Progettazione di veicoli aerospaziali (AA-LZ)

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Lecture series:

Conceptual Design of subsonic commercial aircraft

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Lesson 1: Introduction to Conceptual Design and Initial Guess Estimation

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1.1

Introduction to the Lecture Series on Conceptual Design of subsonic commercial airplanes

Main Goals

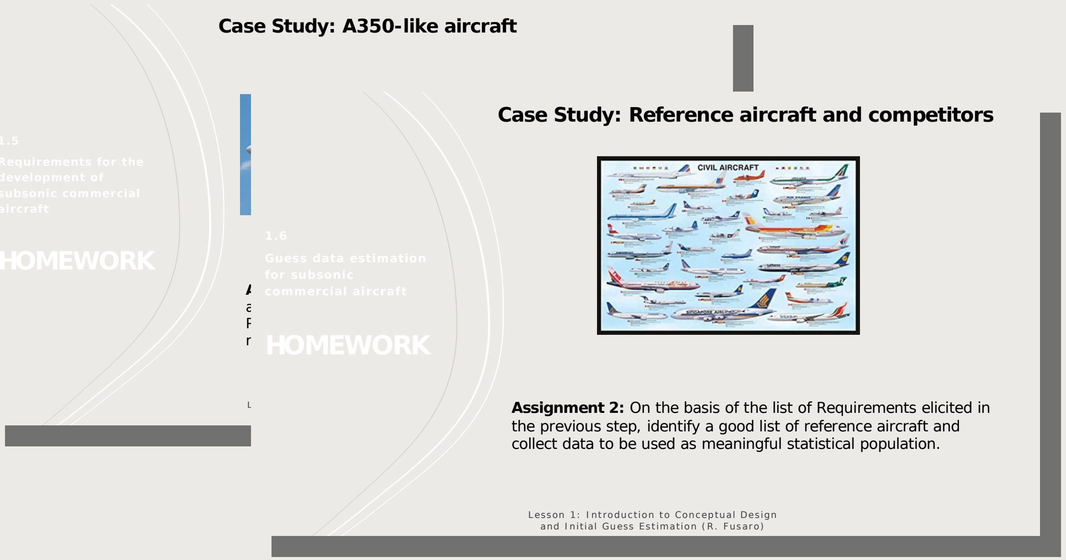
- To understand the importance of Conceptual Design among the design and development phases of an aircraft.
- To acquire knowledge about the most up-to-date methodologies for Conceptual Design of aircraft
- To understand the most influential factors on the Conceptual Design of a modern commercial aircraft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

1.1

Introduction to the Lecture Series on Conceptual Design of subsonic commercial airplanes

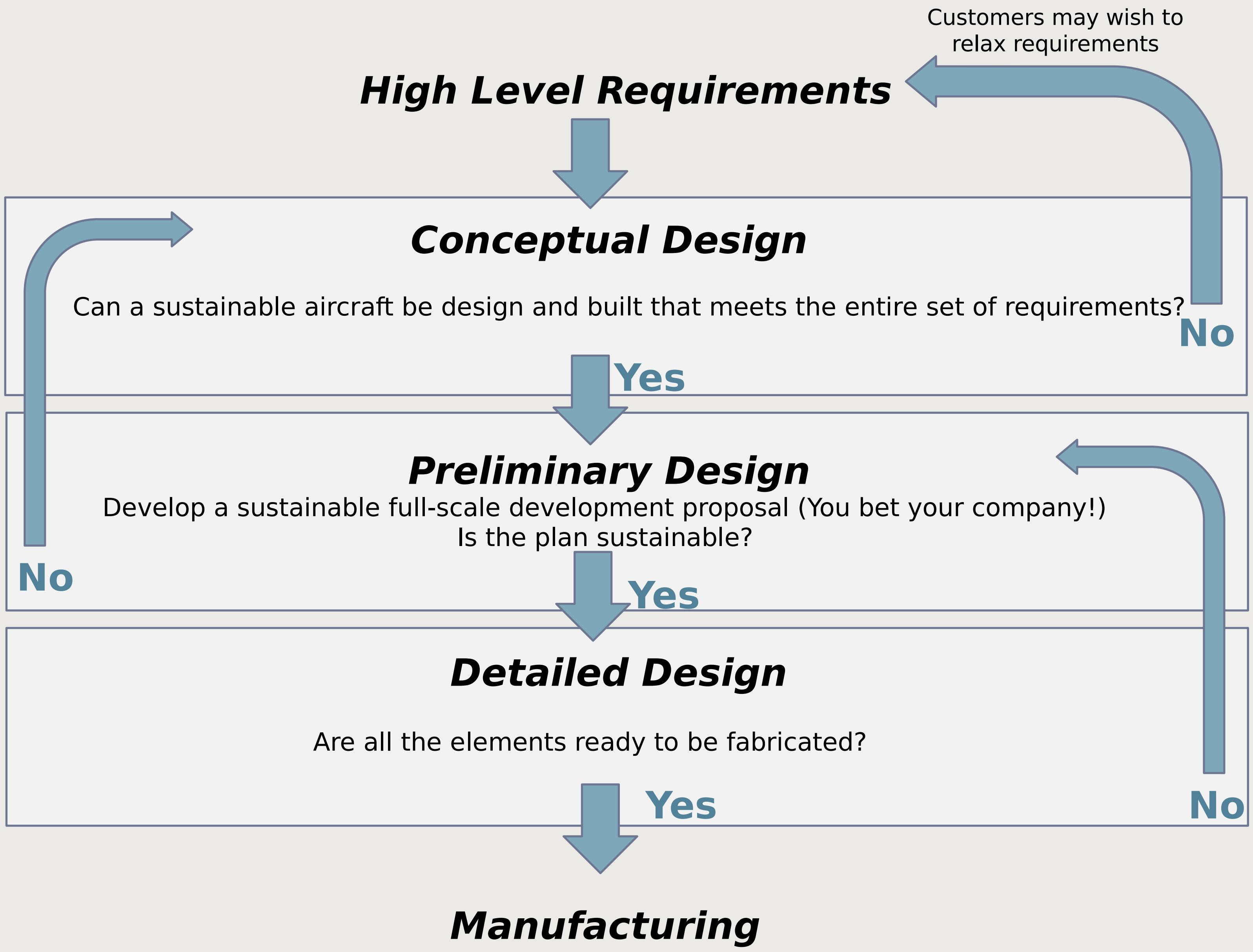
Exam

- Individual Summary Report on the application of the conceptual design methodology for commercial airplanes taught throughout this Lecture Series to a case study.
- The content of the Report will be specified all along the Lectures, with specific requests marked as "Homework"
- The individual report shall be delivered as a .pdf containing as hyperlinks, all supplementary materials (Excel files, Matlab codes, CAD models, etc…)



1.2

Conceptual Design among the Aircraft Design phases



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

Conceptual Design Phase

1.2

Conceptual Design among the Aircraft Design phases

During the Conceptual Design Phase, conventional and novel configurations are considered to suggest **aircraft concepts which shall be technically feasible and commercially viable**.

At the end of the Conceptual Design Phase, a knowledge of the feasibility for a certain number of concepts is expected, supported by a first estimates in terms of size and performance. These first estimates are important to support the selection process, performed through “trade-off” studies, having as final goal the identification of the most suitable configuration.

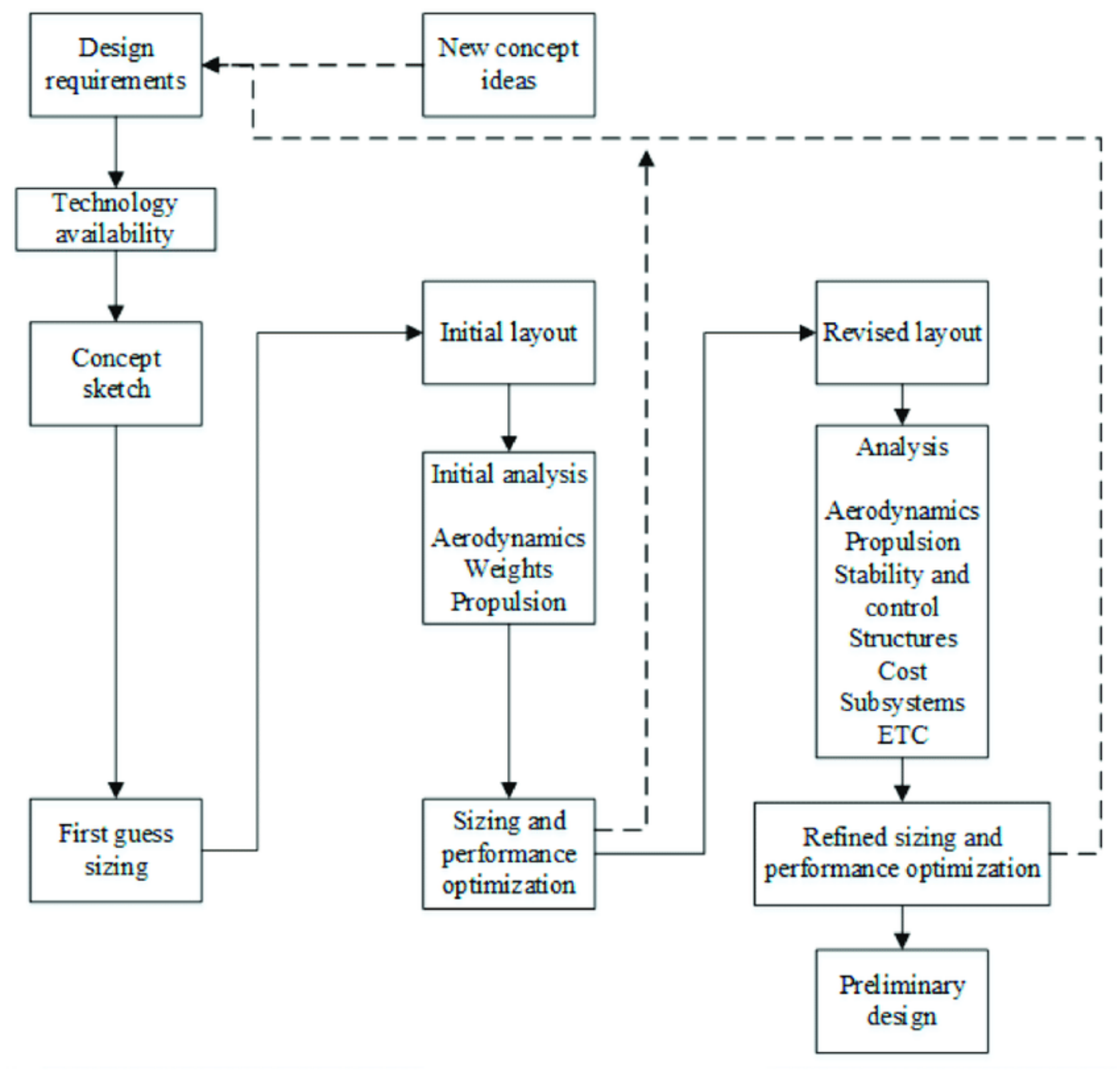
For **conventional layouts** (e.g. development of an evolution of an already existing aircraft or development of a classical layout aircraft), the analysis of reference aircraft and experience from previous design cycles may shorten the conceptual design stage, reducing the number of iterations necessary to converge towards a feasible solution.

For **novel layouts,** statistical analysis and other methods based on already existing aircraft data can only be used to derive first guess data estimation. Novel methodologies and tools shall be developed to support the design of these novel concepts, leading to longer Conceptual Design Phases. Technical, technological and commercial risks have to be duly taken into account.

Aircraft Conceptual Design Process

1.2

Conceptual Design among the Aircraft Design phases



1.2

Conceptual Design among the Aircraft Design phases

Preliminary Design Phase

The best option(s) resulting from the Conceptual Design Phase is subjected to a more rigorous technical analysis. The objective of this phase is to find the best ('optimum') geometry for the aircraft with respect to the list of requirements.
Preliminary Design Phase begins when the major changes are over and specialists in the various disciplines have a sufficient number of elements to start the detailed analysis. During a Preliminary Design Phase, sensitivity analyses are carried out and testing is initiated with the need to develop mock-ups.

Detailed Design Phase

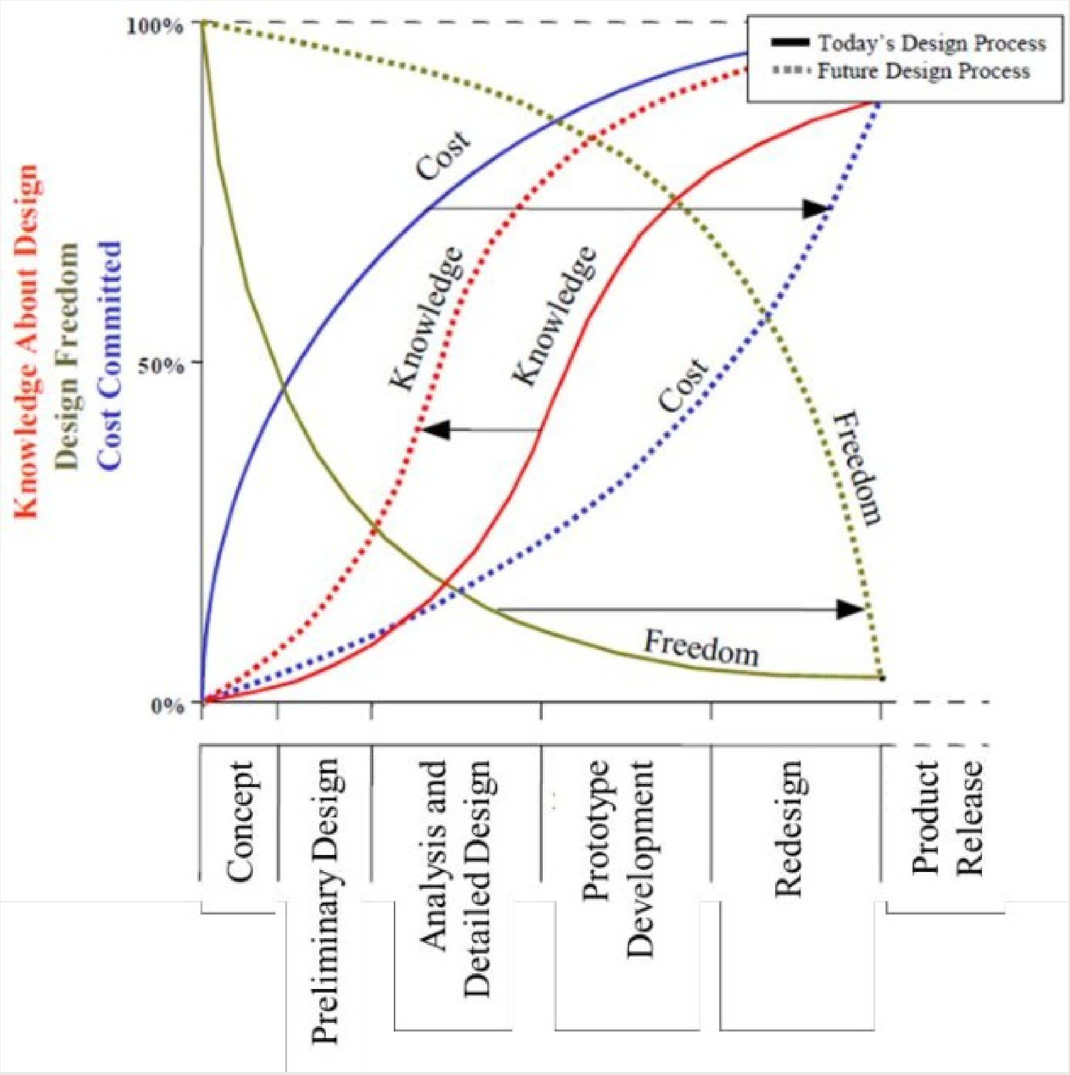
During the Detailed Design Phase, the layout is refined to a greater level of detail. With the external shape fixed, the structural framework is defined. In areas of doubt, finer calculations are performed and validated by component tests. Throughout this phase the aircraft weight and performance estimates are continuously updated as more details of the aircraft layout become available. At the end of this phase the aircraft is 'released for production'

The Paradigm Shift in Aircraft Conceptual Design

1.2

Conceptual Design among the Aircraft Design phases

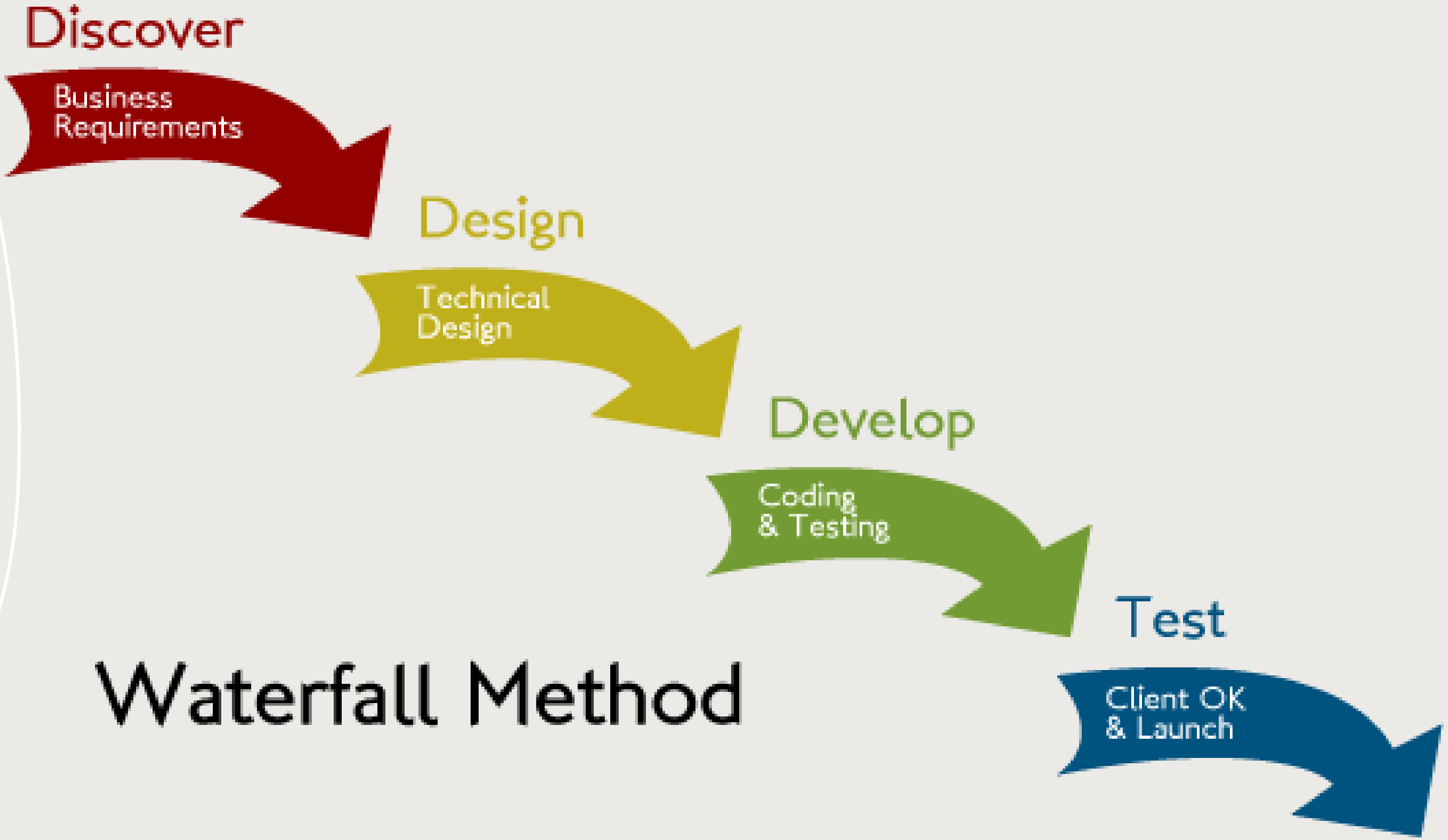
From the industrial standpoint, an urgent need to **reduce the costs committed during the very early design stages** and to **increase the resilience** of the aircraft project, moving as forward as possible the design points.



Traditional Conceptual Design Methodologie

1.3

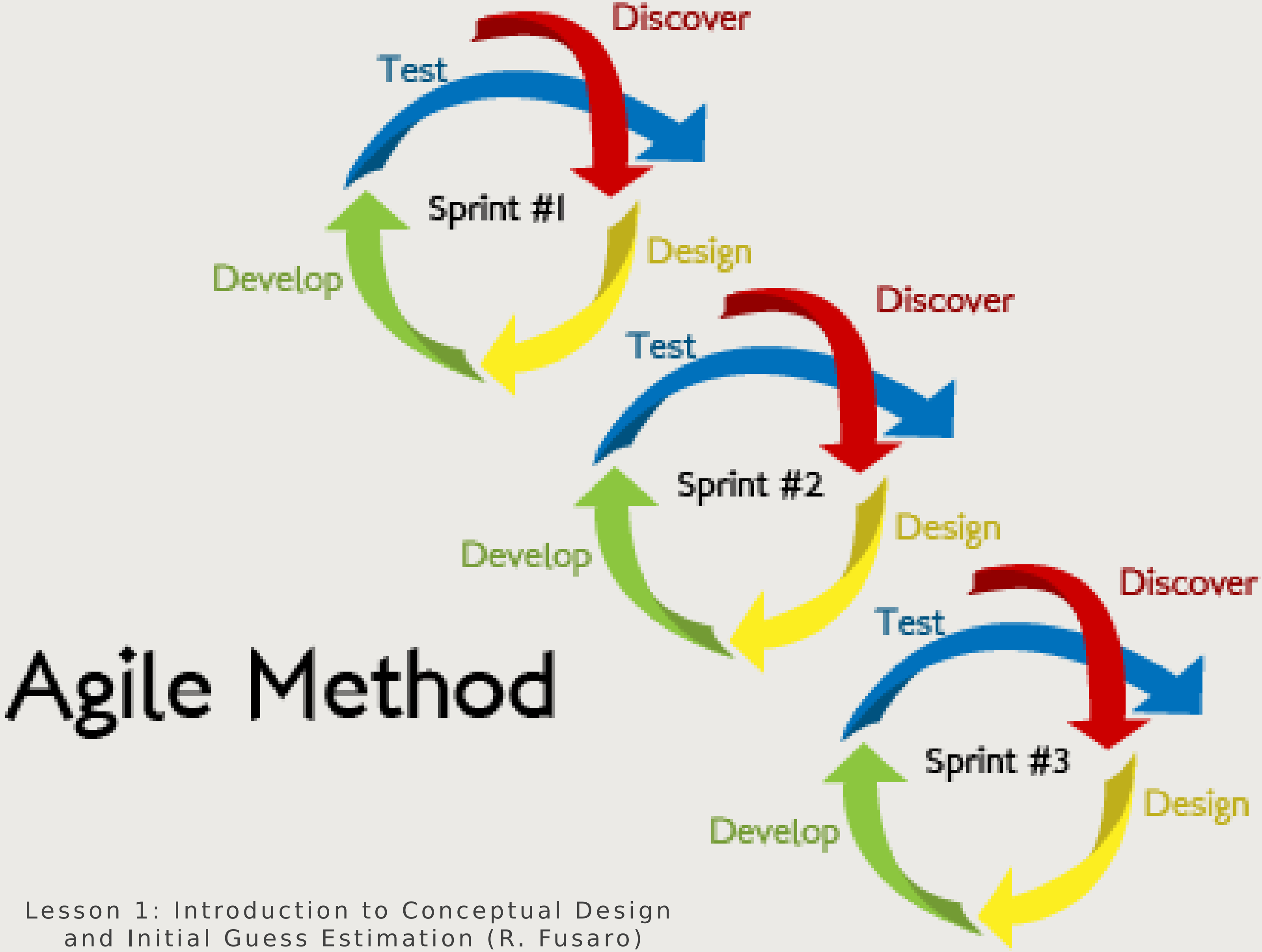
Most recent methodologies for commercial aircraft conceptual design



Innovative Conceptual Design Methodologie

1.3

Most recent methodologies for commercial aircraft conceptual design



1.4

Mathematical formalization of the Conceptual Design Problem

The Conceptual Design Problem: How does it start?

Experts involved into an aircraft design process can never quite agree on which is the entry point of the Design Wheel.

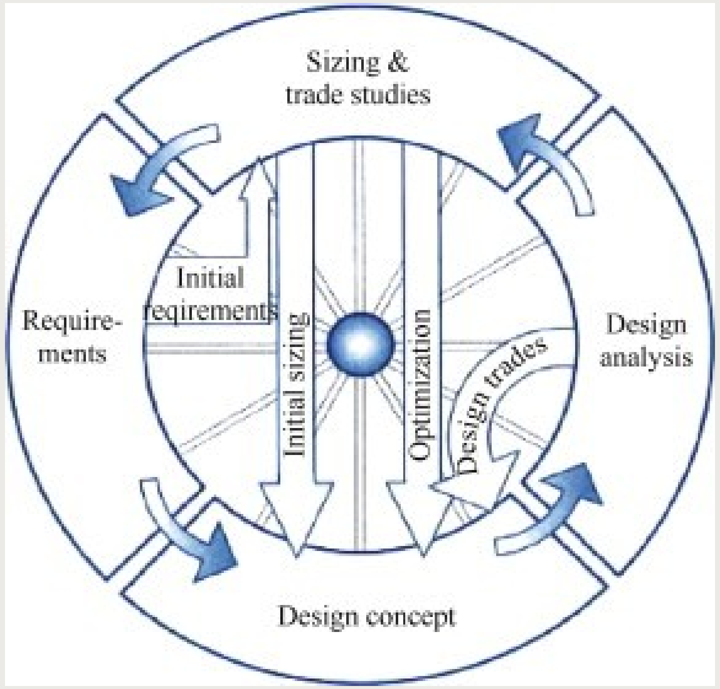
> **Designer**: ”the conceptual design starts with a new airplane concept, i.e., with a sketch!”

> **Sizing Specialists**: ”Nothing can begin until first guess data are made, and especially, before MTOM is estimated ”

But ... Who does really stand at the beginning of the design process? Neither Designers, nor specialists, but *stakeholders!*

> **Stakeholders***:* “The design of a new product of a re-design of an existing one generates from requirements”

Civilian and Military Markets have very different approaches, which can be simplified as “make money” and “win the war” respectively.



Design Wheel [1]

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

1.4

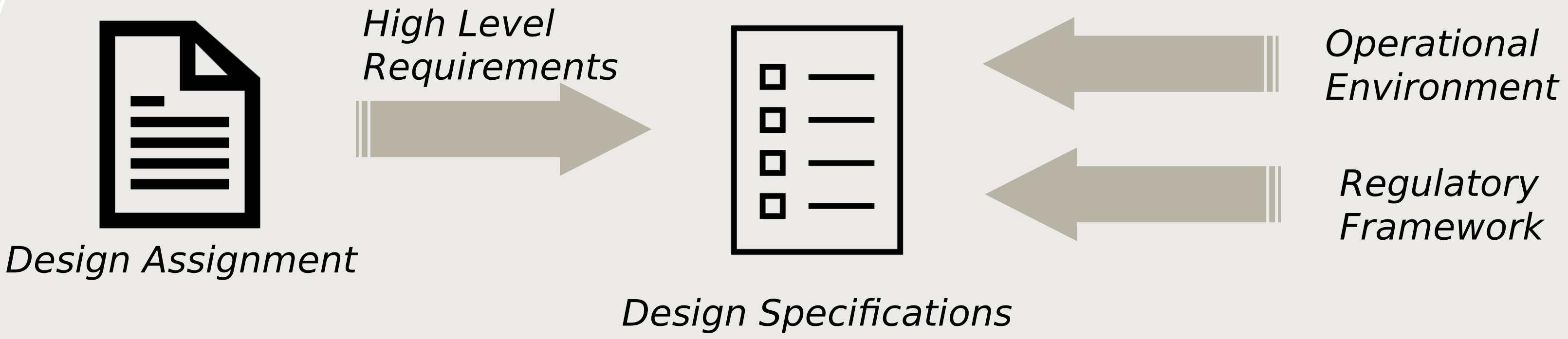
Mathematical formalization of the Conceptual Design Problem

The Conceptual Design Problem

Origin of the Conceptual Design Problem

A Conceptual Design Problem always originates from a *Design Topic* (or assignment), which can be duly expressed through a set of *High Level Requirements*. The set of High Level Requirements usually consists of a list of aircraft performance (e.g. maximum speed, kilometric range, etc...) and a list of aircraft characteristics (e.g. payload mass, fuselage length, wingspan, etc...).

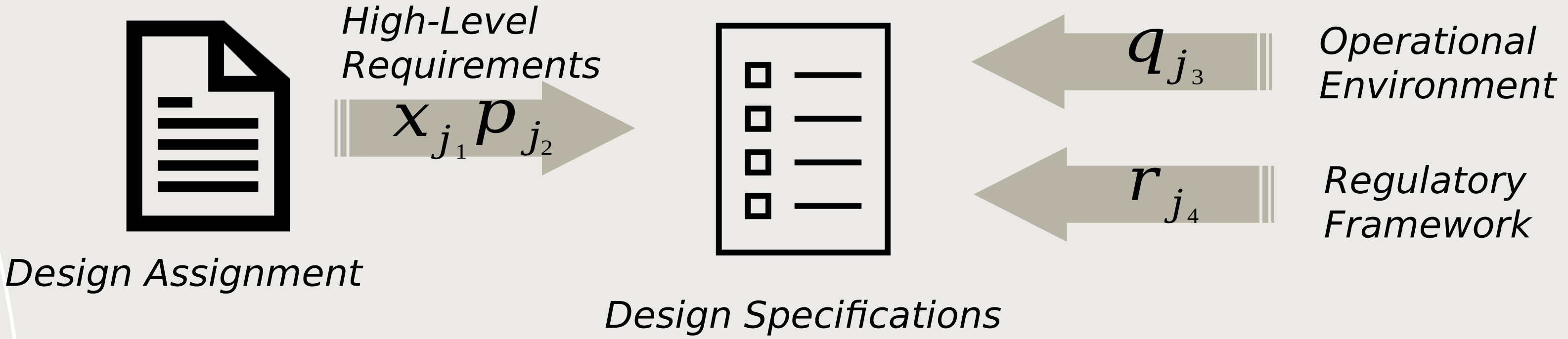
This preliminary list of requirements shall be complemented by a set of requirements and constraints coming from the analysis of the foreseen *operational environment* and of the applicable *regulatory and certification framework*.



1.4

Mathematical formalization of the Conceptual Design Problem

The Conceptual Design Problem



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

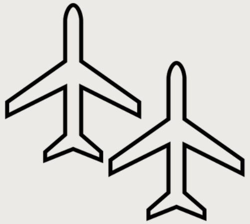
Where

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

Reference Material:
[1] Antona, E. "Fondamenti teorici dell’avamprogetto degli aeromobili." Memorie della Accademia delle Scienze di Torino, Classe di Scienze Fisiche Matematiche e Naturali 31 (2007): 147-170.
[2] NASA systems Engineering Handbook

Origin of the Design Topic and of the Design Specifications

Stakeholders → *High-level performance and design parameters* ← **Competitors**



Mission Analysis → *Operational Requirements* ← **Concept of Operations**

Analysis of Applicable Regulations → *Constraints from Regulatory Framework*

Sustainable aviation!

High Level Requirements for Passenger Aircraft

1.5

Requirements for the development of subsonic commercial aircraft

Where

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

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

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

Set of Operational Requirements

Set of constraints from Regulatory Framework

VIDEO with new AIRBUS commercial planes

New Requirements for new aircraft configurations

Case Study: A350-like aircraft

1.5

Requirements for the development of subsonic commercial aircraft

HOMEWORK

2 pilots
440 passengers
Fuselage length < 70 m
Cruise Mach number 0.85
……

Assignment 1: To write down an initial list of requirements for an aircraft that shall replace A350, with an entry into service in 2030. Please, while listing the requirements, refer to the categories reported in Sect.1.4

1.6

Guess data estimation for subsonic commercial aircraft

Design Problem

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

Origin of the design process

$$f_n\left(y_k, HR\right) = 0$$

$$Unknown\ variables$$

Goal of the design process

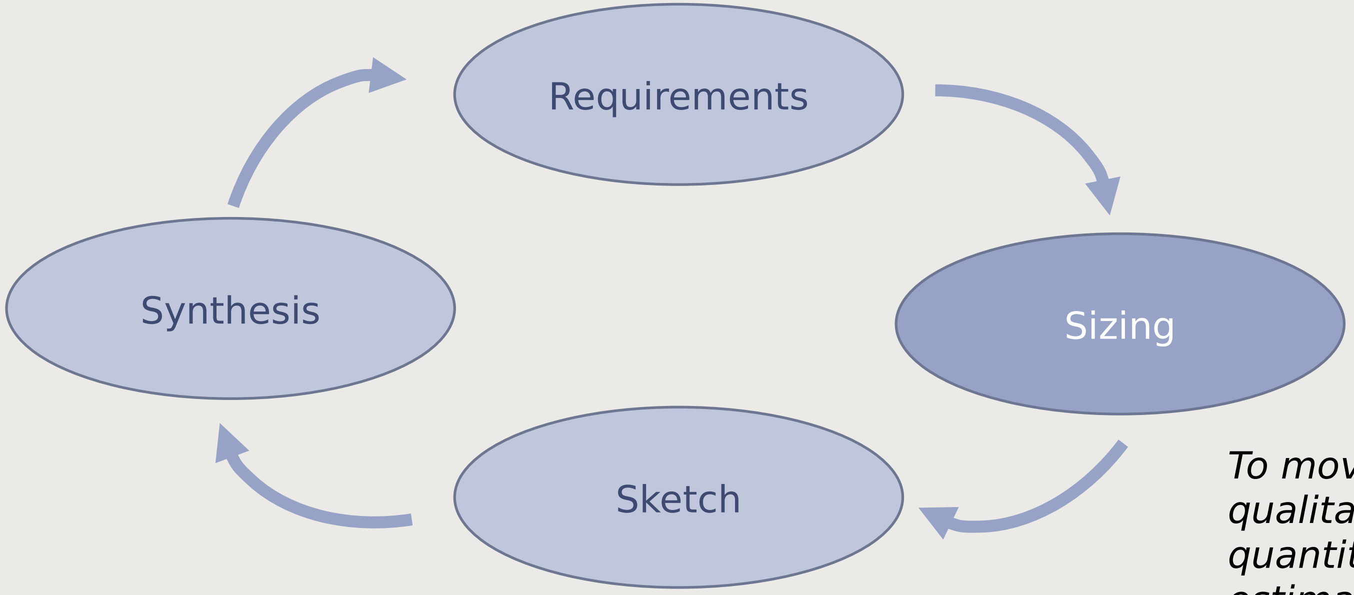
The design problem can be formalized through a set of equations . The problem is properly structured only if the number of equations is equal or higher than the number of unknown variables.

Please, notice that during Conceptual Design, usually, there are a multiplicity of possible solutions. Therefore, the main goal of the Conceptual Design phase is to identify all possible solutions and select the bet one(s)

1.6

Guess data estimation for subsonic commercial aircraft

Design Problem



To move from qualitative data to quantitative estimations

Conceptual Design Process

Highly Iterative
Highly Multidisciplinary

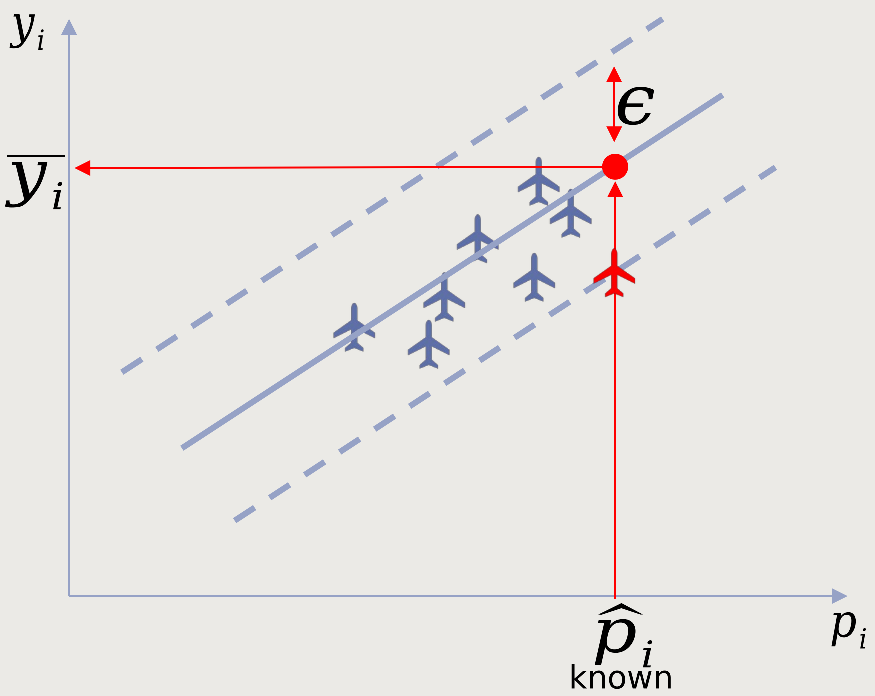
Guess Data Estimation

1.6

Guess data estimation for subsonic commercial aircraft

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 ()
- ✓ Thrust ()
- ✓ 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.

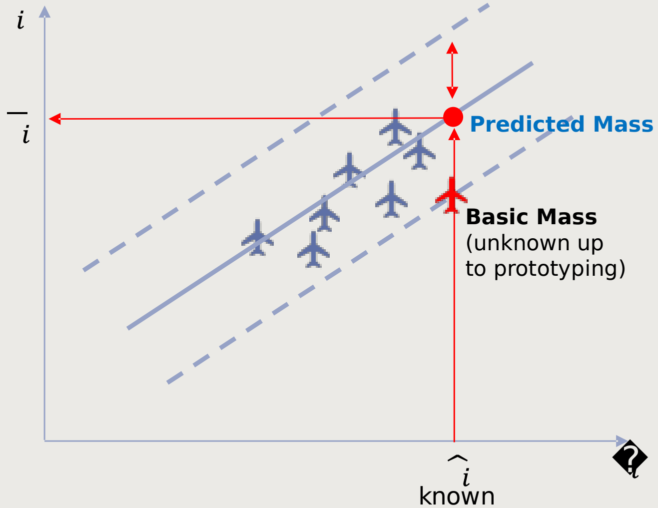
Guess Data Estimation: Uncertainties and Margin Philosophy

1.6

Guess data estimation for subsonic commercial aircraft

Allowable Mass is the requirement set by the customers. It is limit against which mass margins are calculated. Please notice that this requirement already contains a Margin, called “Reserve”.

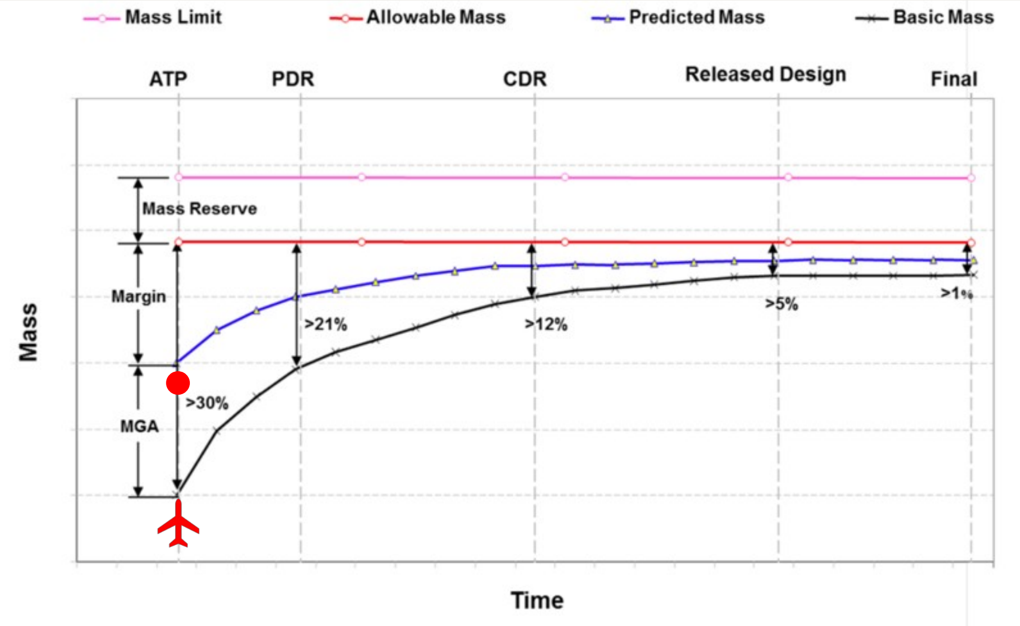
Mass Reserve: mass allowance defined and retained by the customer or program management for potential out-of-scope changes or any other unforeseen mass impacts



Mass Limit
maximum mass that can satisfy all mission performance requirements

Predicted Mass estimates the final mass according to designer’s knowledge (Mass Growth Allowance) and design best practice (Design Margins)

Mass Growth Allowance
the predicted change to the basic mass of an item based on an assessment of the hardware category, design maturity, fabrication status, and an estimate of the in-scope design changes that may still occur throughout life-cycle.



1.6

Guess data estimation for subsonic commercial aircraft

HOMEWORK

Case Study: Reference aircraft and competitors

Assignment 2: On the basis of the list of Requirements elicited in the previous step, identify a good list of reference aircraft and collect data to be used as meaningful statistical population.

Guess Data Estimation: Take-Off Weight

1.6

Guess data estimation for subsonic commercial aircraft:

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!

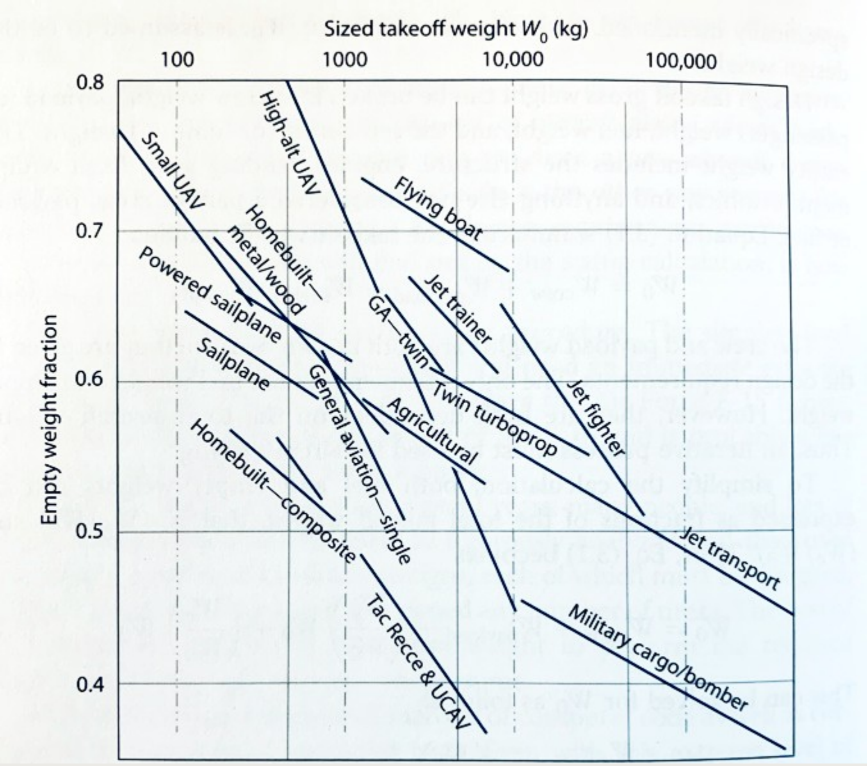
[1] Raymer, Daniel. Aircraft design: a conceptual approach. American Institute of Aeronautics and Astronautics, Inc., 2012.

Guess Data Estimation: Empty Mass fraction trend

1.6

Guess data estimation for subsonic commercial aircraft:

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



The trends can be represented by the following equation:

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

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.

Guess Data Estimation: Fuel Mass ratios

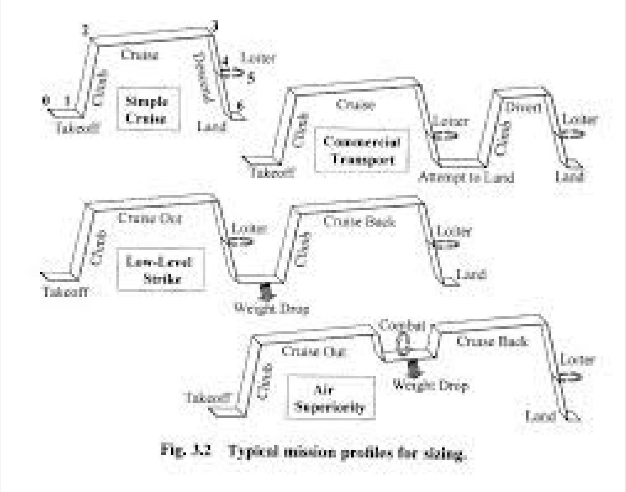
$$m_{TO} = \frac{m_{crew} + m_{payload}}{1 - \left(\frac{m_{fuel}}{m_{TO}}\right) - \left(\frac{m_{empty}}{m_{TO}}\right)}$$

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

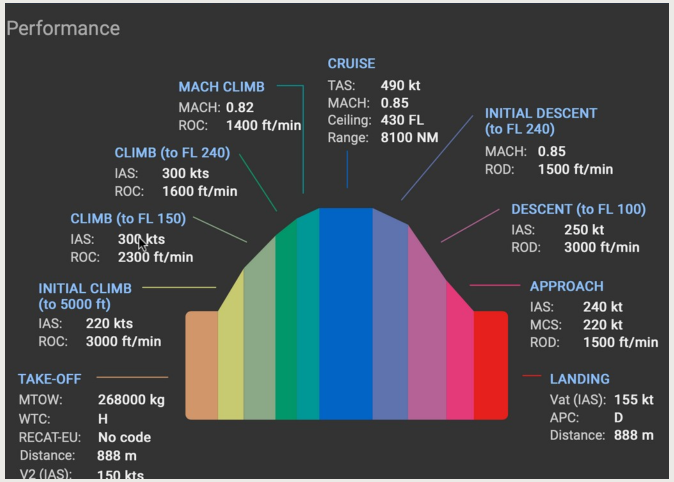
For the definition of a **Mission Profile** for commercial aircraft, various simplified models can be found out in literature. However, for a more precise estimate, real mission profiles of reference aircraft can be used and discretized.

1.6

Guess data estimation for subsonic commercial aircraft:



From [1]



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

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

Guess Data Estimation: Fuel Mass ratios

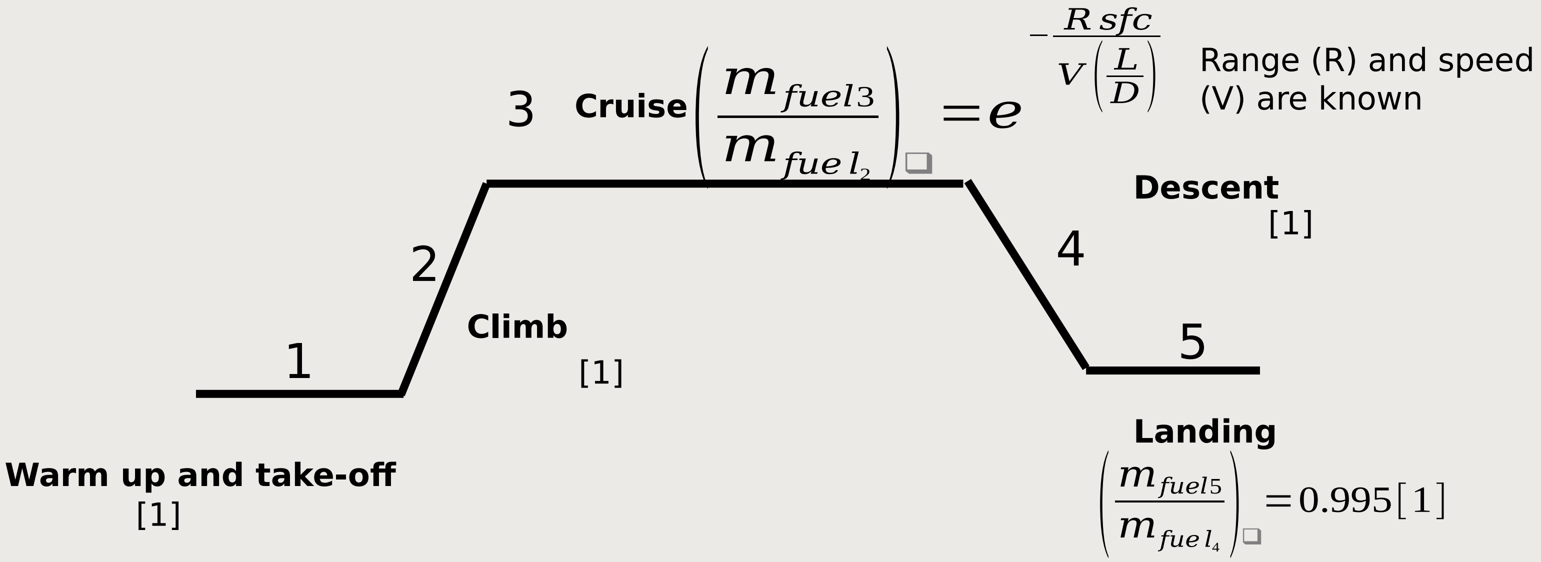
1.6

Guess data estimation for subsonic commercial aircraft:

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

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

$$m_{fuel}=\sum_{i=1}^{n}\left(m_{fuel}\right)_i \text{, where n is the number of mission phases (or legs)}$$



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

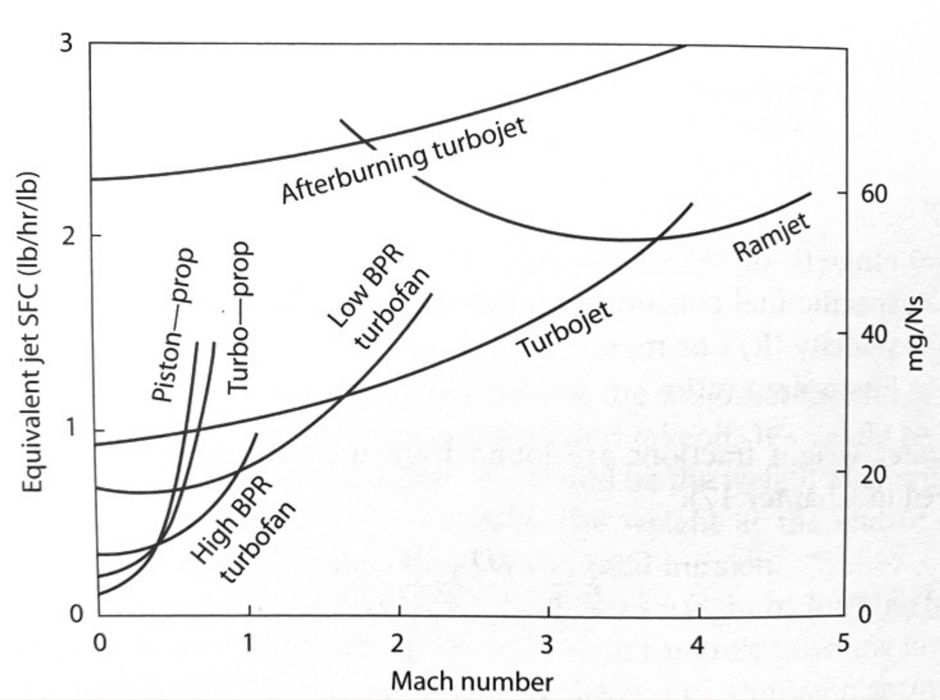
Guess Data Estimation: Specific Fuel Consumption

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

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

1.6

Guess data estimation for subsonic commercial aircraft:



Typical Values for subsonic jet aircraft are reported hereafter

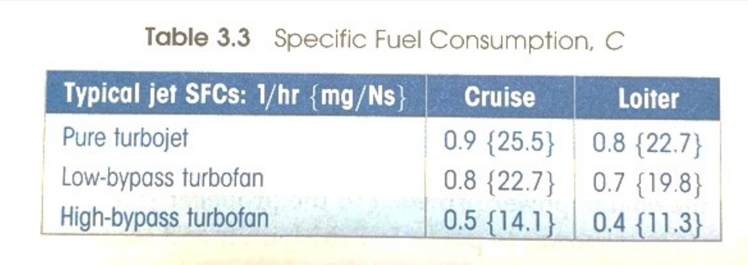


Table 3.3 Specific Fuel Consumption, C

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}

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

Guess Data Estimation: Maximum L/D

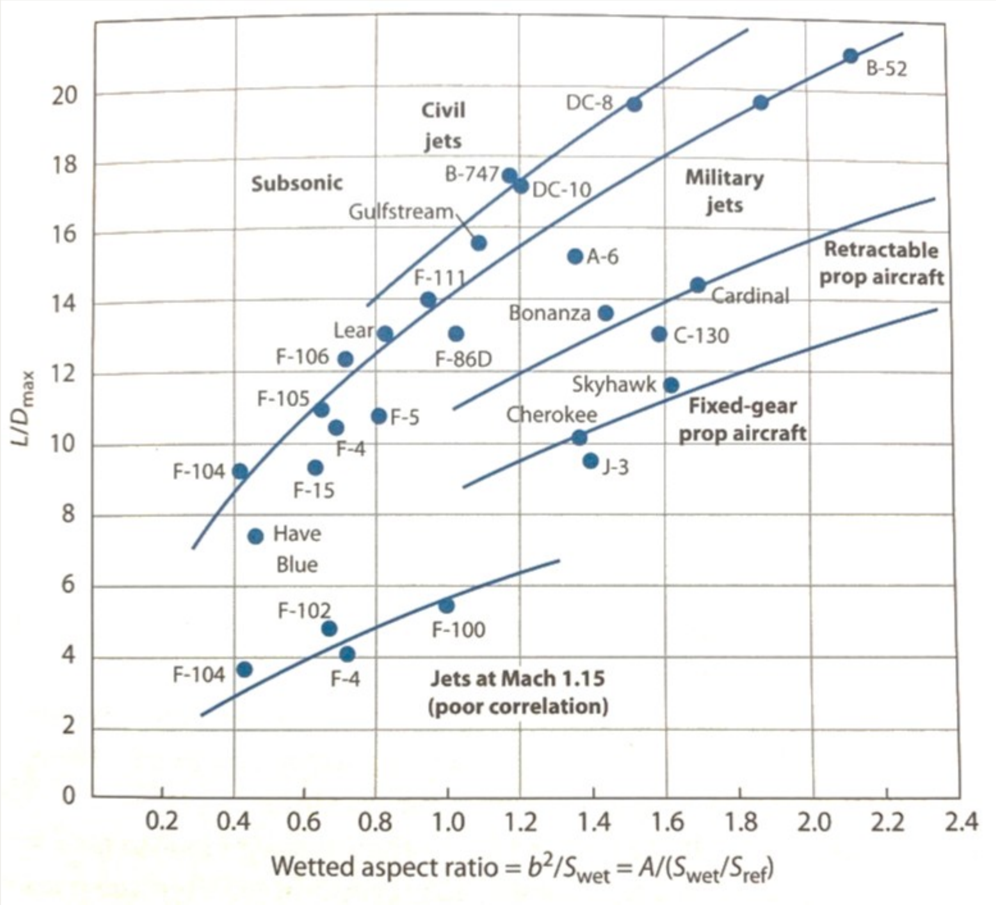
1.6

Guess data estimation for subsonic commercial aircraft:

$$\left(\frac{L}{D}\right)_{max} = k_{LD}\sqrt{A_w}$$

Where

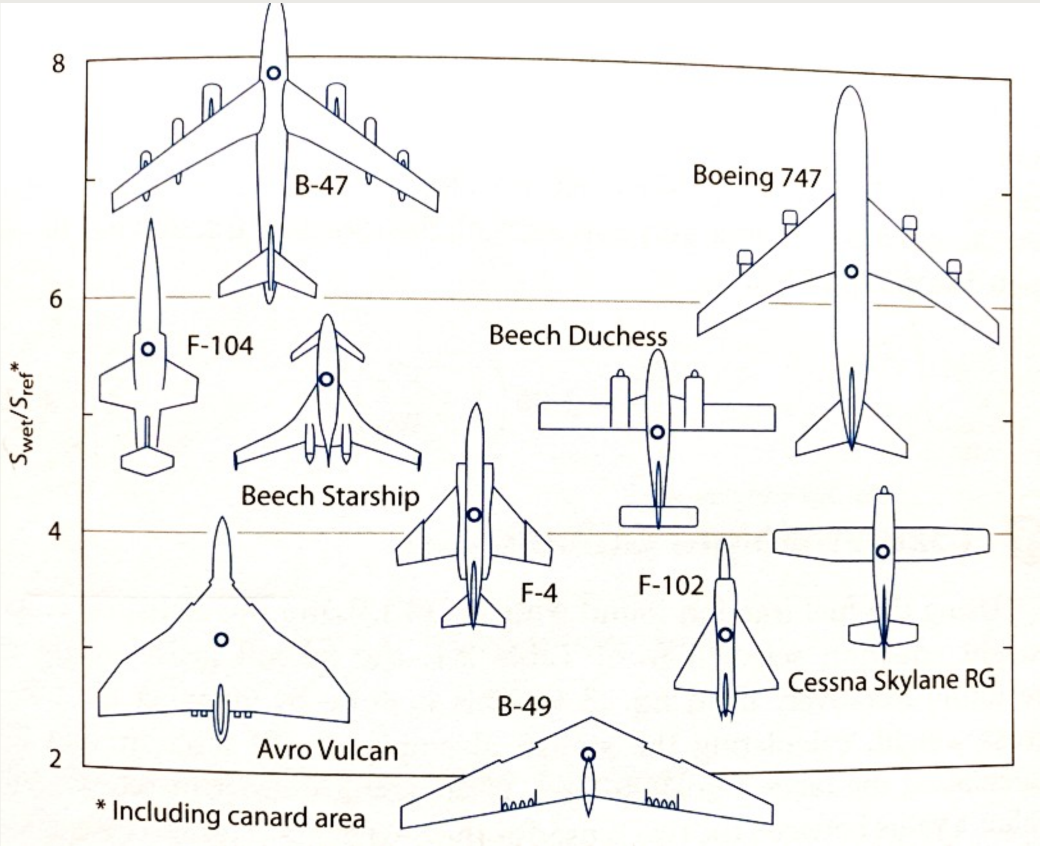
- has different values depending upon the type of aircraft and in particular the type of the propulsive system (e.g. 15.5 for civil jets,...)
-



Guess Data Estimation: Wetted Area ratios

1.6

Guess data estimation for subsonic commercial aircraft:



How can you estimate **wetted aspect ratio** before the aircraft design layout has been fixed?

Case Study: First Guess Data Estimation

1.6

Guess data estimation for subsonic commercial aircraft

HOMEWORK

Assignment 3: Critical Analysis of statistical trends. Verify whether your statistical population fits the trend reported in literature (e.g. Raymer) or suggest improvements to the simple mathematical models (e.g. updates of coefficients).

Assignment 4: Guess data estimation for the reference case study. Apply the original or improved statistical trends to perform the first guess data estimation for the reference case study. Please, report all iterations needed to convergence to the design maximum take-off mass. An example of iterations is reported into [1], pages 43-52.