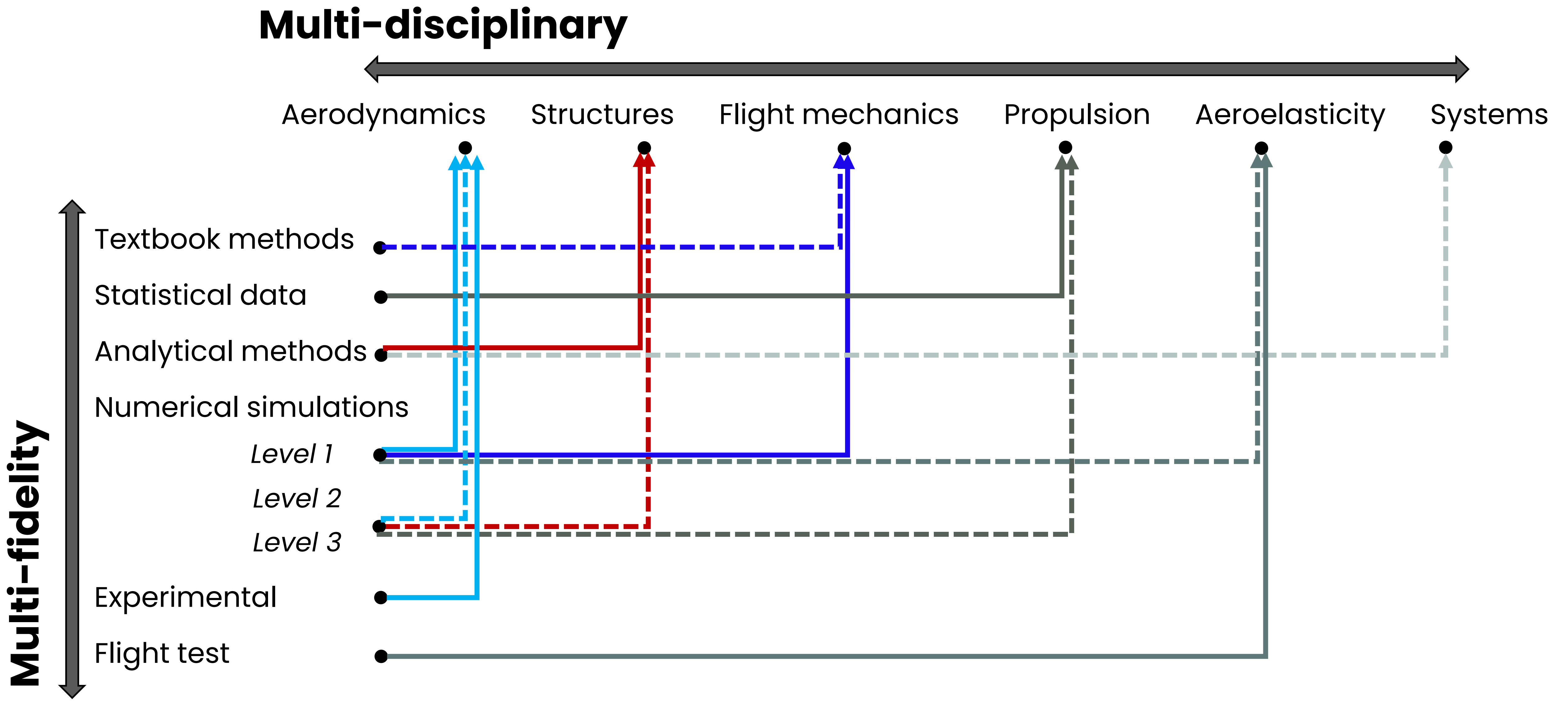
- Flight test

The Aircraft Design process



The Aircraft Design process



Lesson Topic

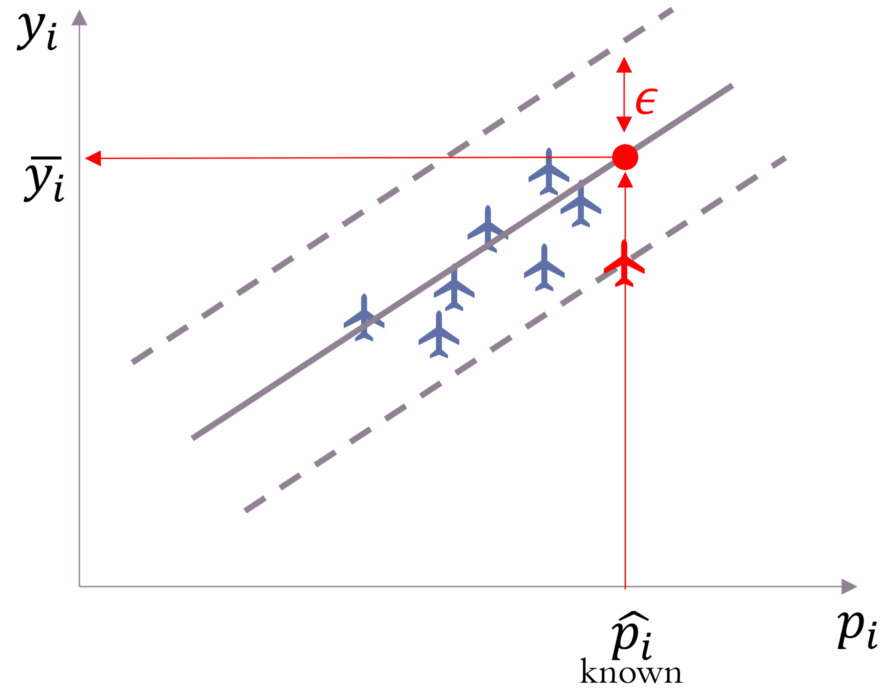
Assessment of the aircraft initial
MTOW

Guess Data Estimation

At the very beginning of the design process, it is important to understand the limits of the design space (sizing procedure), thus it is fundamental to start estimating the main design variables, such as:

- Maximum Take-Off Mass (MTOM)
- Aircraft Level Mass Breakdown (m_{OE}, m_{fuel}, etc ...)
- Thrust (T_{req})
- Wing Loading
- Lift-over-Drag

For conventional configurations, methods for Guess Data Estimation are usually based on statistical analysis. Error margins shall be duly considered.



Take-off weight

Design **Take-off mass** can be broken into different contributions including, crew, payload, structures, subsystems, etc…

$$m_{TO} = m_{crew} + m_{payload} + m_{fuel} + m_{empty}$$

m_{crew}: (known from Requirements, including regulations) **Pilots and all crew members**

$m_{payload}$: (known from Requirements, including applicable regulations) **Passengers and related equipment**

m_{fuel}: **?**

m_{empty}: **?**

This can be rewritten as follows:

$$m_{TO} = \frac{m_{crew} + m_{payload}}{1 - \underbrace{\left(\frac{m_{fuel}}{m_{TO}}\right)}_{?} - \underbrace{\left(\frac{m_{empty}}{m_{TO}}\right)}_{?}}$$

This equation can only be solved **iteratively**!

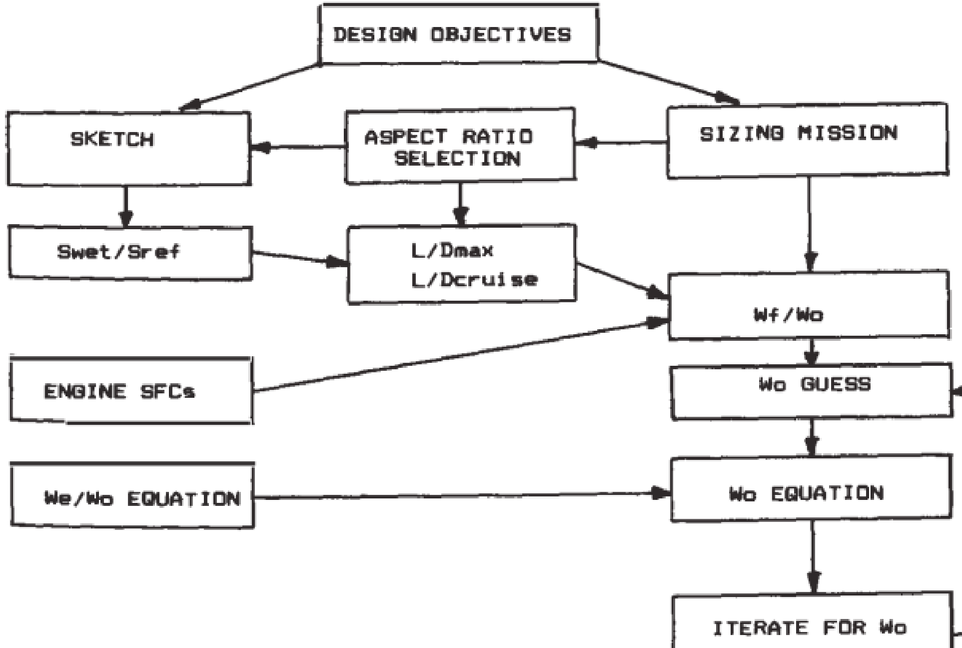


Fig. 3.7 First-order design method.

[1] Raymer, Daniel. Aircraft design: a conceptual approach. American Institute of Aeronautics and Astronautics, Inc., 2012.

Payload mass

Payload $\mathbf{m_{payload}}$ is calculated from:

1. number of seats n_{seat}
2. mass of cargo m_{cargo}

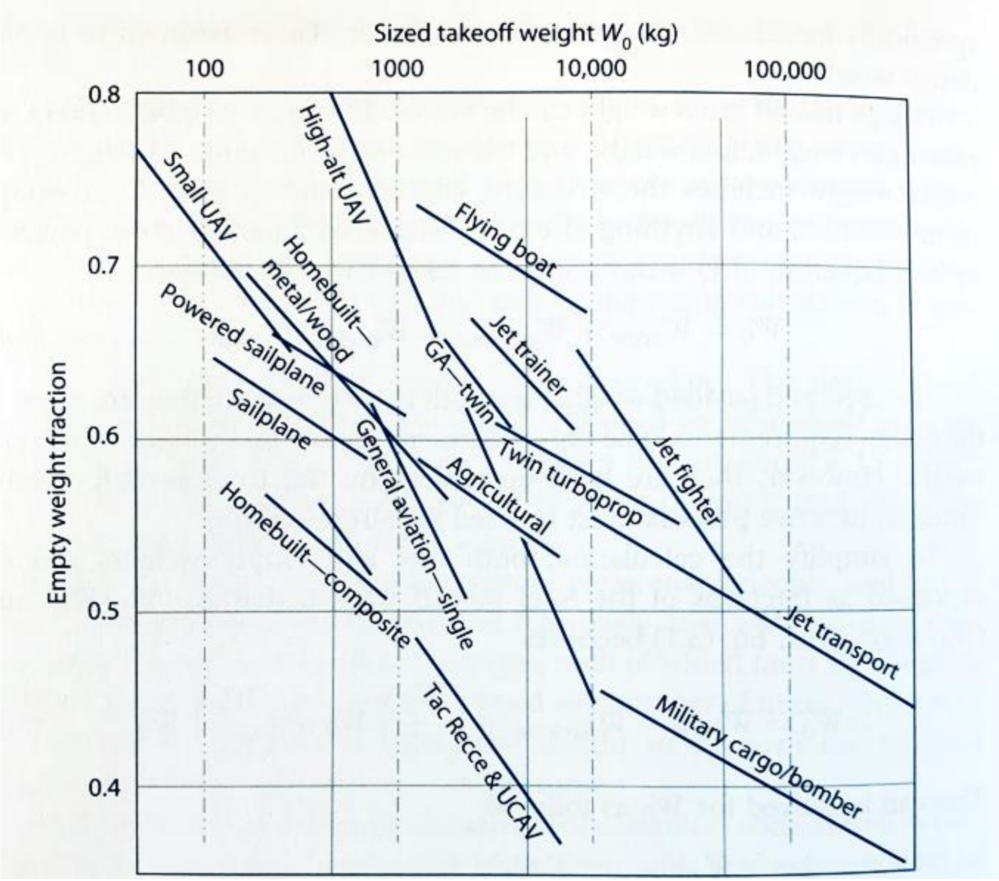
$$m_{payload} = m_{pax}\, N_{seats} + m_{baggage} N_{seats} + m_{cargo}$$

Table 3.1: Assumptions on mass of passengers und their baggage (**Roskam I**)

average mass of	**short and medium range**	**long range**
passenger, m_{PAX}	79.4 kg	79.4 kg
baggage, $m_{baggage}$	13.6 kg	18.1 kg
Sum	93.0 kg	97.5 kg

Empty mass fraction trend

$$m_{TO} = \frac{m_{crew} + m_{payload}}{1 - \left(\frac{m_{fuel}}{m_{TO}}\right) - \left(\frac{\boldsymbol{m_{empty}}}{\boldsymbol{m_{TO}}}\right)}$$



The trends can be represented by the following equation:

$$\frac{\boldsymbol{m_{empty}}}{\boldsymbol{m_{T0}}} = A\, m_{T0}^{C}$$

Table 3.1 Empty Weight Fraction vs W_0

$W_e/W_0 = AW_0^C K_{vs}$	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

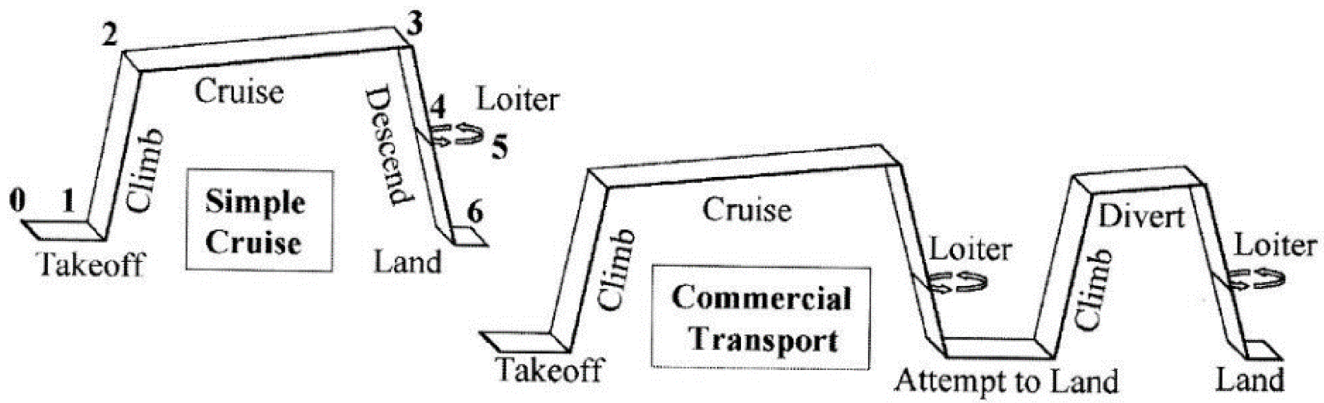
[1] Raymer, Daniel. Aircraft design: a conceptual approach. American Institute of Aeronautics and Astronautics, Inc., 2012.

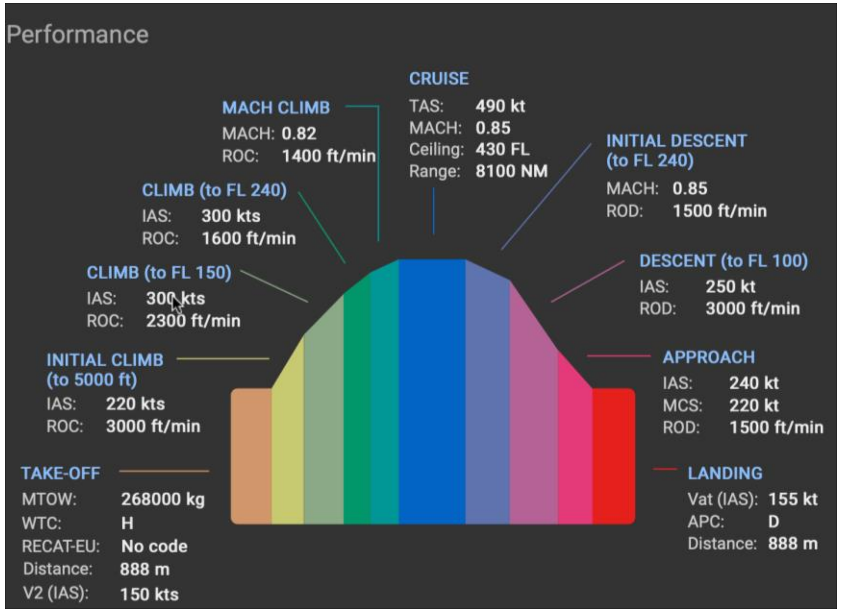
Fuel mass ratios

$$m_{TO} = \frac{m_{crew} + m_{payload}}{1 - \left(\frac{m_{fuel}}{m_{TO}}\right) - \left(\frac{m_{empty}}{m_{TO}}\right)}$$

Fuel Fraction can be estimated based on the **mission to be flown**, once an estimate of **fuel consumption** and **aerodynamic efficiency** is available

For the definition of a **Mission Profile** for commercial aircraft, various simplified models can be found out in literature. However, for a more precise estimate, real mission profiles can be used and discretized.

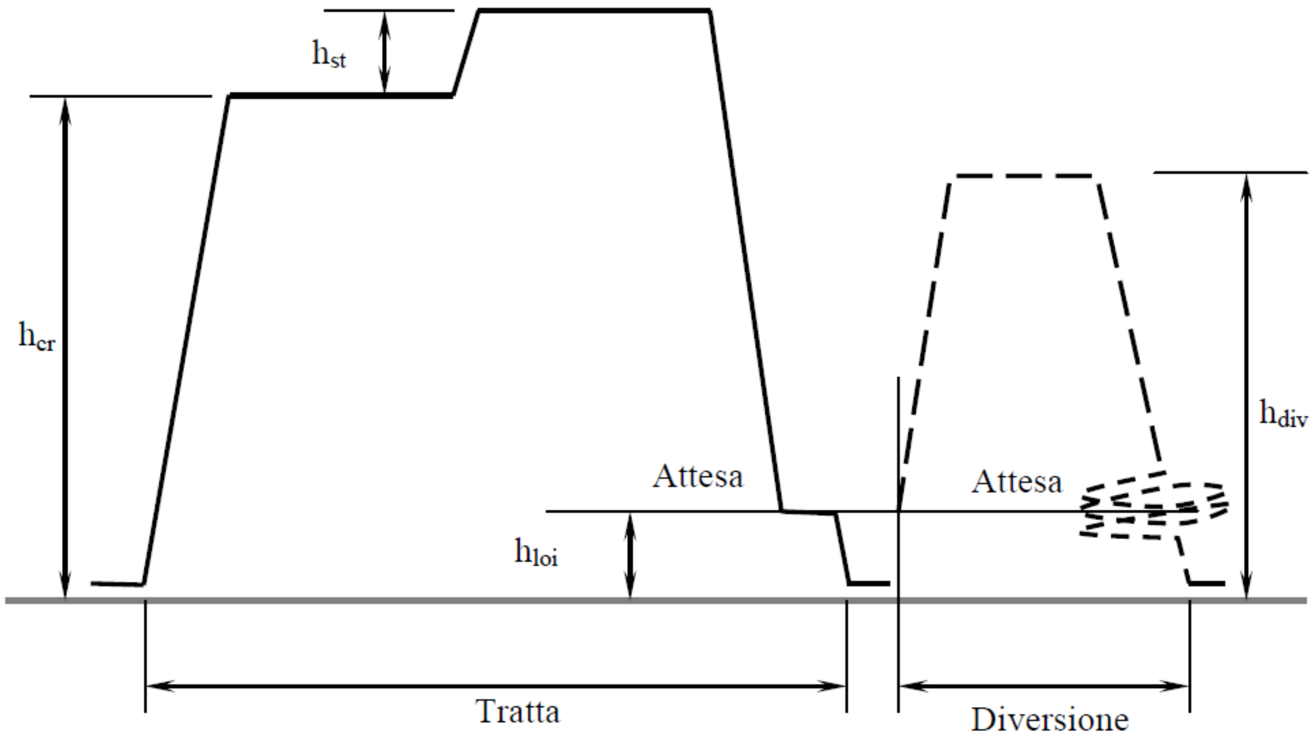




Data taken from Eurocontrol
Aircraft Performance Database
https://contentzone.eurocontrol.int/aircraftperformance

Fuel mass ratios

Definizione della missione di progetto – Esempio



Definizioni	***Lunghezza di tratta***	
SHORT-MEDIUM RANGE	< 3000 n.m.	< 5556 km.
LONG RANGE	> 3000 n.m.	> 5556 km.

Grandezza	***SHORT-MEDIUM RANGE***	***LONG RANGE***
	Missione Ordinaria	
Tratta	Da requisito	
h_{cr}	Selezionare 25000 ft $< h_{cr} <$ 35000ft	
n_{st}[1]	0-1	1-3
h_{st} (se $n_{st} > 0$)	4000 ft (possibile ridurre a 2000 ft per tratte brevi)	
h_{loi}	1500 ft.	1500 ft
Attesa[2]	8 min.	8 min.
	Riserve	
Riserve (trip fuel)[3]	5 %	5 %
Diversione[4]	200 n.m.	250 n.m.
h_{div}	30000 ft	
Attesa[5]	30 min.	30 min.
h_{loi}	1500 ft	1500 ft.

Fuel mass ratios

$$m_{TO} = \frac{m_{crew} + m_{payload}}{1 - \left(\frac{m_{fuel}}{m_{TO}}\right) - \left(\frac{m_{empty}}{m_{TO}}\right)}$$

Fuel Fraction can be estimated based on the **mission to be flown**, once an estimate of **fuel consumption** and **aerodynamic efficiency** is available

By multiplying the weight fractions, the total mission weight fraction, $\frac{m_{final}}{m_{TO}}$, can be calculated .

$$\frac{m_{final}}{m_{TO}} = \prod_{i=1}^{n} \left(\frac{m_i}{m_{i-1}}\right)$$

where n is the number of mission phases (or legs)

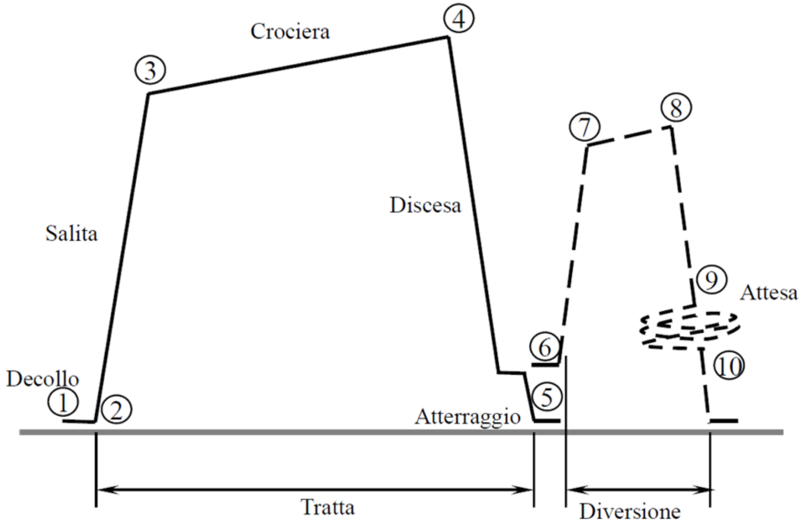
Since the simplified sizing method does not allow segments involving payload drops, all weight lost during the mission must be due to fuel usage. If we assume a typical 5% allowance for reserved and trapped fuel, the total fuel fraction can be estimated as:

$$\frac{m_{fuel}}{m_{TO}} = 1.05\left(1 - \frac{m_{final}}{m_{TO}}\right)$$

Fuel mass ratios

$$m_{TO} = \frac{m_{crew} + m_{payload}}{1 - \left(\frac{m_{fuel}}{m_{TO}}\right) - \left(\frac{m_{empty}}{m_{TO}}\right)}$$

Fuel Fraction can be estimated based on the **mission to be flown**, once an estimate of **fuel consumption** and **aerodynamic efficiency** is available



$$\left(\frac{W_2^{(i)}}{W_{TO}^{(i)}}\right) = 0.970 \qquad \left(\frac{W_7^{(i)}}{W_6^{(i)}}\right) \cong 1$$

$$\left(\frac{W_3^{(i)}}{W_2^{(i)}}\right) = 0.985 \qquad \left(\frac{W_8^{(i)}}{W_7^{(i)}}\right) = ?$$

$$\left(\frac{W_4^{(i)}}{W_3^{(i)}}\right) = ? \qquad \left(\frac{W_9^{(i)}}{W_8^{(i)}}\right) \cong 1$$

$$\left(\frac{W_5^{(i)}}{W_4^{(i)}}\right) = 0.995 \qquad \left(\frac{W_{10}^{(i)}}{W_9^{(i)}}\right) = ?$$

$W_{TO}^{(i)} \longrightarrow$

$$\boxed{\begin{gathered} \left(\frac{W_F^{(i)}}{W_{TO}^{(i)}}\right) = \left(\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right) + \left(\frac{W_{F-RIS}^{(i)}}{W_{TO}^{(i)}}\right) \\ \left(\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right) = 1 - \left(\frac{W_2^{(i)}}{W_{TO}^{(i)}}\right)\left(\frac{W_3^{(i)}}{W_2^{(i)}}\right)\left(\frac{W_4^{(i)}}{W_3^{(i)}}\right)\left(\frac{W_5^{(i)}}{W_4^{(i)}}\right) \\ \left(\frac{W_{F-RIS}^{(i)}}{W_{TO}^{(i)}}\right) = 0.05\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}} + \left(1 - \frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right)\left[1 - \left(\frac{W_7^{(i)}}{W_6^{(i)}}\right)\left(\frac{W_8^{(i)}}{W_7^{(i)}}\right)\left(\frac{W_9^{(i)}}{W_8^{(i)}}\right)\left(\frac{W_{10}^{(i)}}{W_9^{(i)}}\right)\right] \end{gathered}}$$

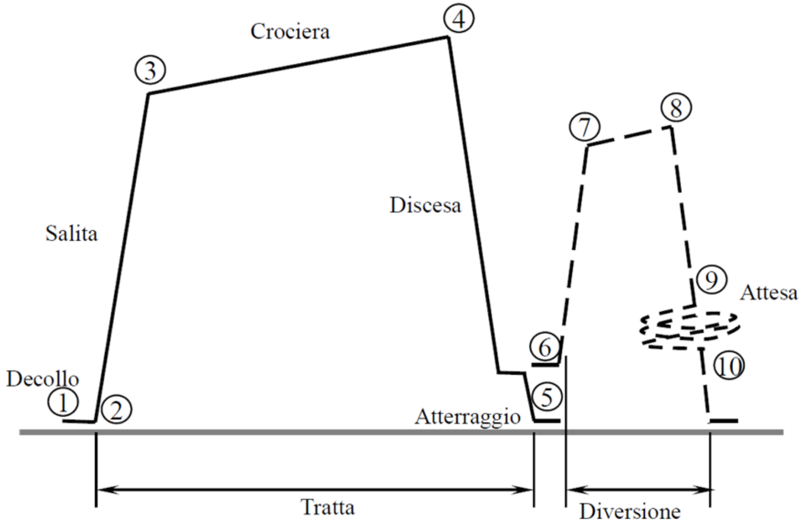
$\longrightarrow \left(\frac{W_F^{(i)}}{W_{TO}^{(i)}}\right)$

[1] Raymer, Daniel. Aircraft design: a conceptual approach. American Institute of Aeronautics and Astronautics, Inc., 2012.

Fuel mass ratios

$$m_{TO} = \frac{m_{crew} + m_{payload}}{1 - \left(\frac{m_{fuel}}{m_{TO}}\right) - \left(\frac{m_{empty}}{m_{TO}}\right)}$$

Fuel Fraction can be estimated based on the **mission to be flown**, once an estimate of **fuel consumption** and **aerodynamic efficiency** is available



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$$\left(\frac{W_5^{(i)}}{W_4^{(i)}}\right) = 0.995 \qquad \boxed{\left(\frac{W_{10}^{(i)}}{W_9^{(i)}}\right) = ?}$$

$$\frac{dx}{dW} = -\frac{V}{c \cdot T} \xrightarrow{T = D \quad L = W} \frac{dx}{dW} = -\frac{V \cdot L}{c \cdot D \cdot L} = -\frac{V \cdot E}{c \cdot W}$$

$$\boxed{\frac{dW}{W} = -\frac{c \cdot dx}{V \cdot E}}$$

Ipotesi:

$V =$ Costante Assetto Costante $\Longrightarrow$ $E =$ Costante

$$\boxed{\frac{W_{i+1}}{W_i} = e^{\frac{c \cdot \Delta x_i}{V \cdot E}}} \qquad \boxed{\frac{W_{i+1}}{W_i} = e^{-\frac{C \Delta t}{E}}}$$

Autonomia chilometrica Autonomia oraria

$$W_{TO}^{(i)} \longrightarrow$$

$$\left(\frac{W_F^{(i)}}{W_{TO}^{(i)}}\right) = \left(\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right) + \left(\frac{W_{F-RIS}^{(i)}}{W_{TO}^{(i)}}\right)$$

$$\left(\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right) = 1 - \left(\frac{W_2^{(i)}}{W_{TO}^{(i)}}\right)\left(\frac{W_3^{(i)}}{W_2^{(i)}}\right)\left(\frac{W_4^{(i)}}{W_3^{(i)}}\right)\left(\frac{W_5^{(i)}}{W_4^{(i)}}\right)$$

$$\left(\frac{W_{F-RIS}^{(i)}}{W_{TO}^{(i)}}\right) = 0.05\frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}} + \left(1 - \frac{W_{F-MIS}^{(i)}}{W_{TO}^{(i)}}\right)\left[1 - \left(\frac{W_7^{(i)}}{W_6^{(i)}}\right)\left(\frac{W_8^{(i)}}{W_7^{(i)}}\right)\left(\frac{W_9^{(i)}}{W_8^{(i)}}\right)\left(\frac{W_{10}^{(i)}}{W_9^{(i)}}\right)\right]$$

$$\longrightarrow \left(\frac{W_F^{(i)}}{W_{TO}^{(i)}}\right) \longrightarrow$$

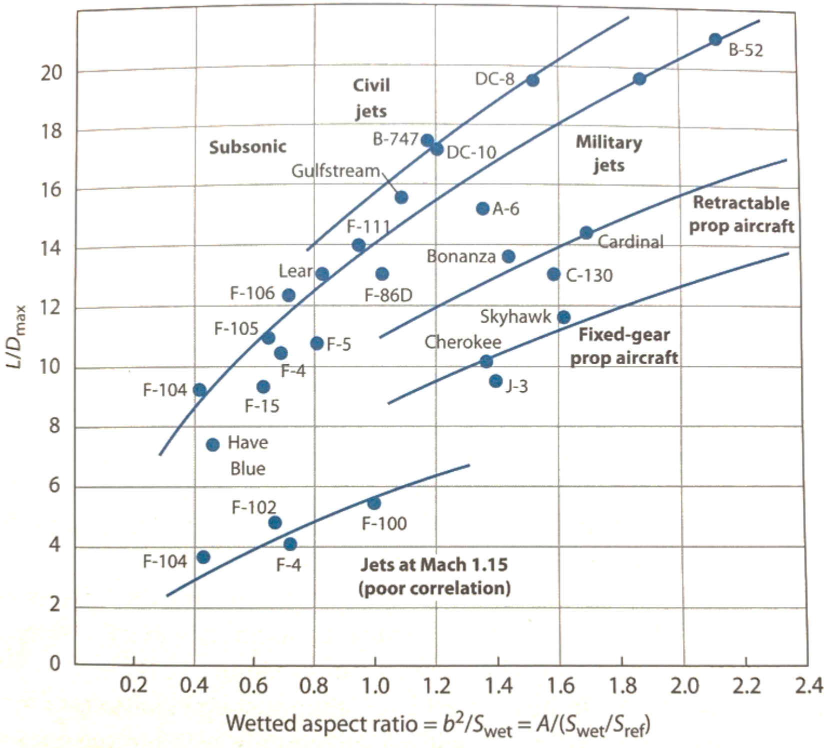
[1] Raymer, Daniel. Aircraft design: a conceptual approach. American Institute of Aeronautics and Astronautics, Inc., 2012.

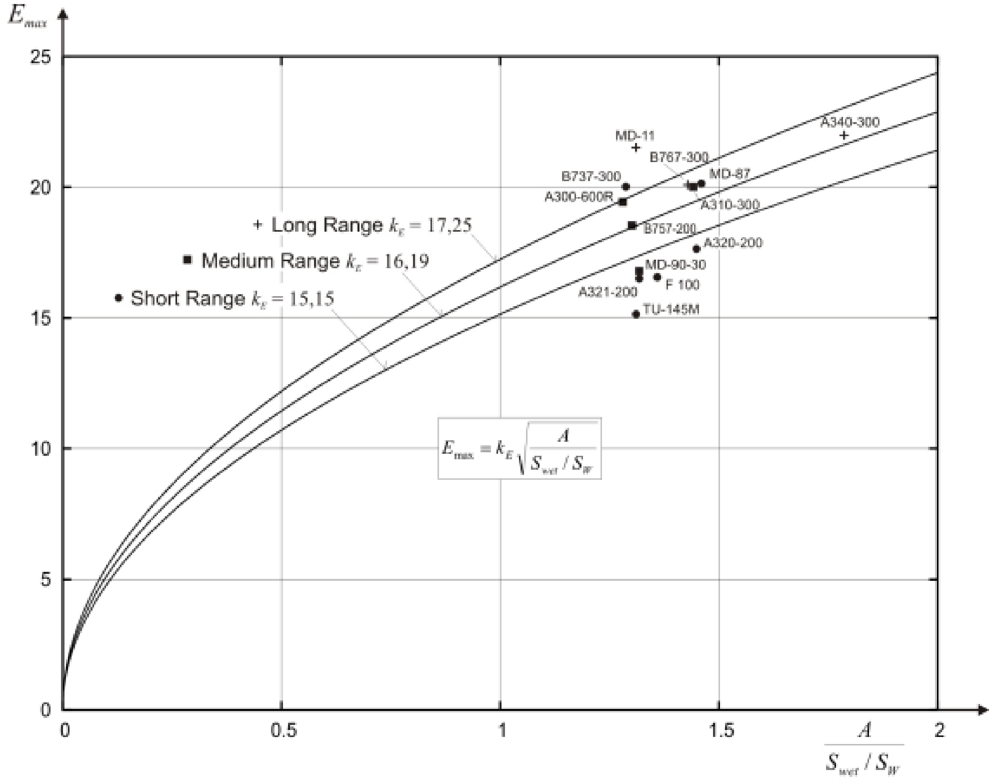
Maximum L/D

$$\left(\frac{L}{D}\right)_{max} = k_E\sqrt{AR_w}$$

Where

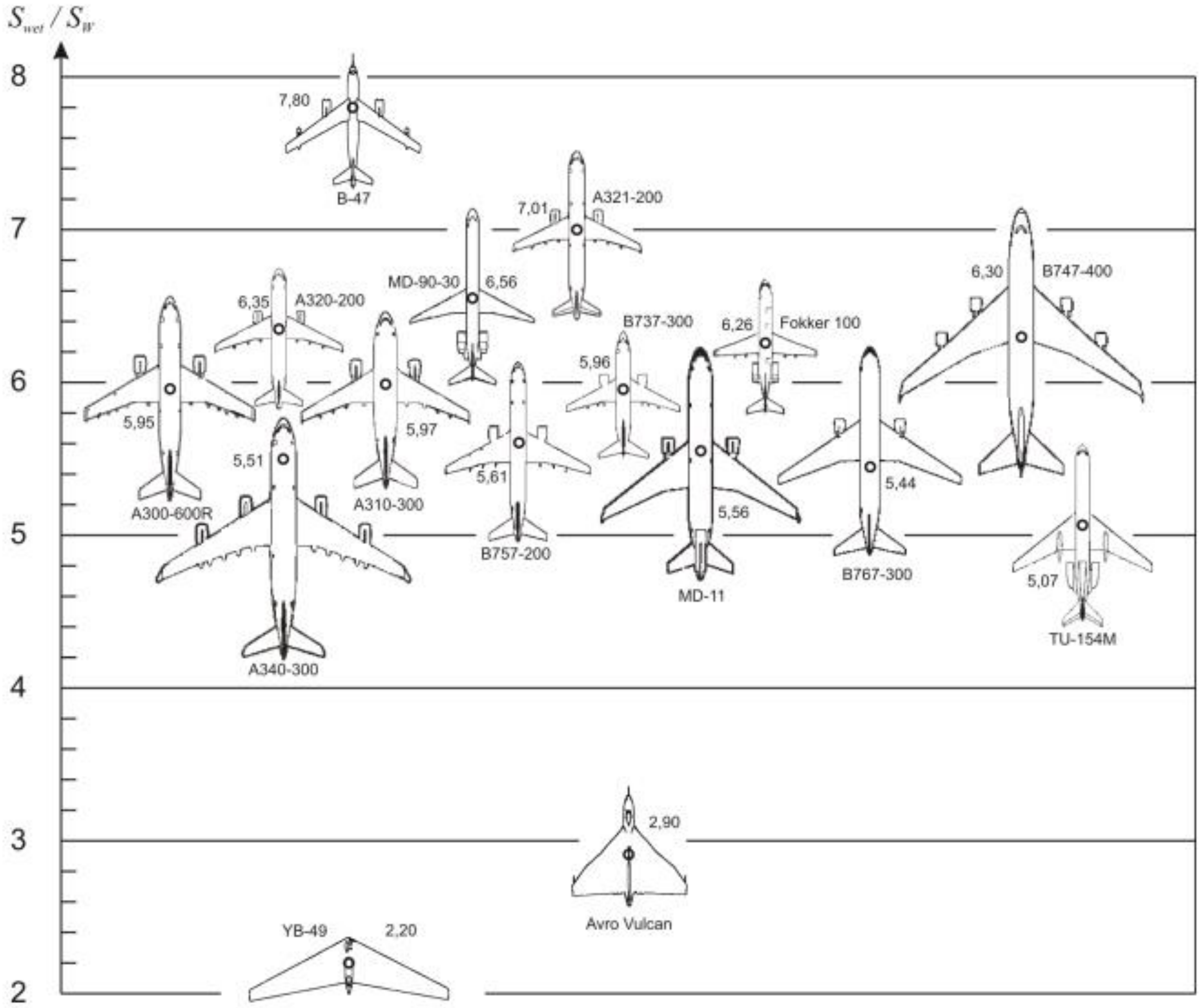
- k_E has different values depending upon the type of aircraft (e.g. 15.5 for civil jets,…)
- $AR_w = \frac{\mathrm{AR}}{\frac{S_{wet}}{S_{ref}}}$





	Cruise	Loiter
Jet	$0.866\ L/D_{max}$	L/D_{max}
Prop	L/D_{max}	$0.866\ L/D_{max}$

S_{wet}/S_W



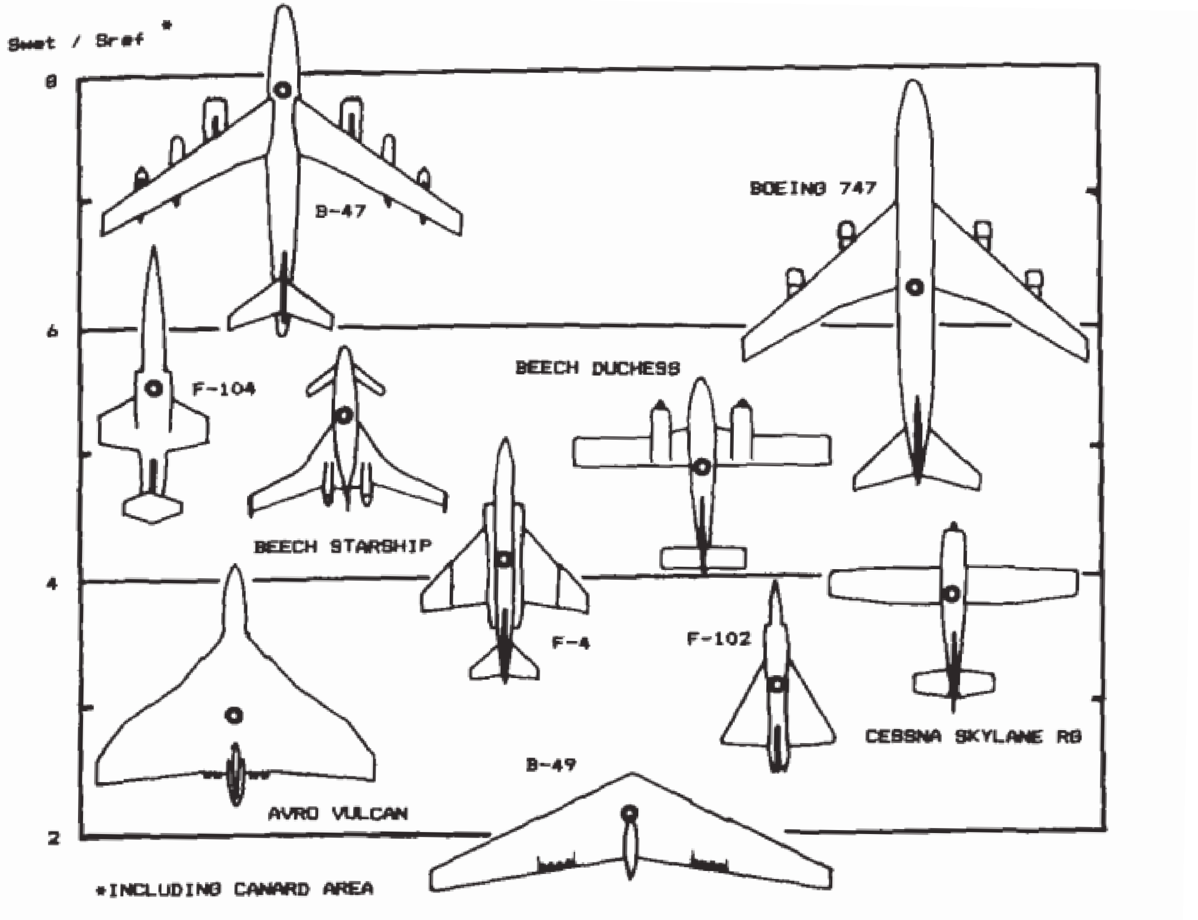
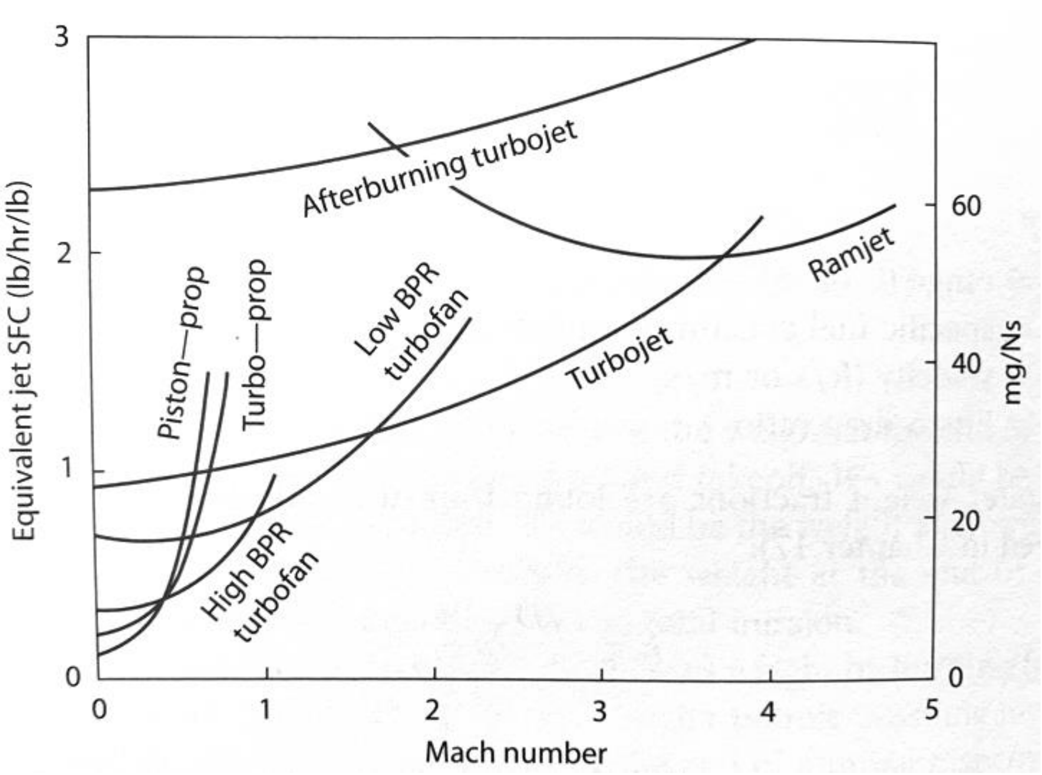


Fig. 3.5 Wetted area ratios.

Specific fuel consumption

$$m_{TO} = \frac{m_{crew} + m_{payload}}{1 - \left(\frac{m_{fuel}}{m_{TO}}\right) - \left(\frac{m_{empty}}{m_{TO}}\right)}$$

Fuel Fraction can be estimated based on the **mission to be flown**, once an estimate of **fuel consumption** and **aerodynamic efficiency** is available



Typical Values for subsonic jet aircraft are reported hereafter

Table 3.3 Specific fuel consumption (C)

Typical jet SFC's	Cruise	Loiter
Pure turbo jet	0.9	0.8
Low bypass turbofan	0.8	0.7
High-bypass turbofan	0.5	0.4

Unit [1/h]

TSFC or SFC for thrust engines is the mass of fuel needed to provide the net thrust for a given period.

Iterative solution

Tentative $\mathrm{m_{TO}}$

$$m_{payload} = m_{pax}\, N_{seats} + m_{baggage} N_{seats} + m_{cargo}$$

$$\frac{m_{fuel}}{m_{TO}} = 1.05\left(1 - \frac{m_{final}}{m_{TO}}\right)$$

$$\frac{m_e}{m_{TO}} = A\, m_{TO}^{C}$$

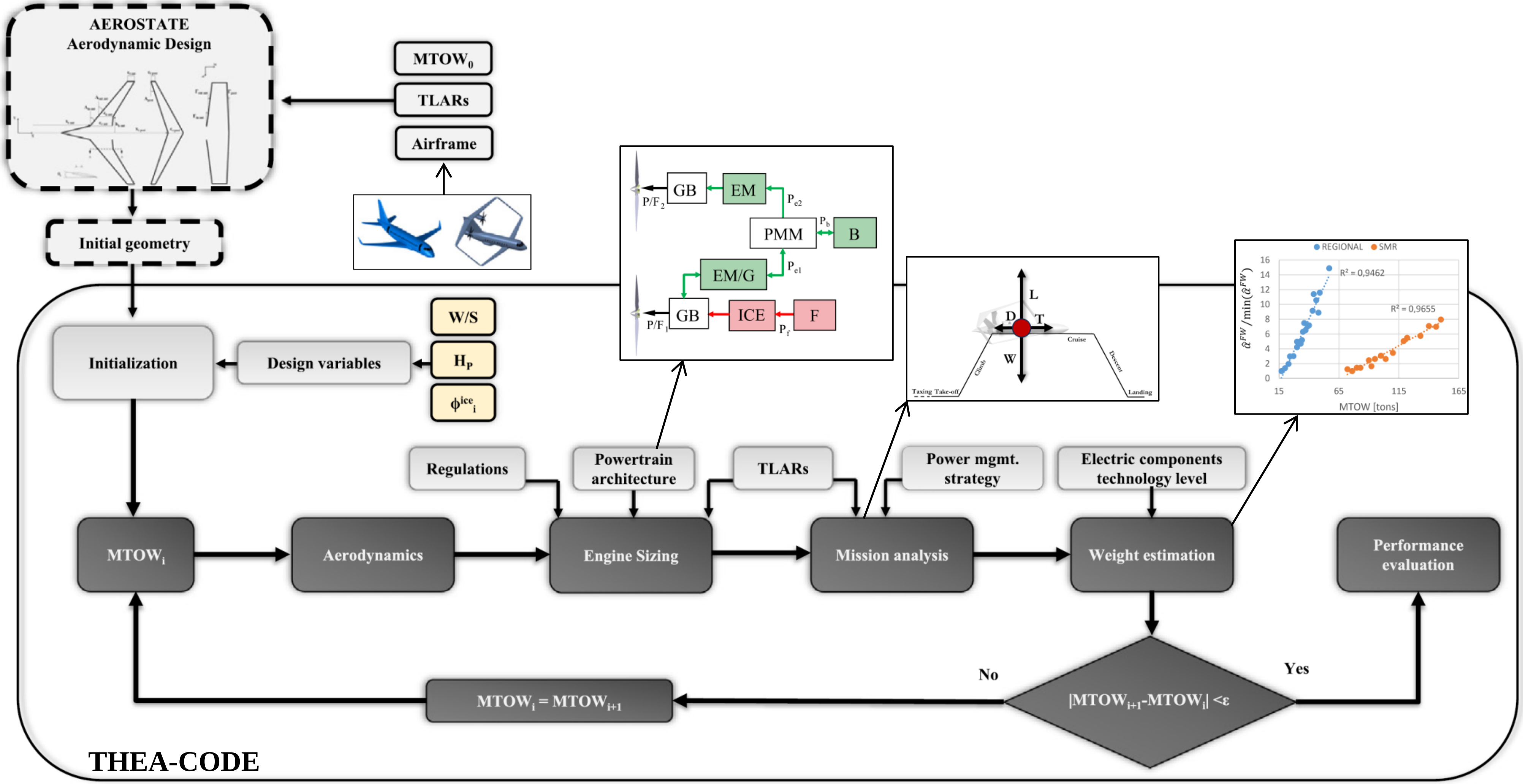
$$\boldsymbol{m_{TO}} = \frac{m_{crew} + m_{payload}}{1 - \left(\frac{m_{fuel}}{m_{TO}}\right) - \left(\frac{m_{empty}}{m_{TO}}\right)}$$

If $\mathrm{m_{TO}}$ -$\boldsymbol{m_{TO}}$ < toll

If $\mathrm{m_{TO}}$ -$\boldsymbol{m_{TO}}$ > toll

$$\boldsymbol{m_{TO}}$$

Iterative solution



Task 2.1

On the basis of the formulation presented, estimate the take-off mass of the aircraft. Perform a trade-off analysis considering different ranges, payload and performances (sfc, L/D).