Chapter 4

Introduction to Aircraft Design Principles

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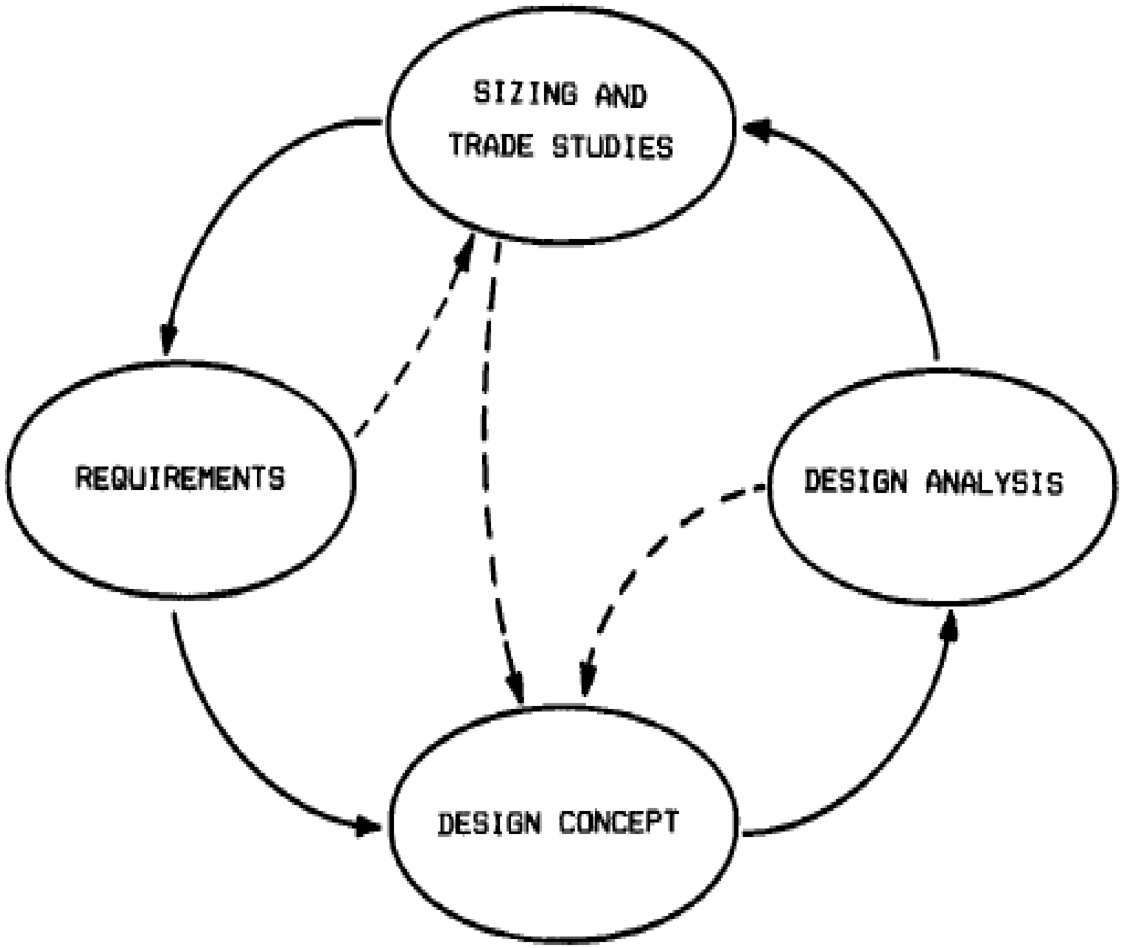
Contents

1. Introduction

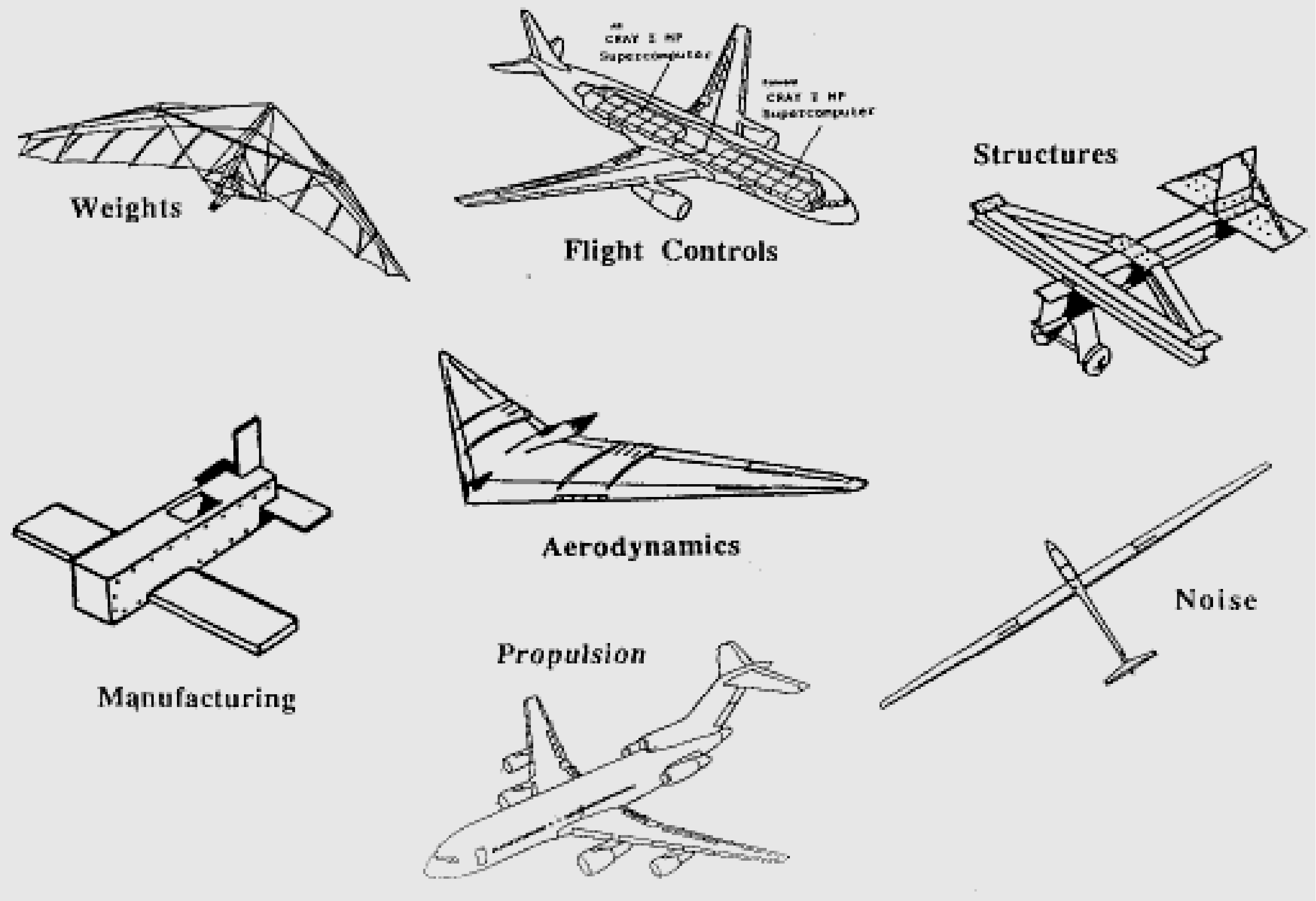
- Design requirements include parameters such as the aircraft range and payload, takeoff and landing distances, and maneuverability and speed requirements.
- The design requirements also include a vast set of civil or military design specifications which must be met. These include landing sink-speed, stall speed, structural design limits, pilots' outside vision angles, reserve fuel, and many others.
- Sometimes a design will begin as an innovative idea rather than as a response to a given requirement.
- The flying wings pioneered by John Northrop were not conceived in response to a specific Army Air Corps requirement at that time, but instead were the product of one man's idea of the "better airplane." Northrop pursued this idea for years before building a flying wing to suit a particular military requirement.

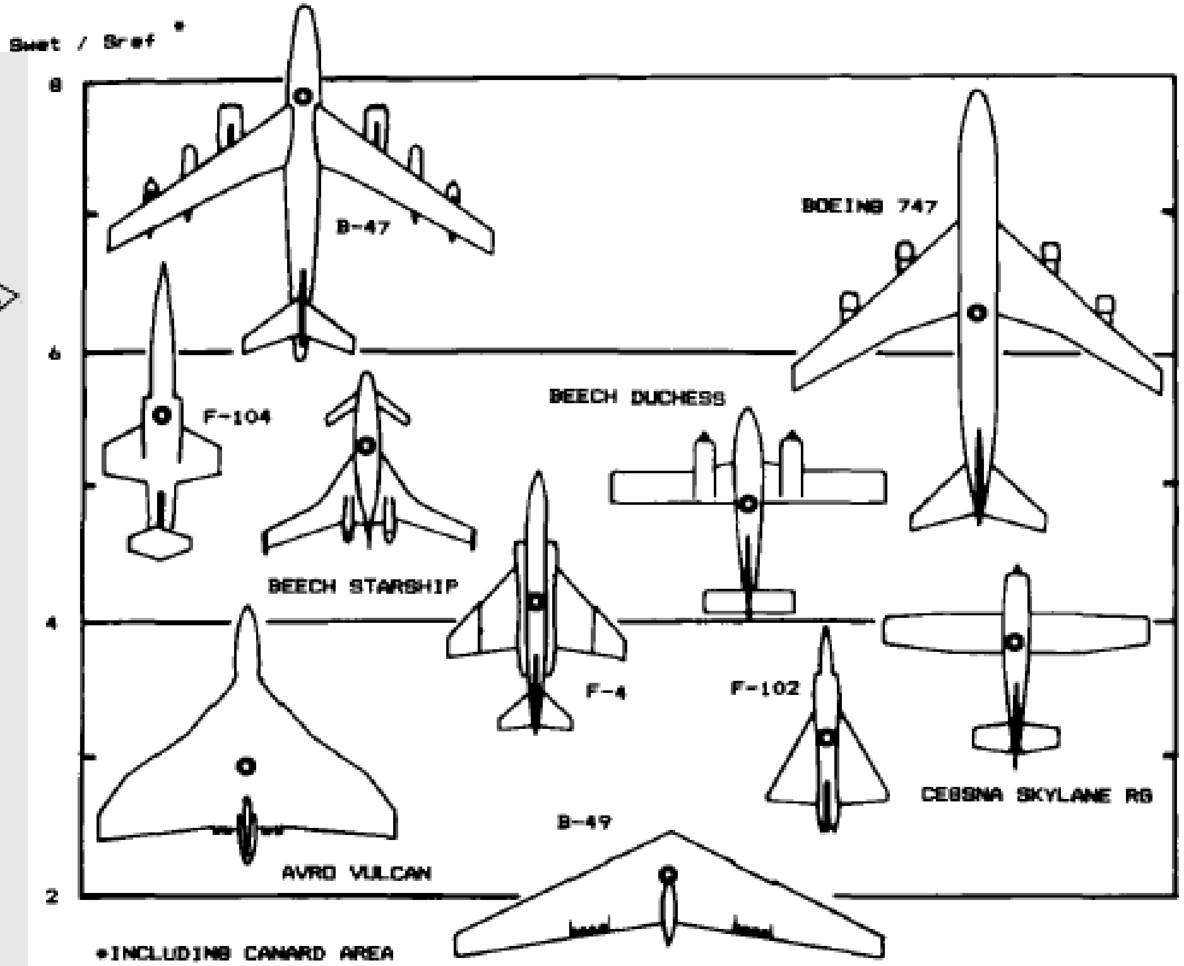


1. Introduction

- Before a design can be started, a decision must be made as to what technologies will be incorporated.
- If a design is to be built in the near future, it must use only currently-available technologies as well as existing engines and avionics.
- If it is being designed to be built in the more distant future, then an estimate of the technological state of the art must be made to determine which emerging technologies will be ready for use at that time.
- An optimistic estimate of the technology availability will yield a lighter, cheaper aircraft to perform a given mission, but will also result in a higher development risk .

2. Aircraft Configurations

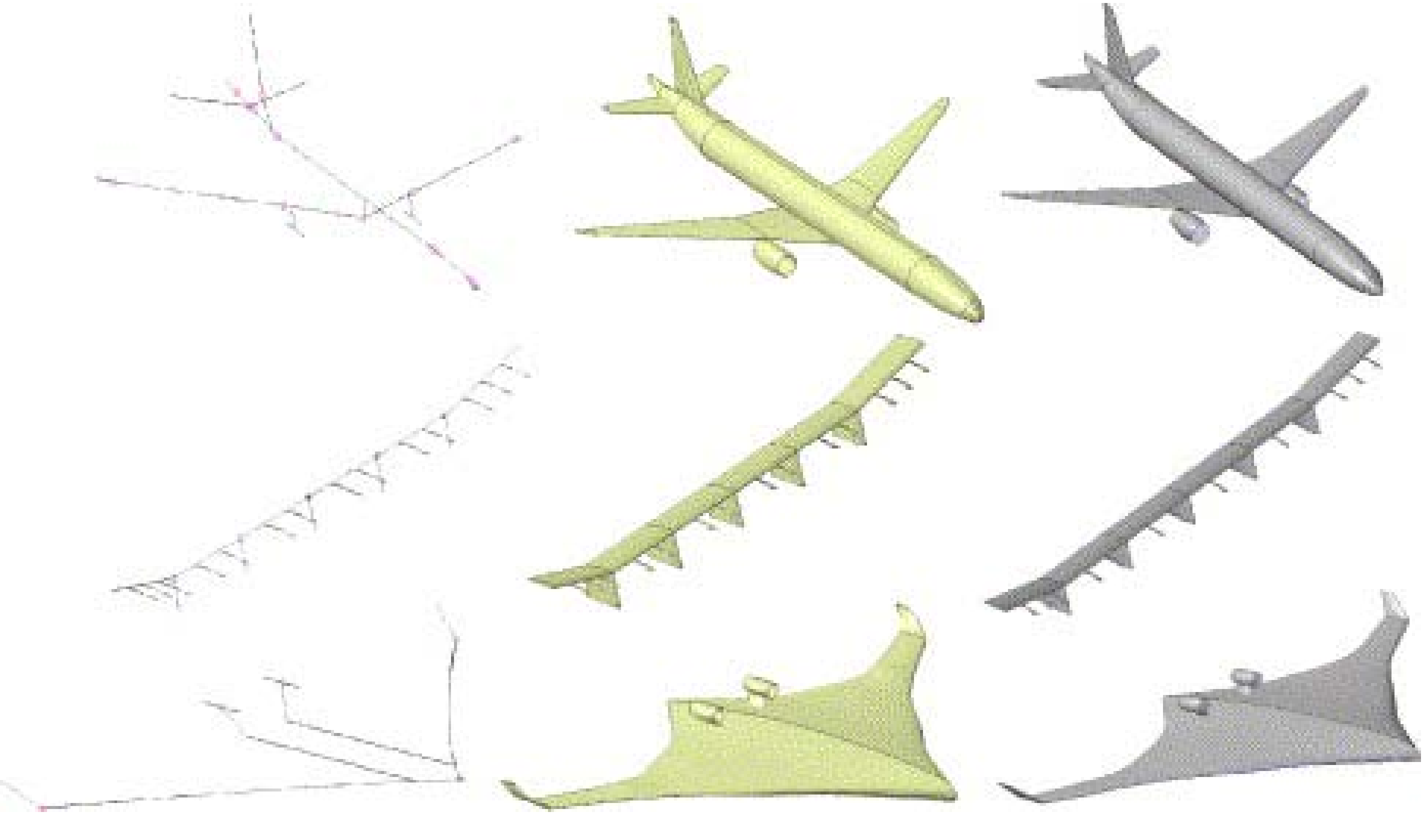


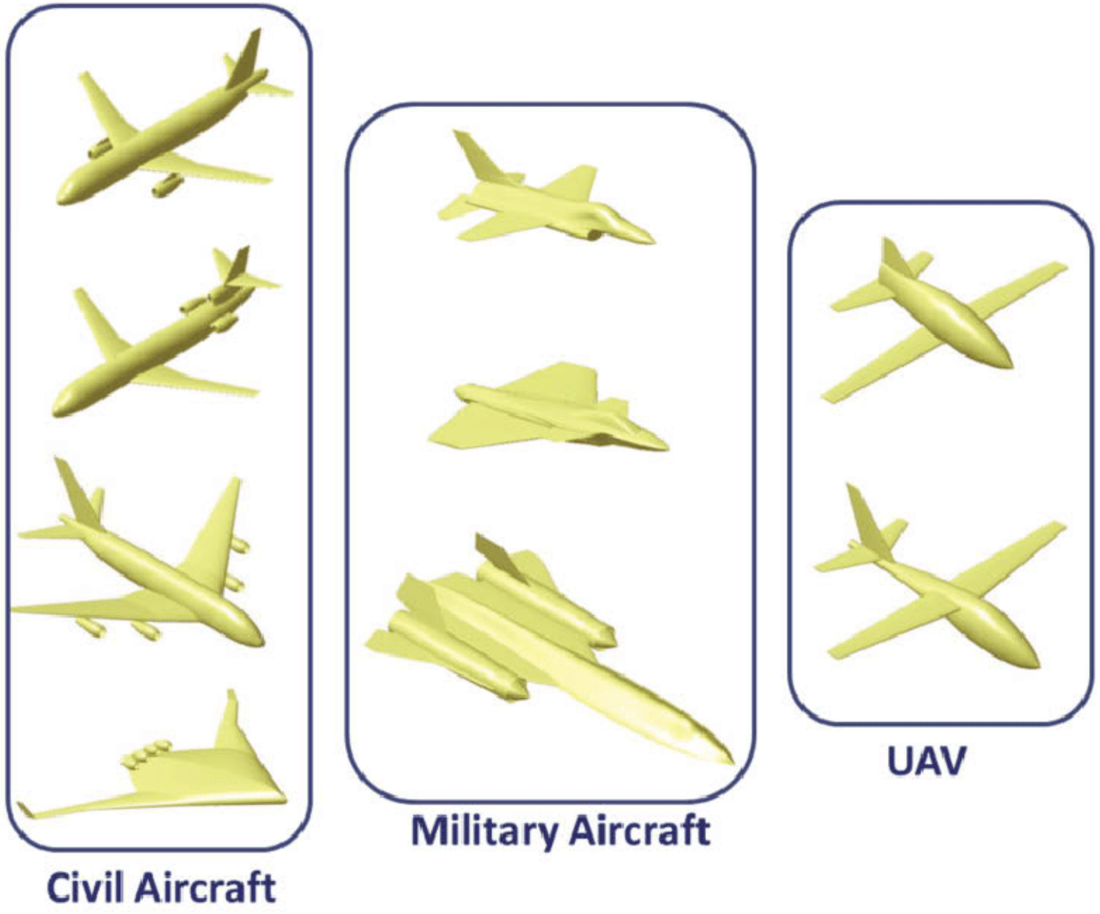


Wetted area ratios for different wing configurations.

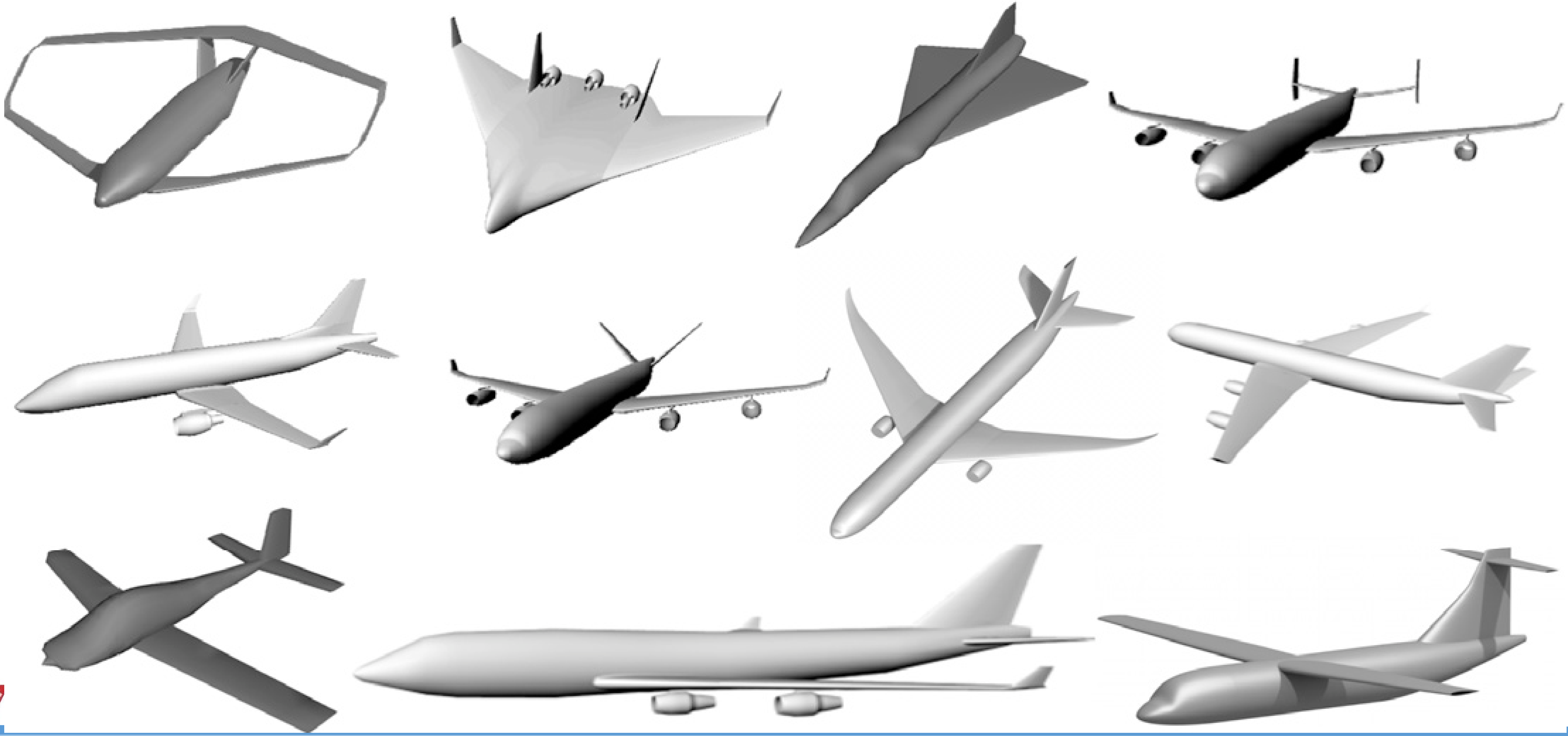
2. Aircraft Configurations

Design and Analysis



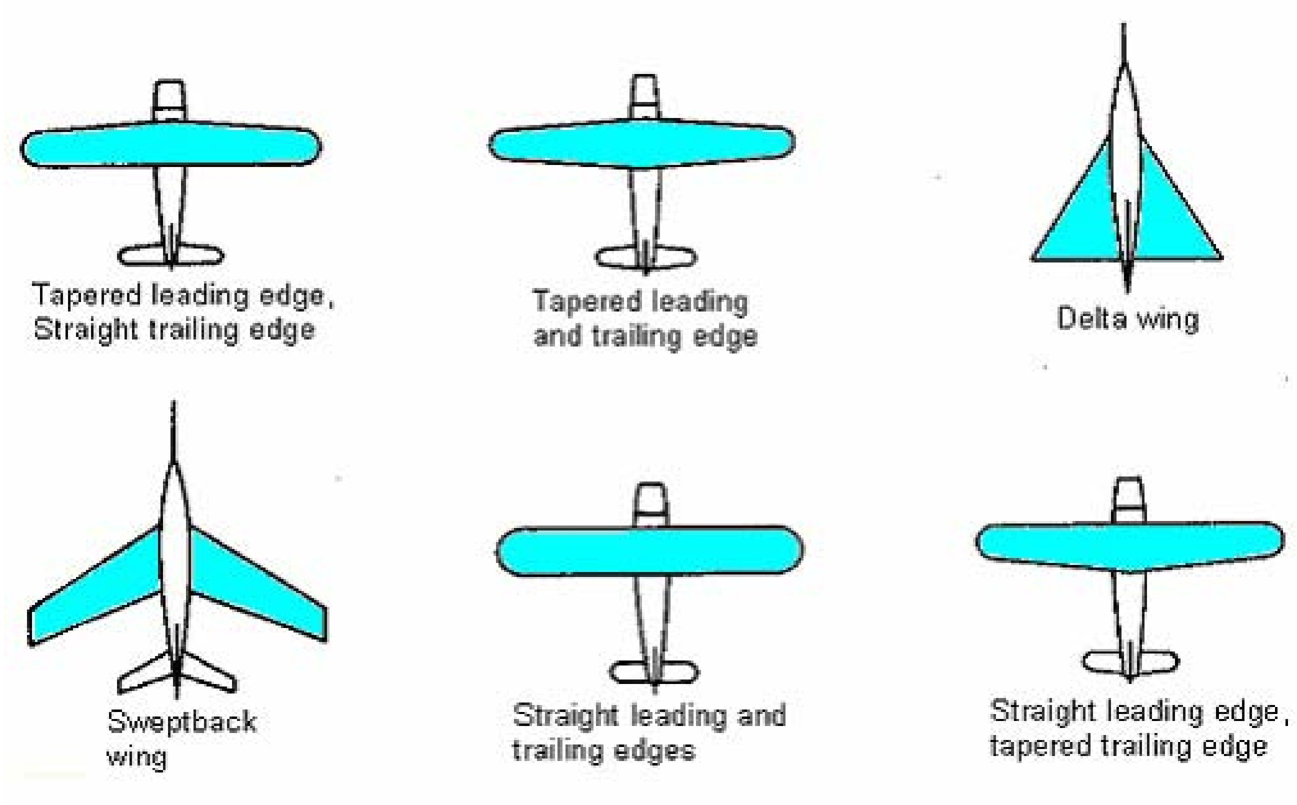


2. Aircraft Configurations



2. Aircraft Configurations

Wing Configurations

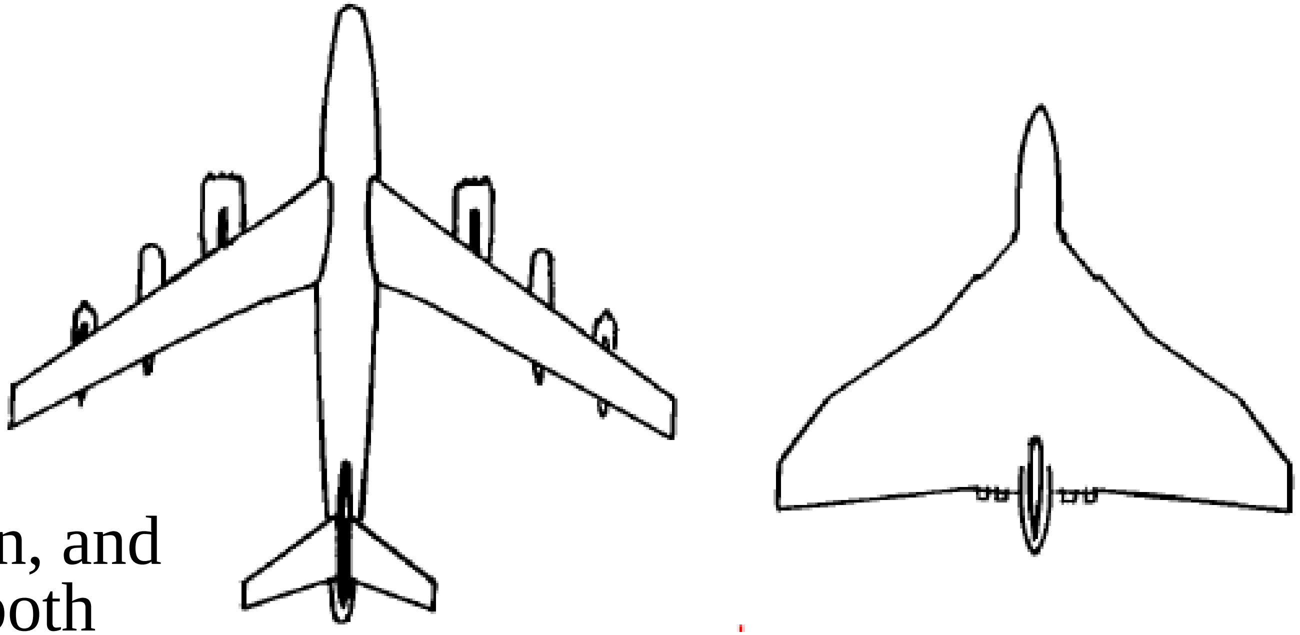


Delta-Wing: Avro Vulcan

Wing Configurations

The AVRO Vulcan bomber has an aspect ratio of only 3, yet it attains almost exactly the same L/D as B-47.

Both aircraft have about the same wing span, and both have about the same wetted areas, so both have about the same *L/D*. *The* aspect ratio of the B-47 is higher not because of a greater wing span, but because of a smaller wing area. However, this reduced wing area is offset by the wetted area of the fuselage and tails.

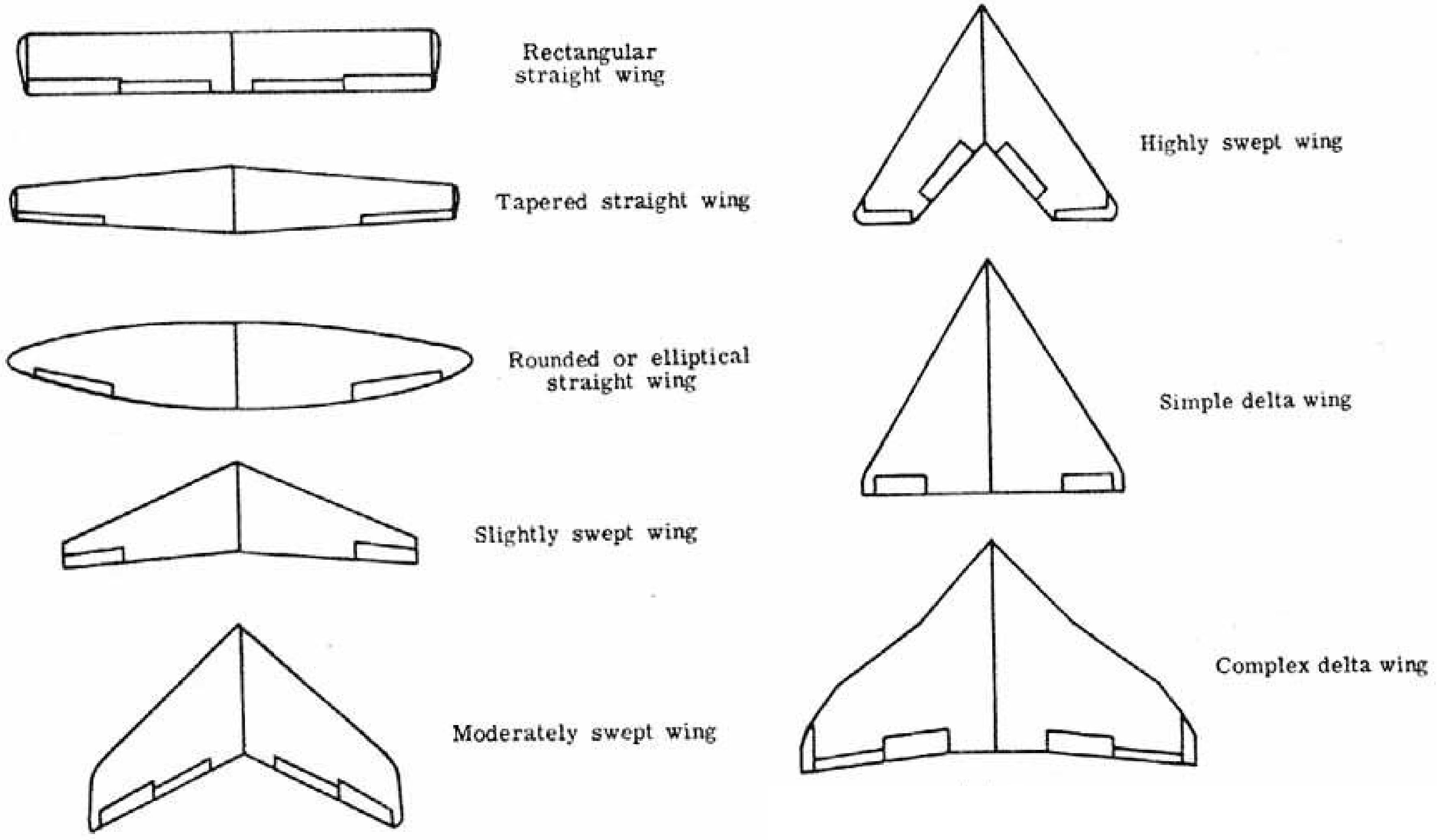


	B-47	AVRO VULCAN
S reference	1430	3446
S wetted	11300	9600
SPAN	116	90
Swet/Sref	7.9	2.8
ASPECT RATIO	9.4	3.0
WETTED ASPECT RATIO	1.2	1.1
L/D max	17.2	17.0

Aspect ratio and drag prediction

2. Aircraft Configurations

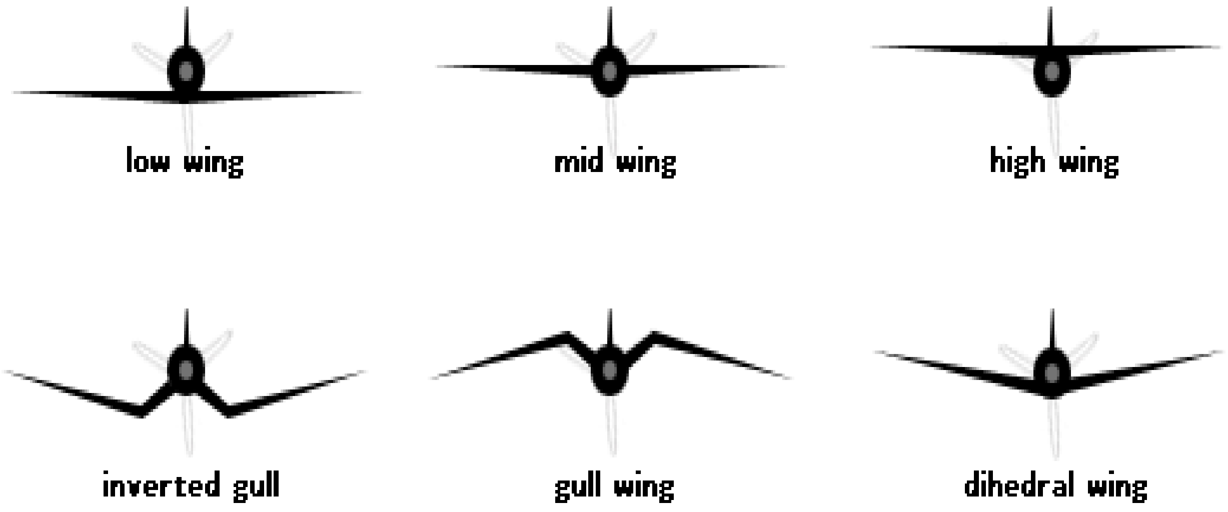
Wing Configurations



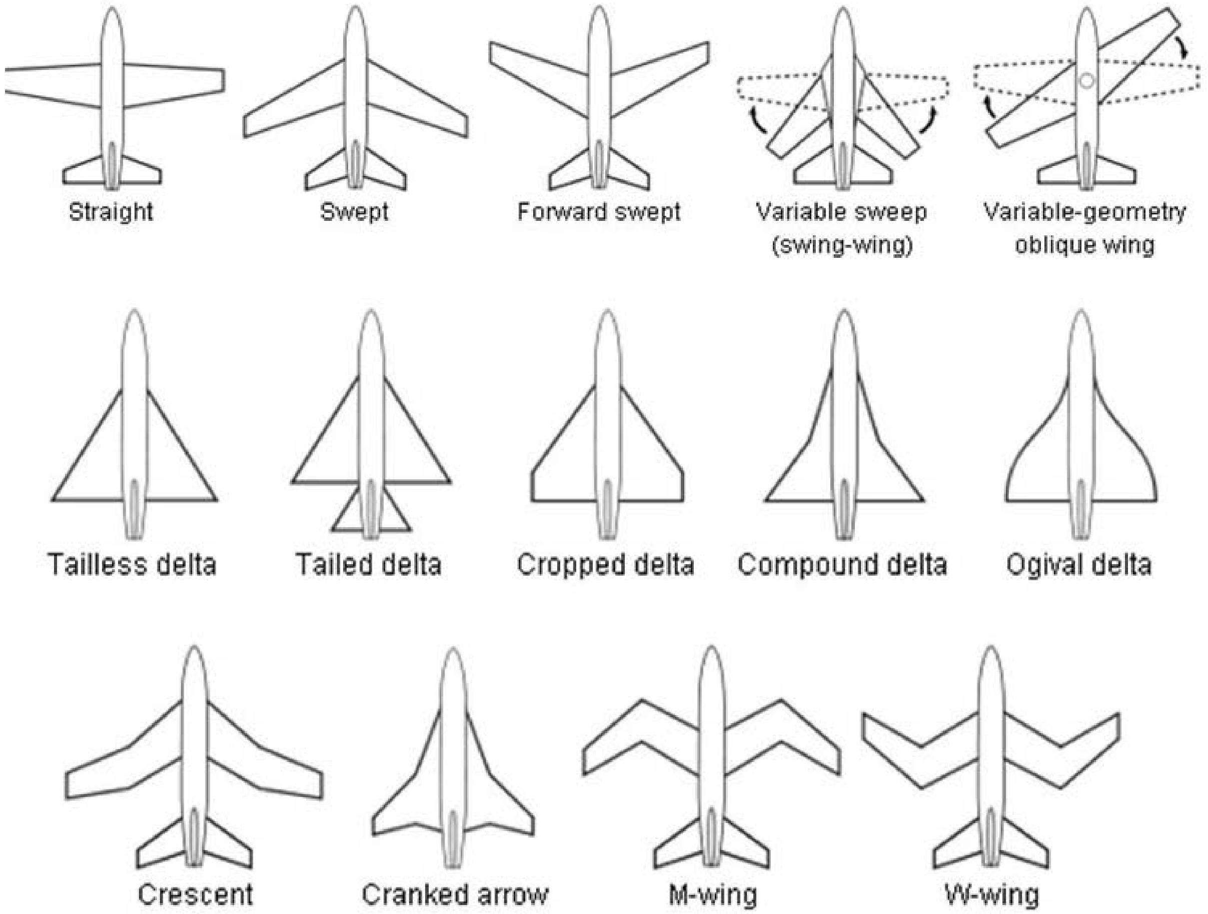
Examples of Wing Planform

2. Aircraft Configurations

Wing Configurations

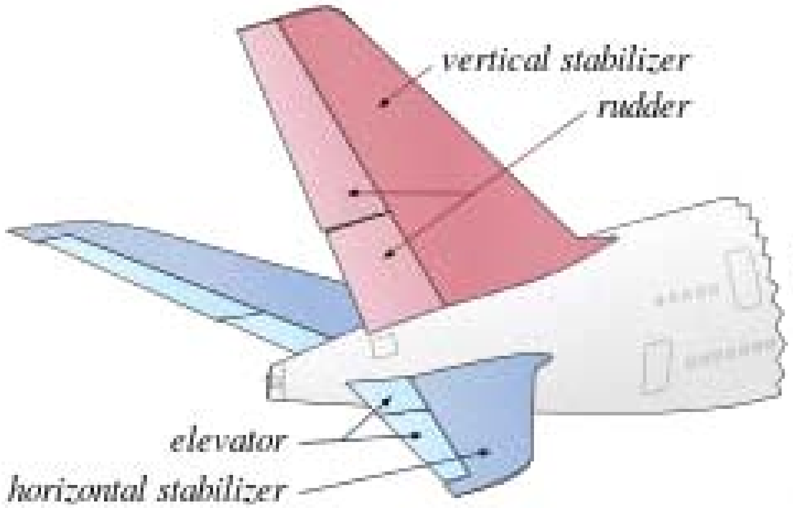


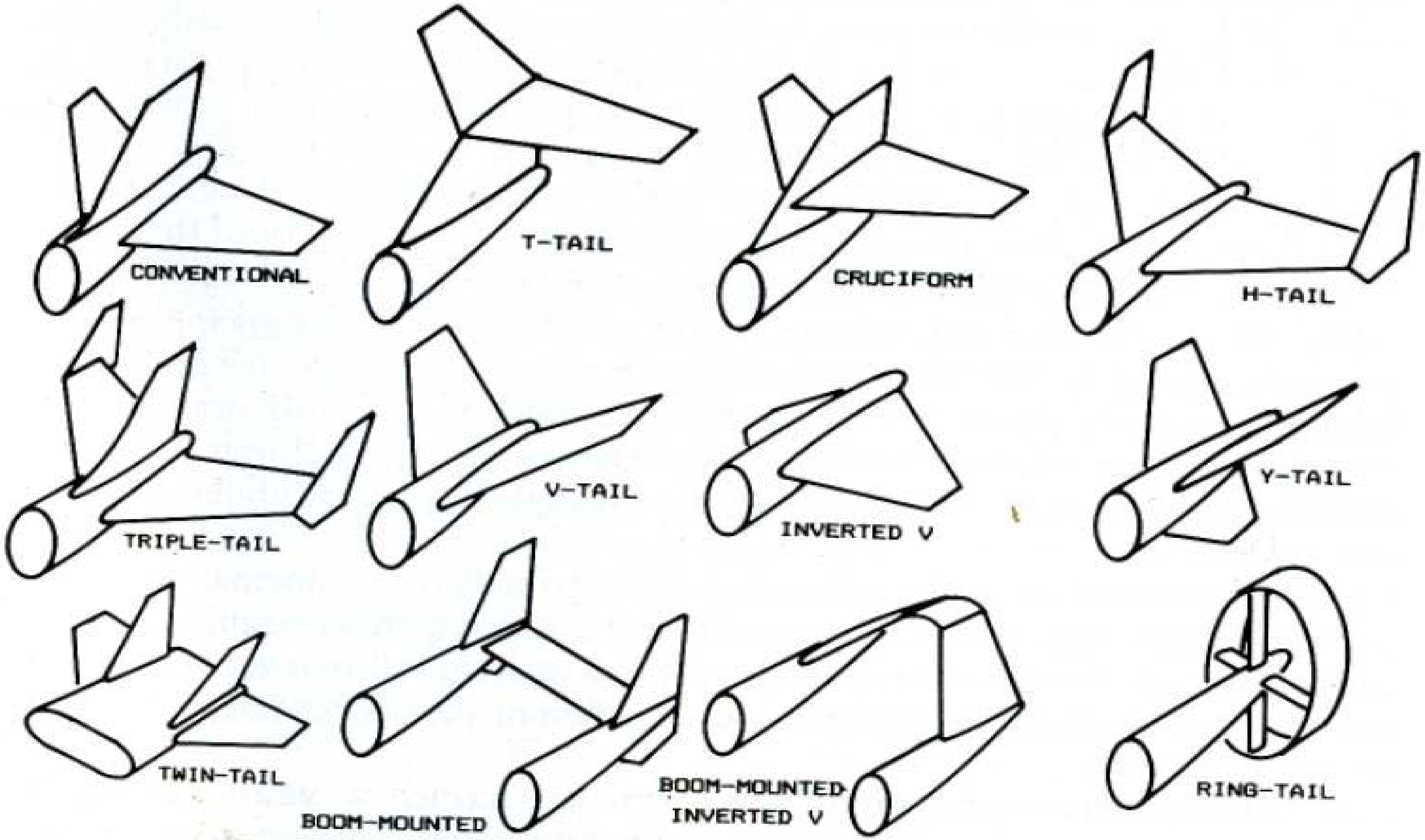
Seagull: Black-Back Seagulls have upto 1.7 m wingspan.

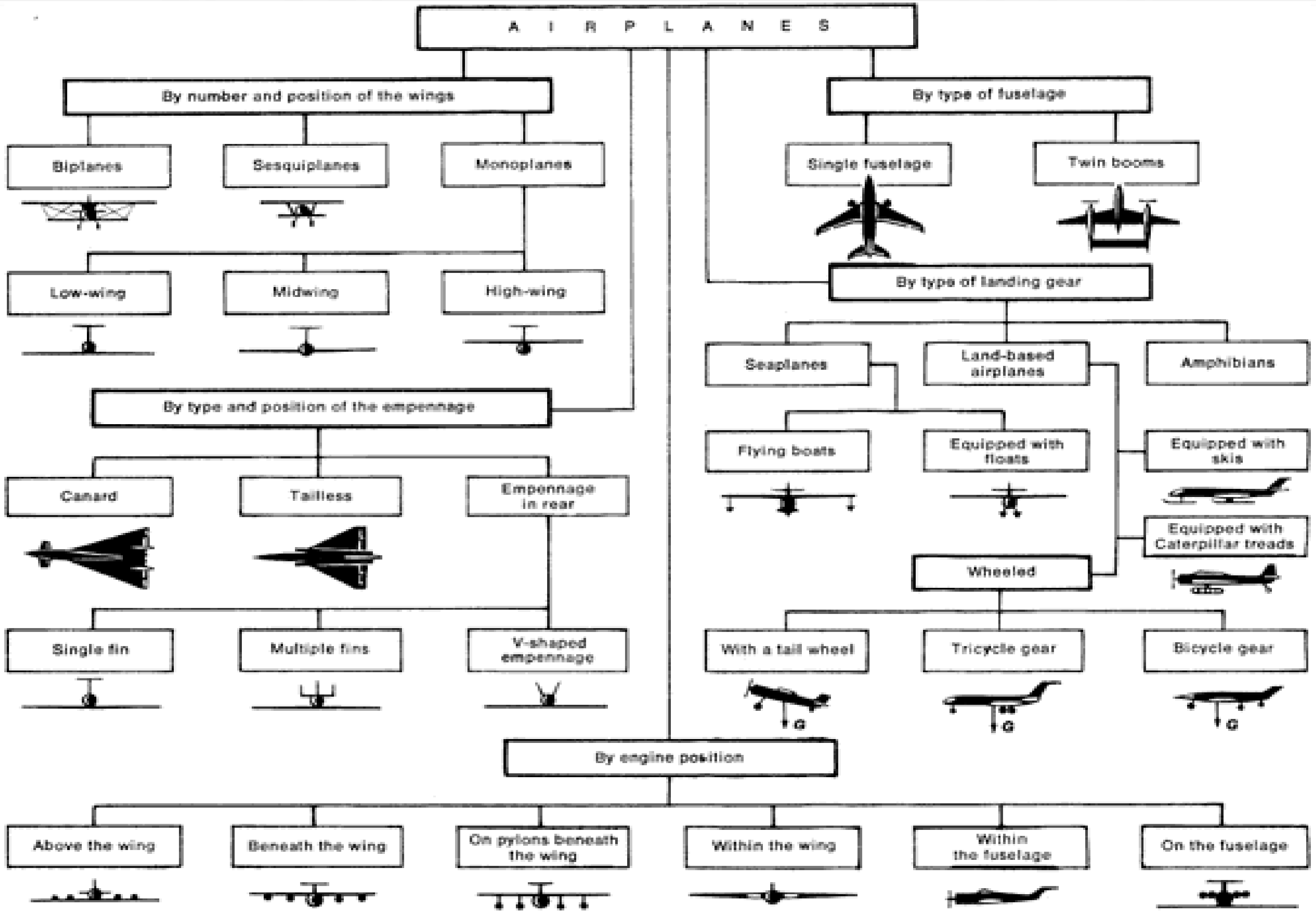


2. Aircraft Configurations

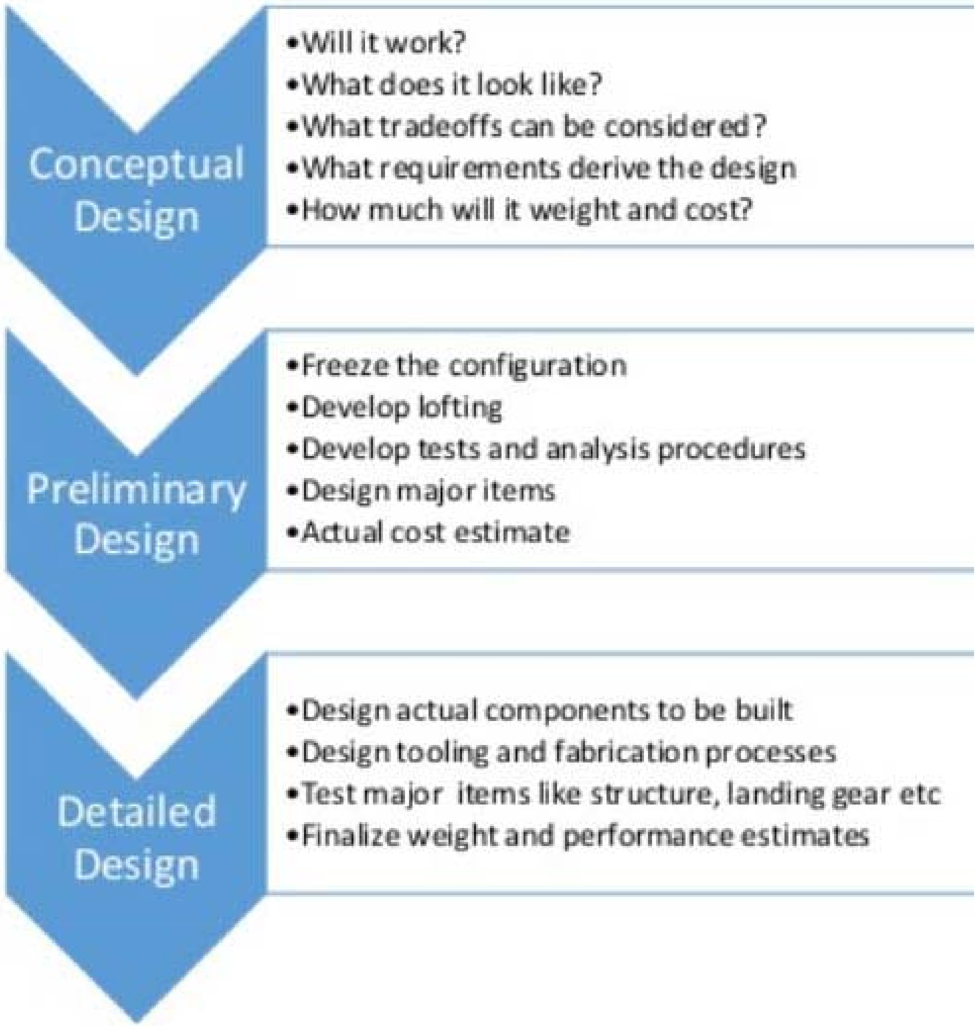
Tail Configurations






A I R P L A N E S
By number and position of the wings
Biplanes
Sesquiplanes
Monoplanes
Low-wing
Midwing
High-wing
By type and position of the empennage
Canard
Tailless
Empennage in rear
Single fin
Multiple fins
V-shaped empennage
By type of fuselage
Single fuselage
Twin booms
By type of landing gear
Seaplanes
Land-based airplanes
Amphibians
Flying boats
Equipped with floats
Equipped with skis
Equipped with Caterpillar treads
Wheeled
With a tail wheel
Tricycle gear
Bicycle gear
G
G
G
By engine position
Above the wing
Beneath the wing
On pylons beneath the wing
Within the wing
Within the fuselage
On the fuselage

3. Overview of Design Process



- Design is an iterative process as shown in the design wheel.
- Requirements are set by the prior design trade studies- e.g. between structure, aerodynamics and manufacturing departments. Concepts are developed to meet requirements.
- There are three important phases in an aircraft design process:
  - **Conceptual Design**: Each time the latest design is analyzed and sized, it must be redrawn to reflect the new gross weight, fuel weight, wing size, engine size, and other changes. Early wind-tunnel tests often reveal problems requiring some changes to the configuration.
  - **Preliminary Design**: Preliminary design can be said to begin when the major changes are over. A key activity during preliminary design is “lofting”.
  - **Detail/Final Design**: Assuming a favorable decision for entering full-scale development, the detail design phase begins in which the actual pieces to be fabricated are designed.

3. Overview of Design Process

Conceptual Design
(Many Solution Candidates)

- Develop project plan
Brainstorm solutions
- Sketch designs
- Select candidates for further analysis

Preliminary Design
(Fewer Solution Candidates)

- Explore and constrain candidates
- Select airfoils
- Perform lower-order structural analyses
- Perform low-order aerodynamic analyses
- Perform analyses to evaluate candidates against the Objective Function
- Down select candidates based on analyses

Detailed Design
(One solution Candidate)

- Use higher order analyses to refine candidate (aerodynamics, structural, and load)
- Perform analyses to evaluate against Objective Function

3. Overview of Design Process

Conceptual Design

- This phase is typically carried out by a staff of 15-30 engineers, defines the mission in the light of anticipated market requirements, and determines a general preliminary configuration, together with first estimates of size, weight and performance.
- The costs of this phase can be in the order of $10mil.
- Is based on historical data and empirical rules. Rules are usually configuration specific and analysis can provide rough ideas of sizing, weight, performance, wing sweep angles, etc.
- Shape often does not play a role in the analysis. It makes the best educated guess of what will work best, taking all the quantifiable and non-quantifiable objectives into account.
- **The output of a conceptual design is a configuration.**

3. Overview of Design Process

- **<u>Preliminary design</u>**- the aerodynamic shape and structural skeleton progress to the point where detailed performance estimates can be made and guaranteed to potential customers, who can then, in turn, formally sign binding contracts for the purchase of a certain number of aircraft.
- A staff of 100-300 engineers is generally employed for up to 2 years, at a cost of 60-120 million dollars.
- Initial aerodynamic performance is explored by computational simulations and through wind tunnel tests.
- While the costs are still fairly moderate, decisions made at this stage essentially determine both the final performance and the development costs.

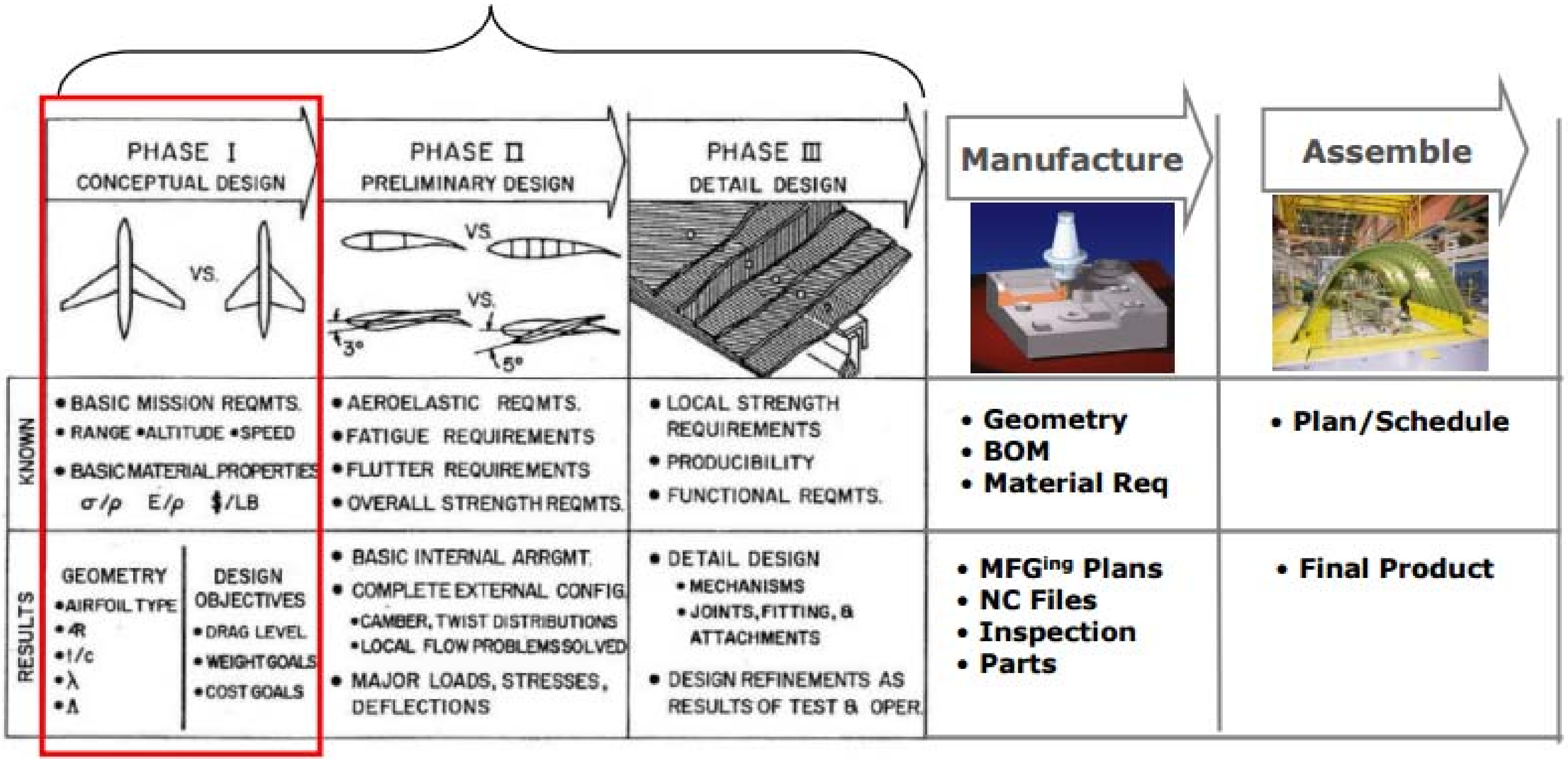
- Collection of comparative data
- Selection of aircraft parameters
- Preliminary weight estimations
- Selection of Power plant
- Airfoil selection, flaps
- Wing layout
- Critical performance parameters
- 3 view diagram

3. Overview of Design Process

- **<u>Final (Detailed) detailed design</u>** In the final design stage the structure must be defined in complete detail, together with complete systems, including the flight deck, control systems (involving major software development for fly-by-wire systems), avionics, electrical and hydraulic systems, landing gear, weapon systems for military aircraft, and cabin layout for commercial aircraft.
- Major costs are incurred at this stage, during which it is also necessary to prepare a detailed manufacturing plan.
- Thousands of engineers define every part of the aircraft. Total costs are 3-10 billion dollars.
- Thus, the final design would normally be carried out only if sufficient orders have been received to indicate a reasonably high probability of recovering a significant fraction of the investment.

3. Overview of Design Process

Three design stages



4. Modern Design Tools and Techniques

Integrated Product Development (IPD)

- Increasingly, aircraft design is being done in what is now called an Integrated Product Development (IPD) environment, and the design work is being accomplished by Integrated Product Teams (IPT).
- It *systematically employs a teaming of functional disciplines to integrate and concurrently apply all necessary processes to produce an effective and efficient product that satisfies customer's needs*.
- IPT refutes the traditional hierarchical structure of large, bureaucratic engineering organizations and calls for decision making to be pushed down to the lowest possible level.
- **Concurrent engineering** is an important part of the IPT environment.
- The designer trying to develop a new aircraft would see, on the next CAD scope, a production designer trying to develop tooling for the aircraft that hasn't been designed yet.

4. Modern Design Tools and Techniques

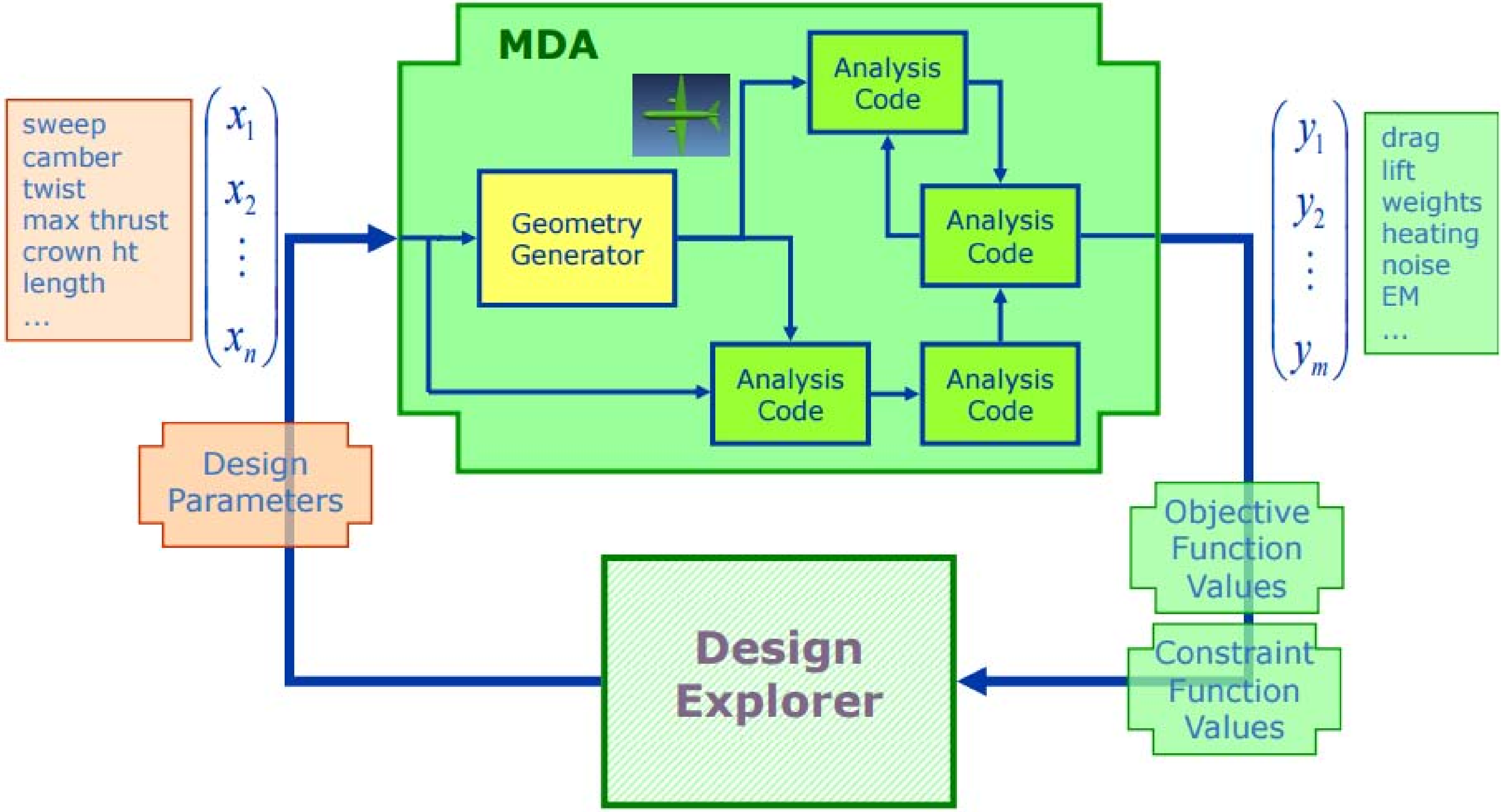
Integrated Product Development (IPD)

- Integrated product development (IPD) is a management process that integrates all activities from product concept through production and field support.
- IPD uses a multifunctional team to optimize simultaneously the product and its manufacturing processes to meet cost and performance objectives

- Multidisciplinary IPT bring together design, engineering, production, and operations personnel along with customer representatives to define and develop new products, up to and including entire new aircrafts.
- IPTs are to be established for the creation of one particular product, and are not to become self-perpetuating organizations.

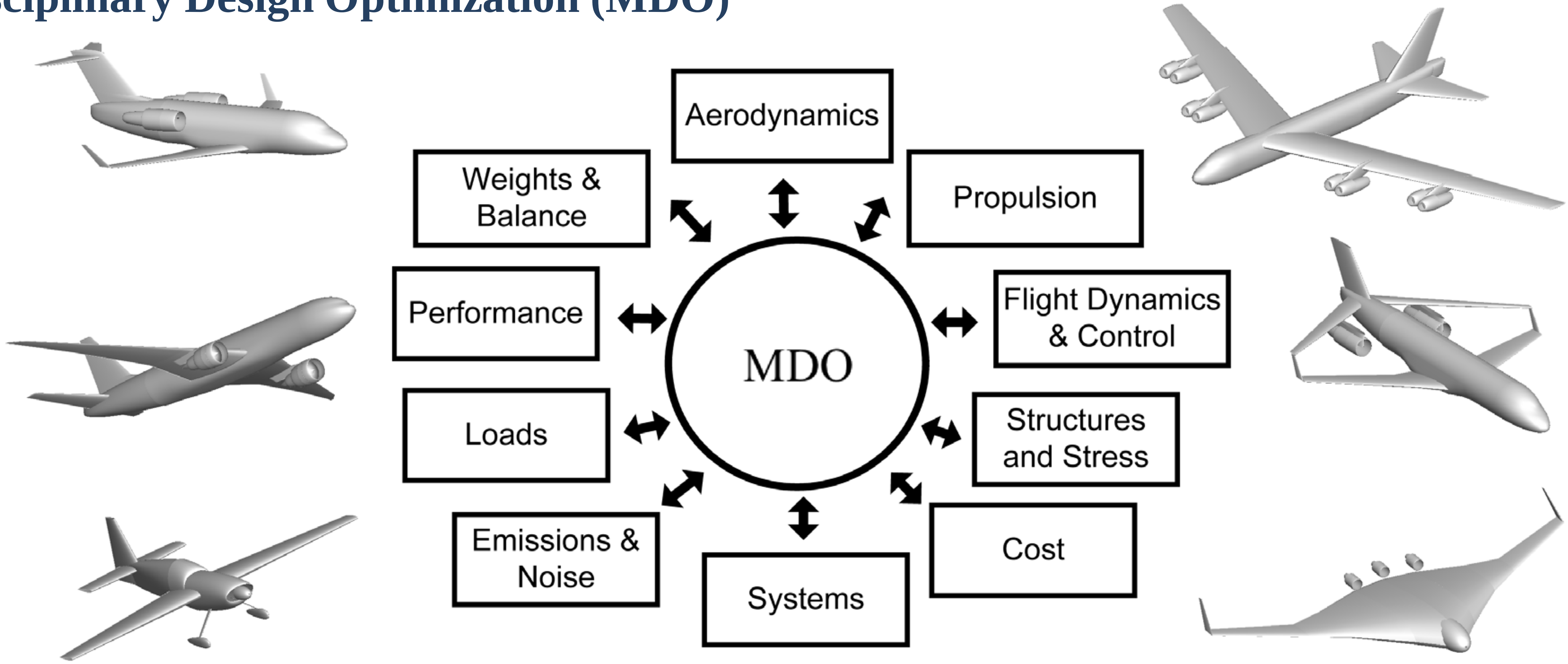
4. Modern Design Tools and Techniques

Multidisciplinary Design Optimization (MDO)



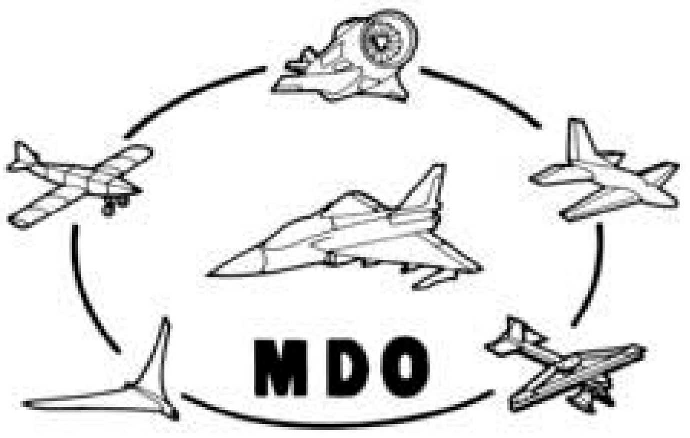
4. Modern Design Tools and Techniques

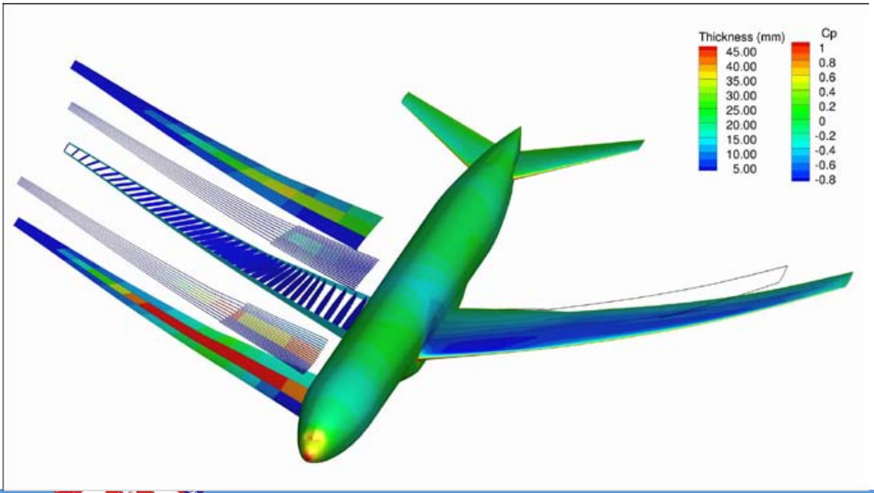
Multidisciplinary Design Optimization (MDO)



4. Modern Design Tools and Techniques

Multidisciplinary Design Optimization (MDO)

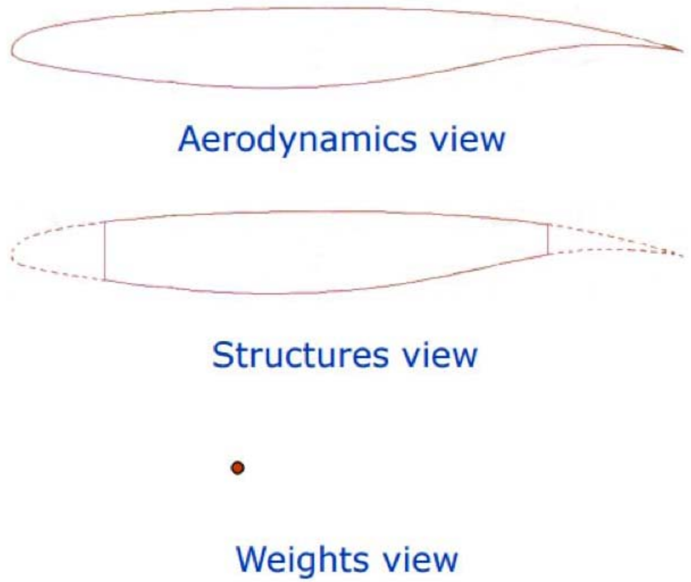




1. Provide input to analysis codes
2. Support multiple engineering views
3. Maintain parametric configuration
4. Satisfy known engineering requirements and principles by integrating physics with geometry
5. Satisfy geometric shape requirements
6. Provide differentiability of morphing
7. Produce analytic sensitivities
8. Satisfy known continuity requirements
9. Parametrize complex shapes with relatively few parameters
10. Provide integration with upstream and downstream CAD processes

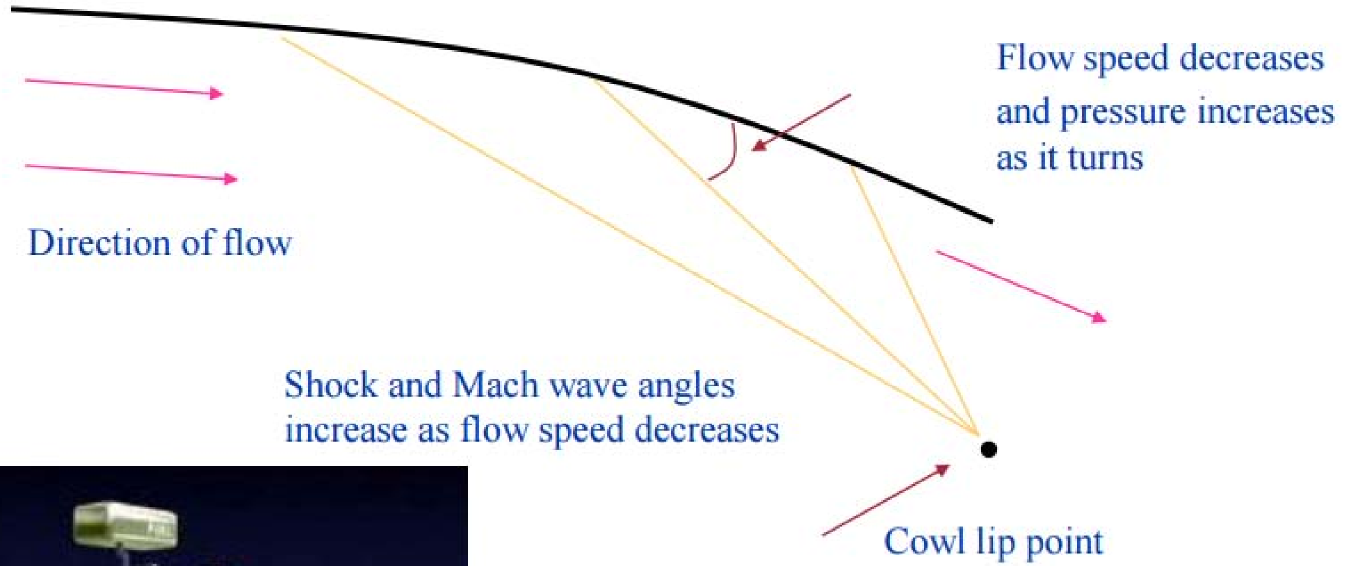
4. Modern Design Tools and Techniques

Multidisciplinary Design Optimization (MDO)



Example: Isentropic high speed inlets

The engine should capture all the compression waves without spillage

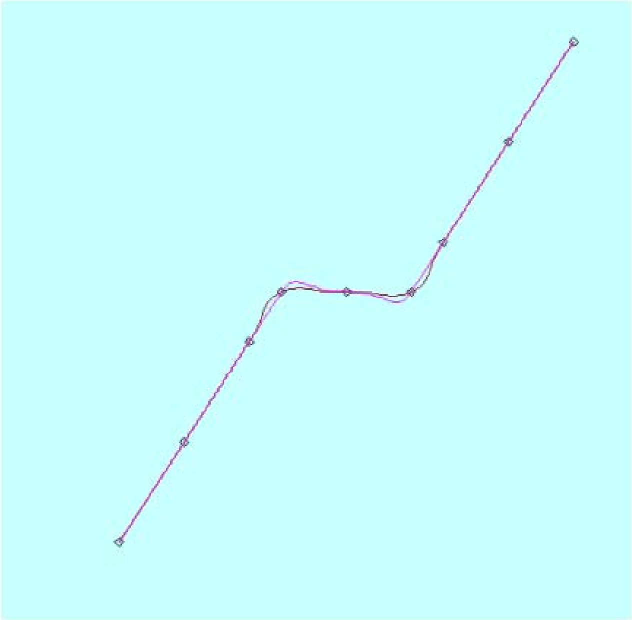


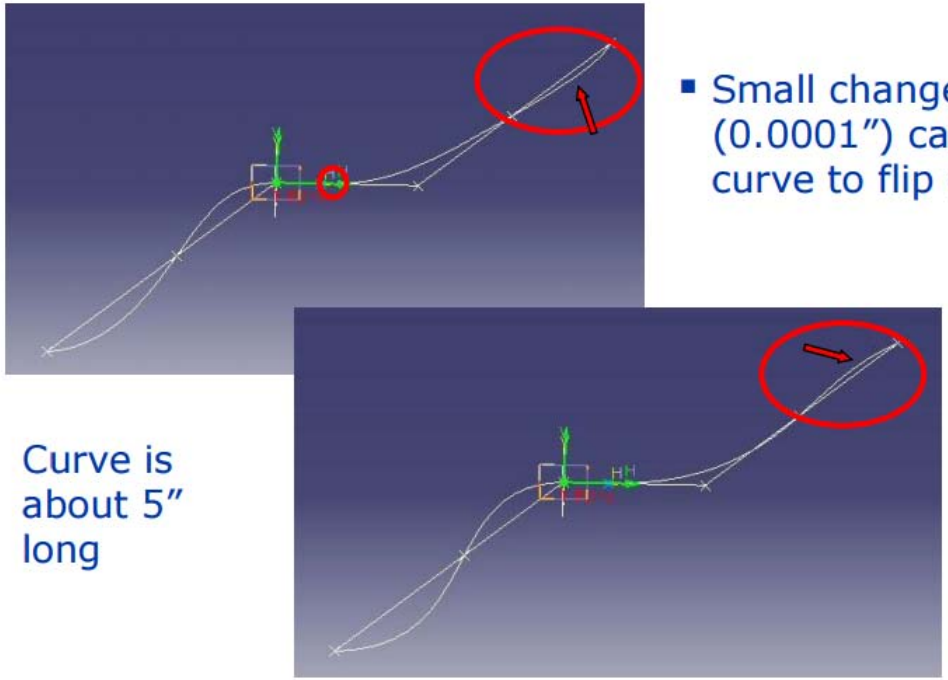
- ❖ Create appropriate geometry for each analysis code.
- ❖ Use “sole source” data to create discipline-specific views

4. Modern Design Tools and Techniques

Multidisciplinary Design Optimization (MDO)

- Small changes in design parameters should not produce large changes in geometry
- “Open source” algorithms required to create program specific workarounds to inevitable problems



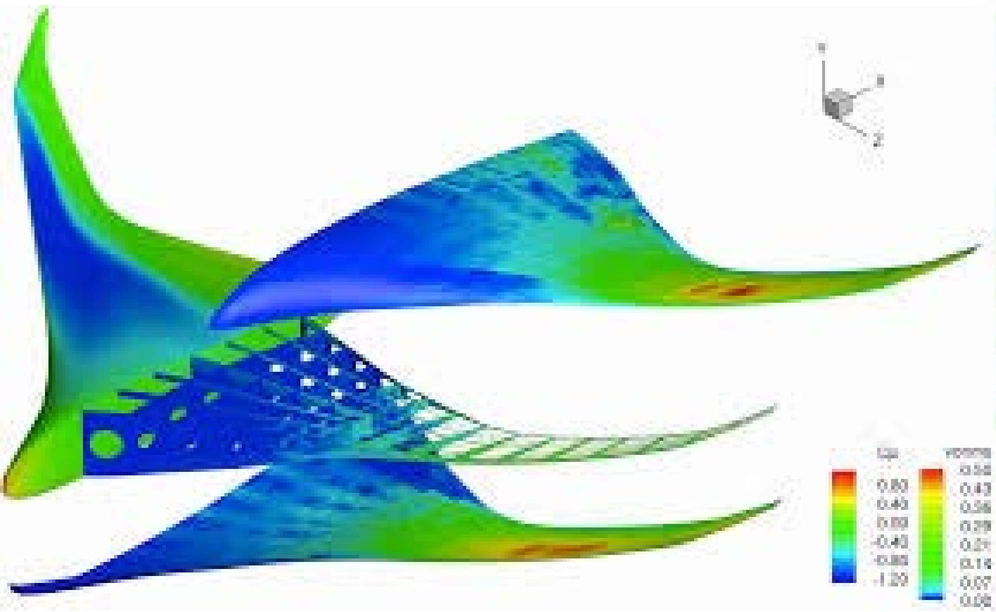


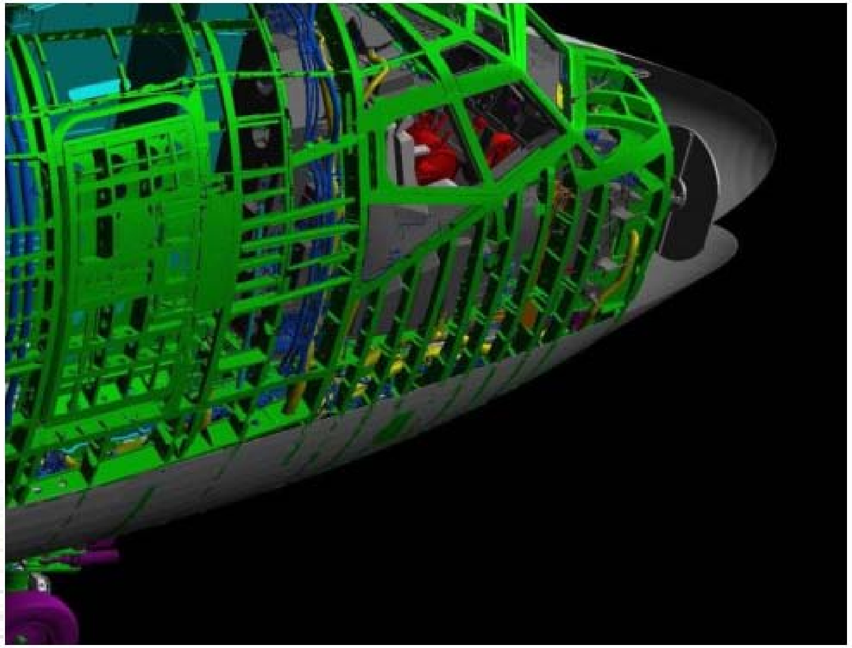
- Small change (0.0001”) causes curve to flip over

Curve is about 5” long

4. Modern Design Tools and Techniques

Multidisciplinary Design Optimization (MDO)





- Geometry models for the entire airplane are created in this stage
- Commercial CAD/CAM systems are preeminent
- Little scope for systematic design at the vehicle level remains, but individual components are frequently optimized
- Analysis of individual components is more common than system or vehicle level analysis

<u>Detail design</u> is what most people would consider a ‘design’

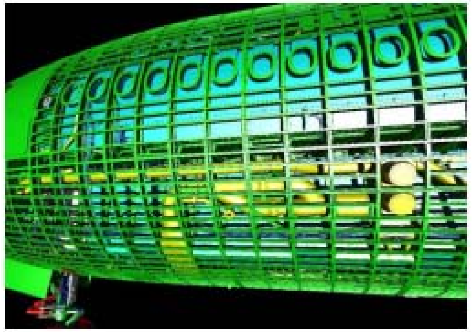
4. Modern Design Tools and Techniques

Multidisciplinary Design Optimization (MDO)

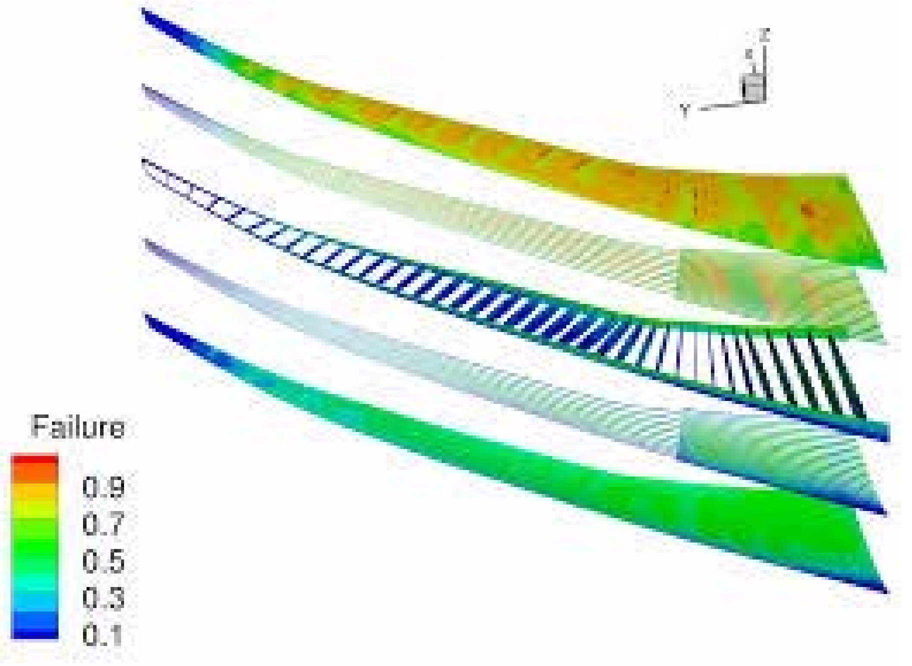
Then

- B2707 Supersonic Transport (1966-1971)
- Prototype made out of wood!
- Cost: Several million US$ (in 1970)

Now



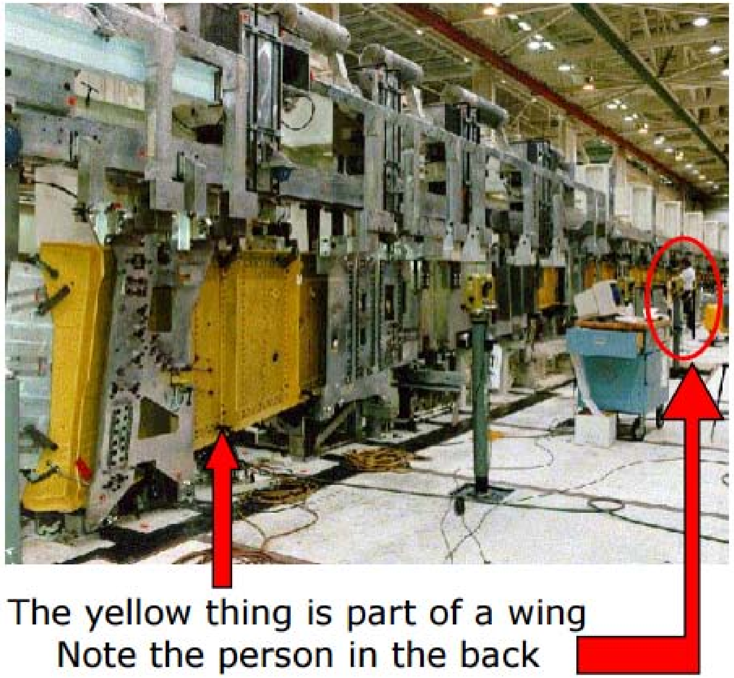
- Elimination of any physical prototyping
- Early interference detection
- > 50% reduction of engineering change requests, rework and error
- Alignment to within .023" versus .5" previously (20 x better)



4. Modern Design Tools and Techniques

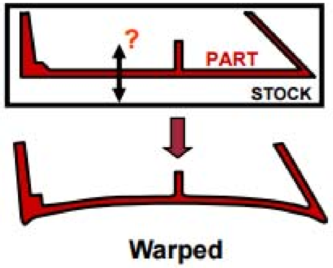
Aerospace manufacturing technologies

A floppy structure



The yellow thing is part of a wing
Note the person in the back

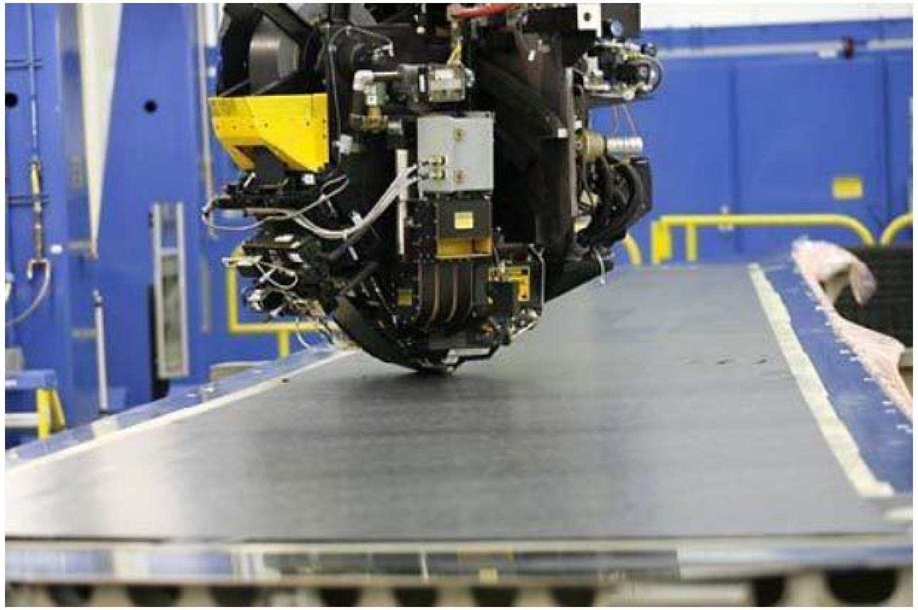
Issues:
- Part growth during assembly
- Sagging
- As built shape is different from in-flight shape
- Thermal effects (several models to represent engine)
- Warpage due to internal stresses
- Current CAD technology does not model dynamic structures very well



Floppy structures contain many subcomponents linked by a single component.

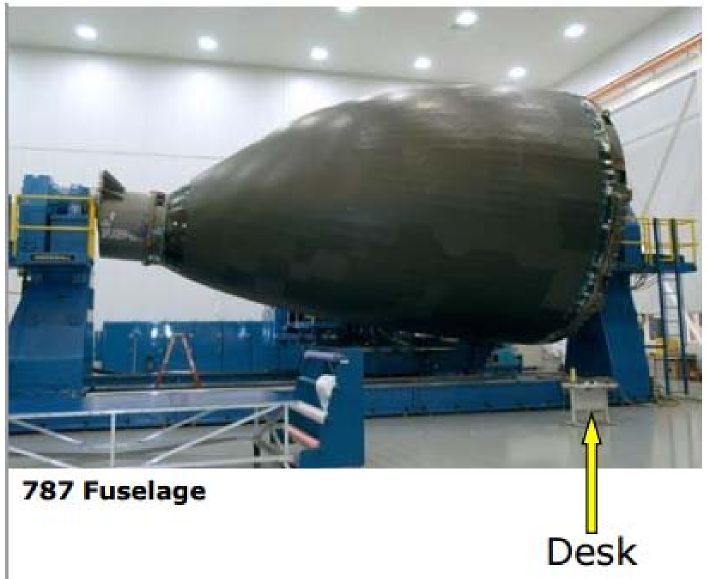
4. Modern Design Tools and Techniques

Aerospace manufacturing technologies

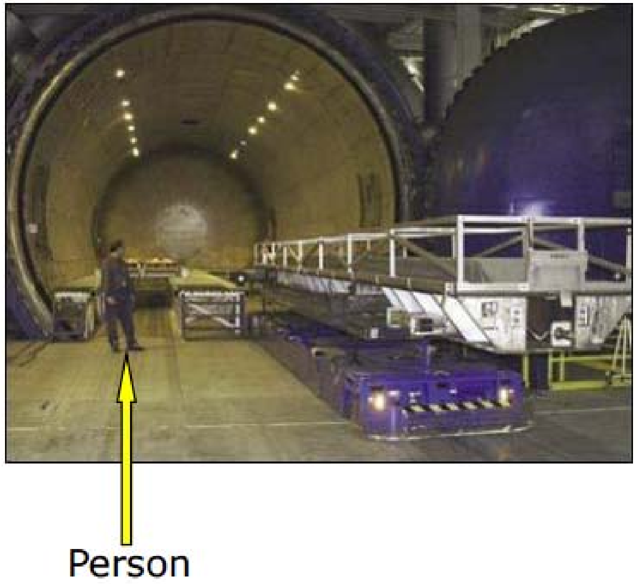


Preheats, lays down, & cuts the material

Automated tape laying (ATL): a high speed automated process in which prepreg tape is laid down continuously to form parts.



Tape is wound over a barrel

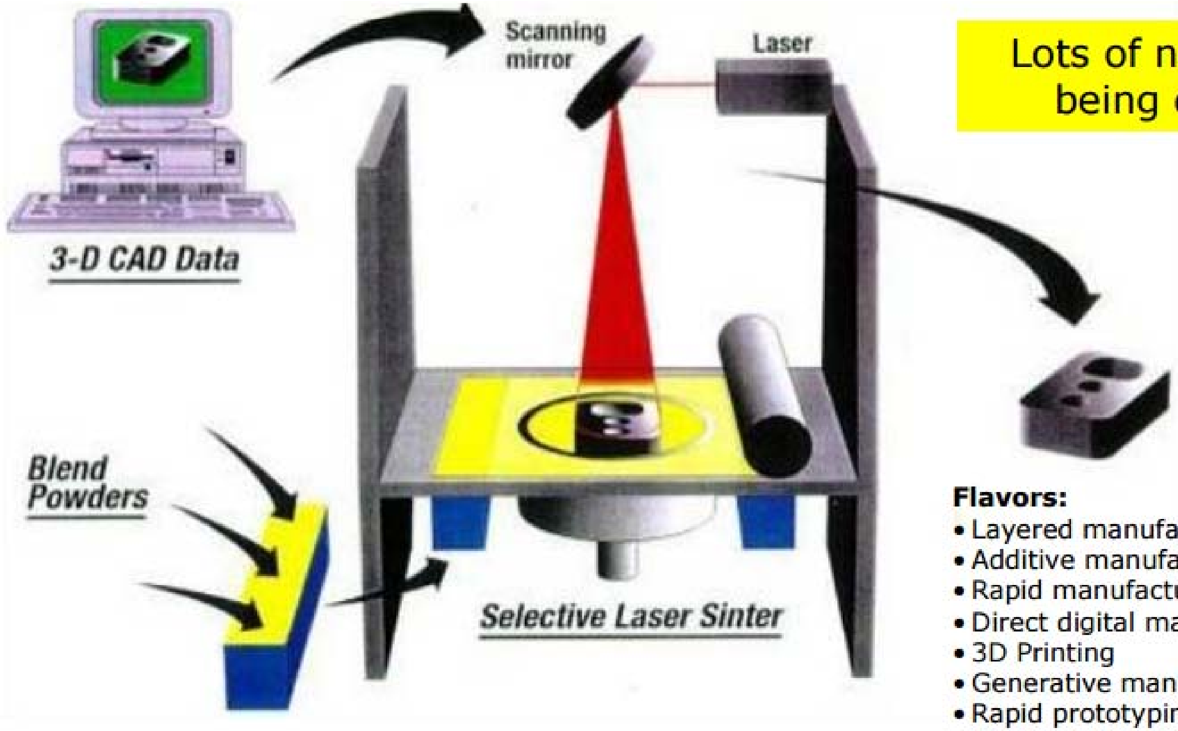


Then baked

Wing and curing processes of a composite B787 fuselage section. Note that it is prepared without cutouts.

4. Modern Design Tools and Techniques

Aerospace manufacturing technologies



Lots of new methods being developed


Complex parts


"Impossible" parts


Molds for complex casting

Flavors:
- Layered manufacturing
- Additive manufacturing
- Rapid manufacturing (RM)
- Direct digital manufacturing (DDM)
- 3D Printing
- Generative manufacturing
- Rapid prototyping
- Selective Laser Sintering (SLS)
- Selective Laser Melting (SLM)
- Fused Deposition Modeling (FDM)
- Electron Beam Melting (EBM)
- Stereo-Lithography Apparatus (SLA)


"Plastic" parts
(Nylon, PEEK, ...)

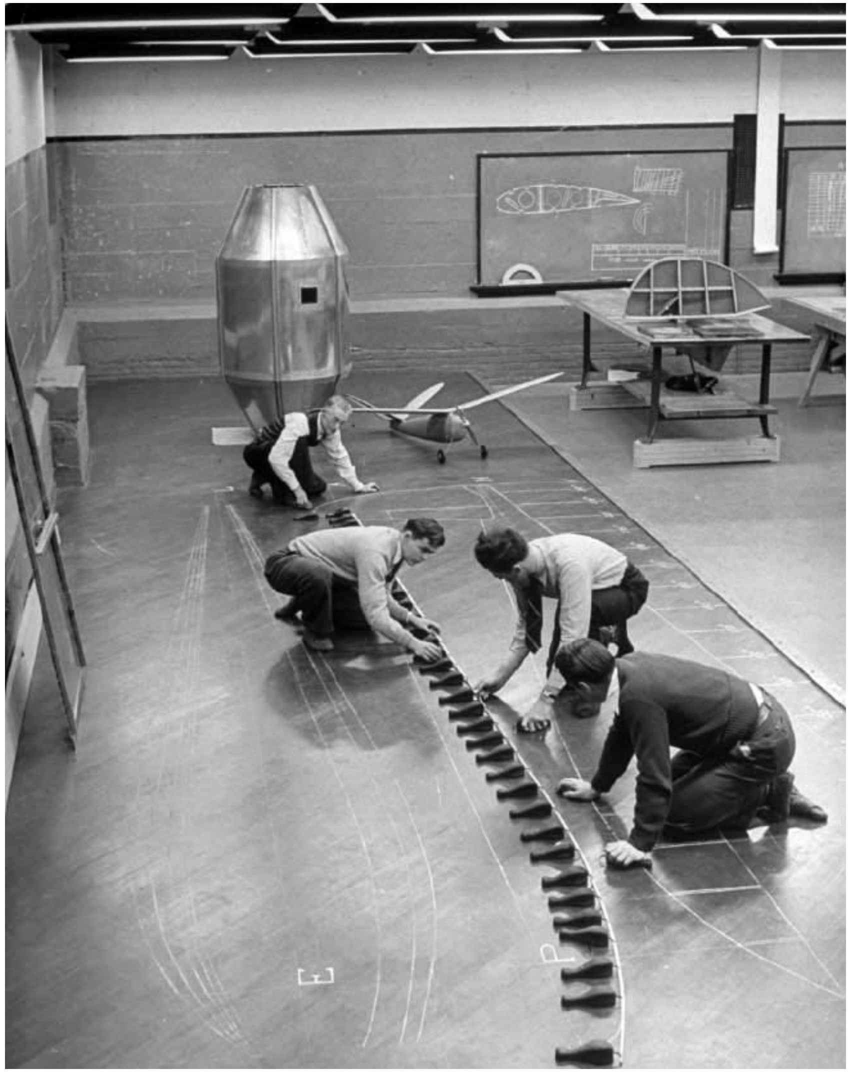

Metals


Biologicals
(bone & bladder scaffolds
teeth, ...)

4. Modern Design Tools and Techniques

Conventional design techniques

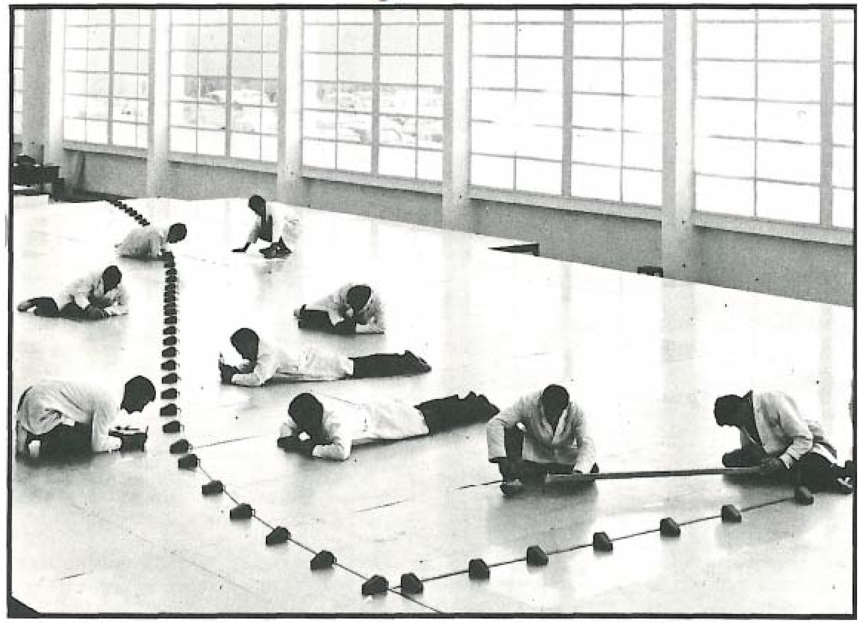
- **Lofting** is a drafting technique (sometimes using mathematical tables) whereby curved lines are generated, to be used in plans for streamlined objects such as aircraft and boats.
- The lines may be drawn on wood and the wood then cut for advanced woodworking.
- The technique can be as simple as bending a flexible object, such as a long strip of thin wood or thin plastic, so that it passes over three non-linear points and scribing the resultant curved line, or plotting the line using computers or mathematical tables.



4. Modern Design Tools and Techniques

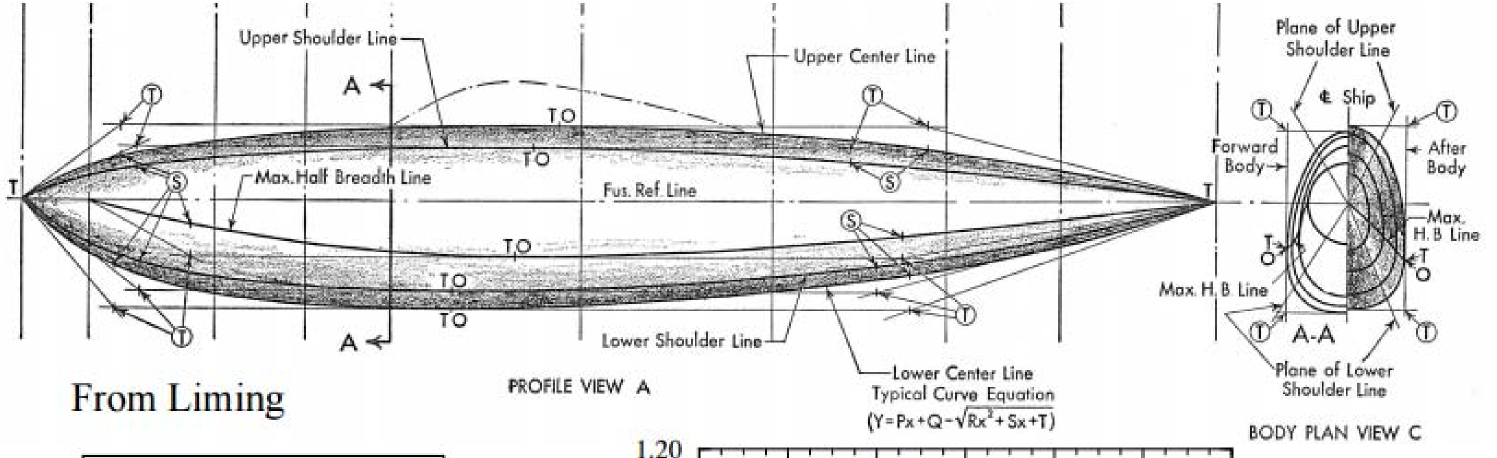
Conventional design techniques

Lofting and Ducks!



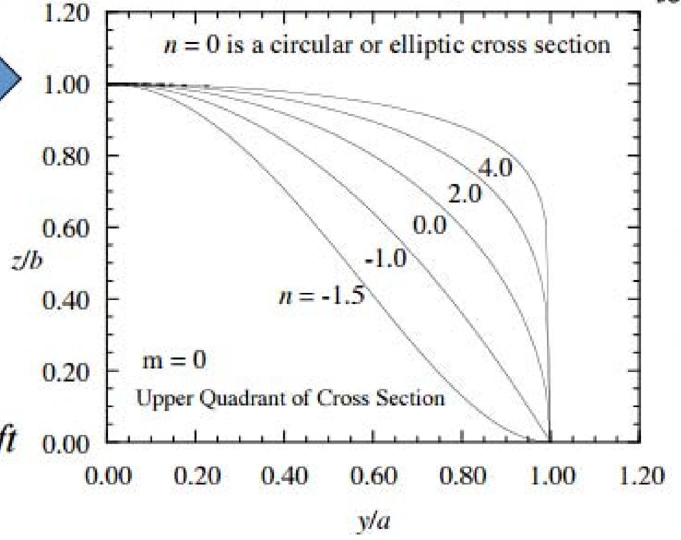
Brits laying out the Concorde Wing!

Longitudinal lines: upper/lower centerline, max half-breadth line, etc.



From Liming

Example – one quadrant of fuselage



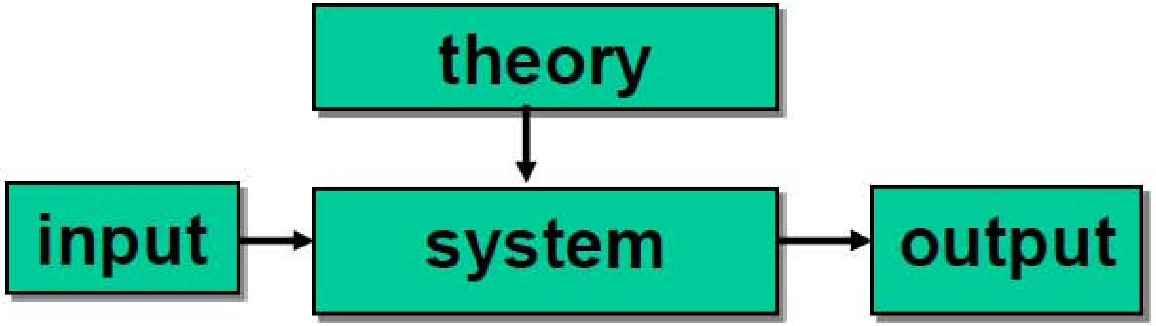
Use whatever you want for a cross-section, super-ellipses are good choices for a wide range of shapes from rectangles to chines.

NASA CR 4465, or *Journal of Aircraft* May-June 1994, pp. 480-487

See App A for the equation of a super ellipse

DESIGN ANALYSIS

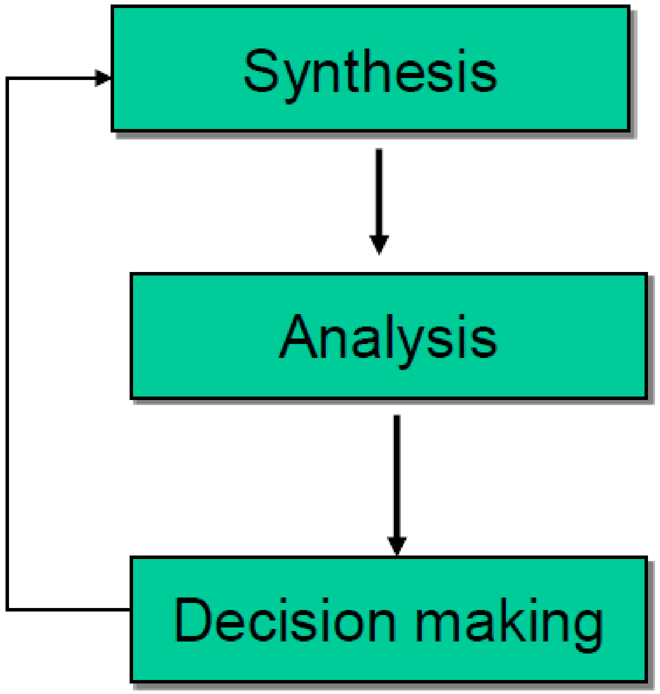
Difference between Design and Analysis



Given	Solution	Process
Input, theory, system	output	analysis
Input, theory, output	system	design
Input, system, output	theory	science research

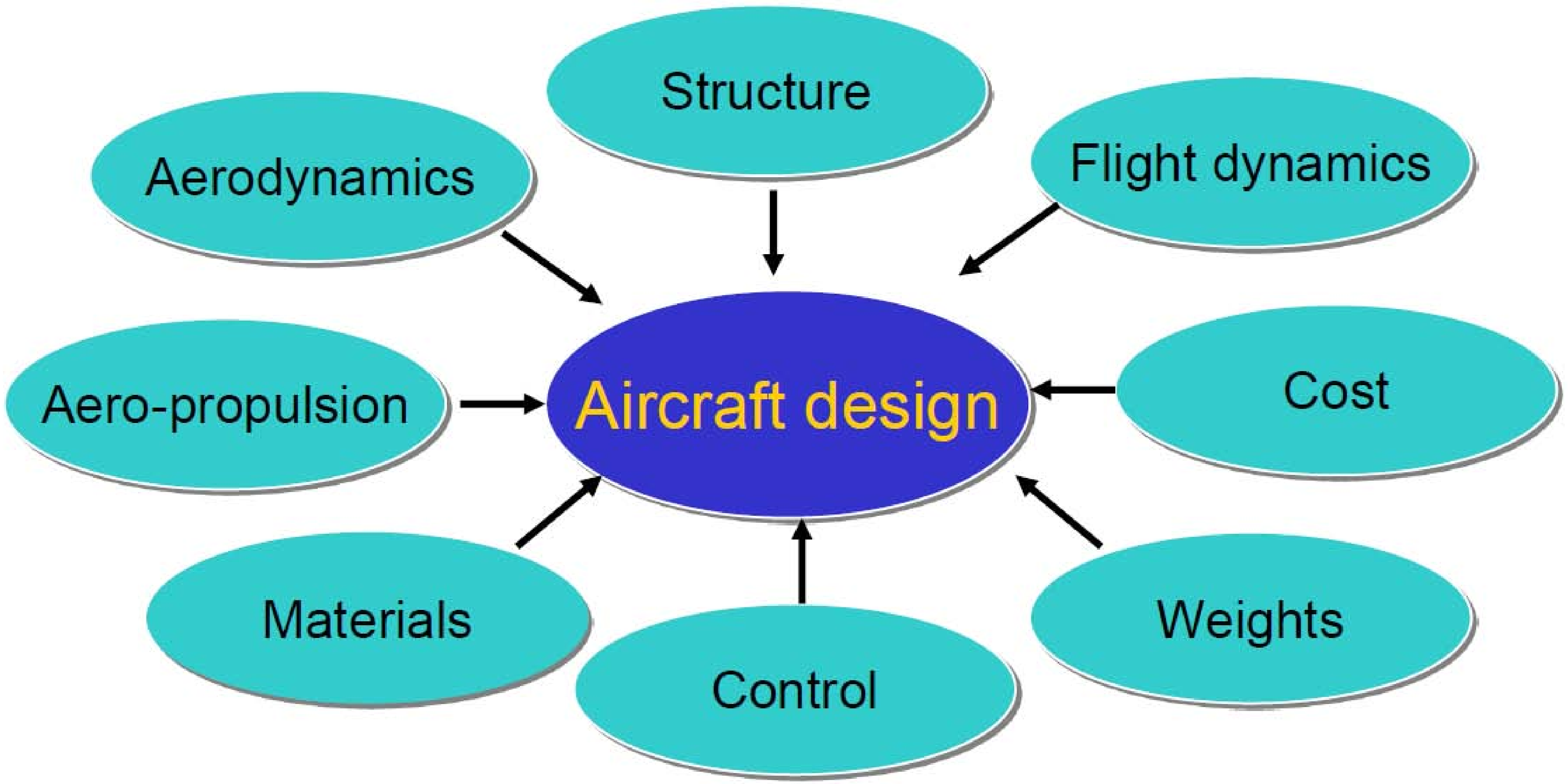
Elements of Design

- Synthesis
  - The combining of separate elements or substances to form a coherent whole.
    - think of some possible solutions (creativity)
    - identify a variety of possible concepts (concept generation)
- Analysis
  - Concept evaluation
    - Mass, aerodynamics, performance analysis,…
- Decision making
  - what's the optimal wing planform ?
  - which airfoil ?
  - what materials ?

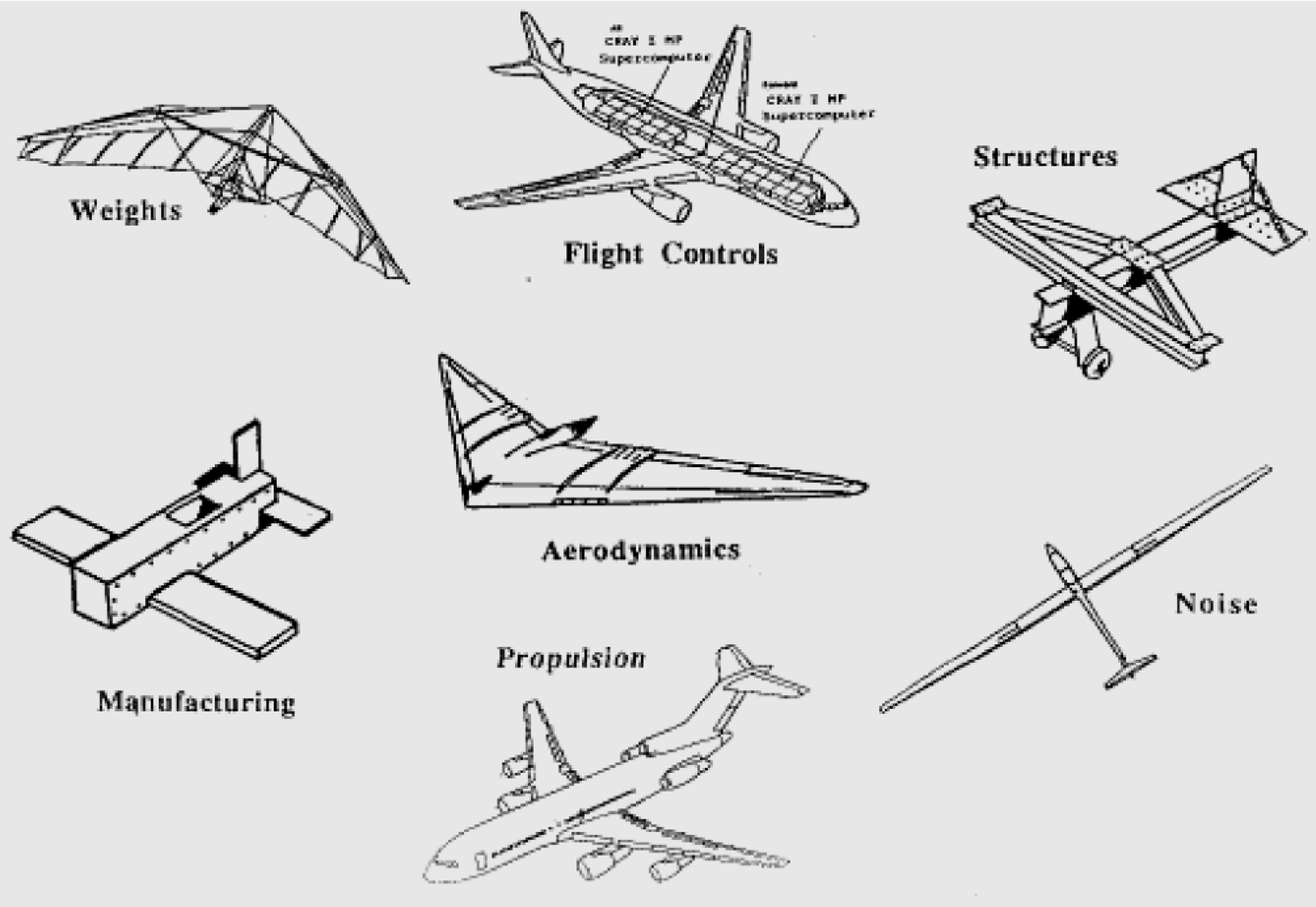


What is Aircraft Design

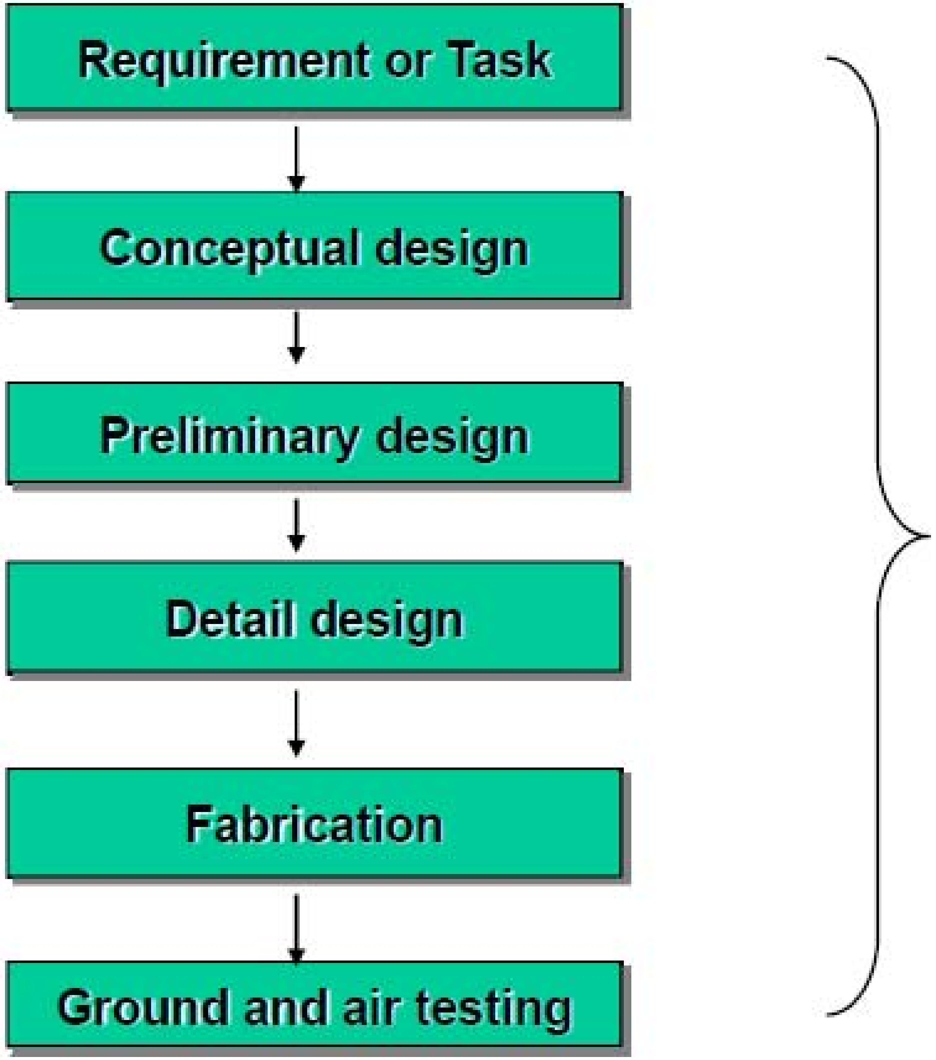
- **Somebody has to understand how it all fits together!**
  - **It is you the *Designer* !**



Aircraft Design Needs Trade-off

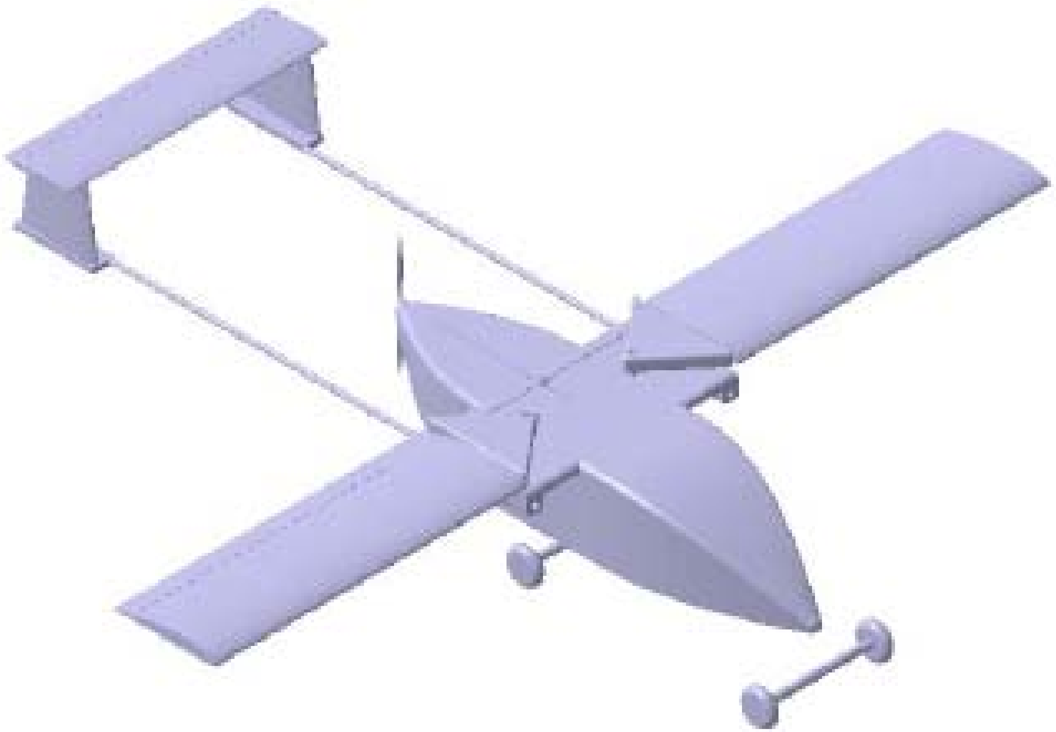


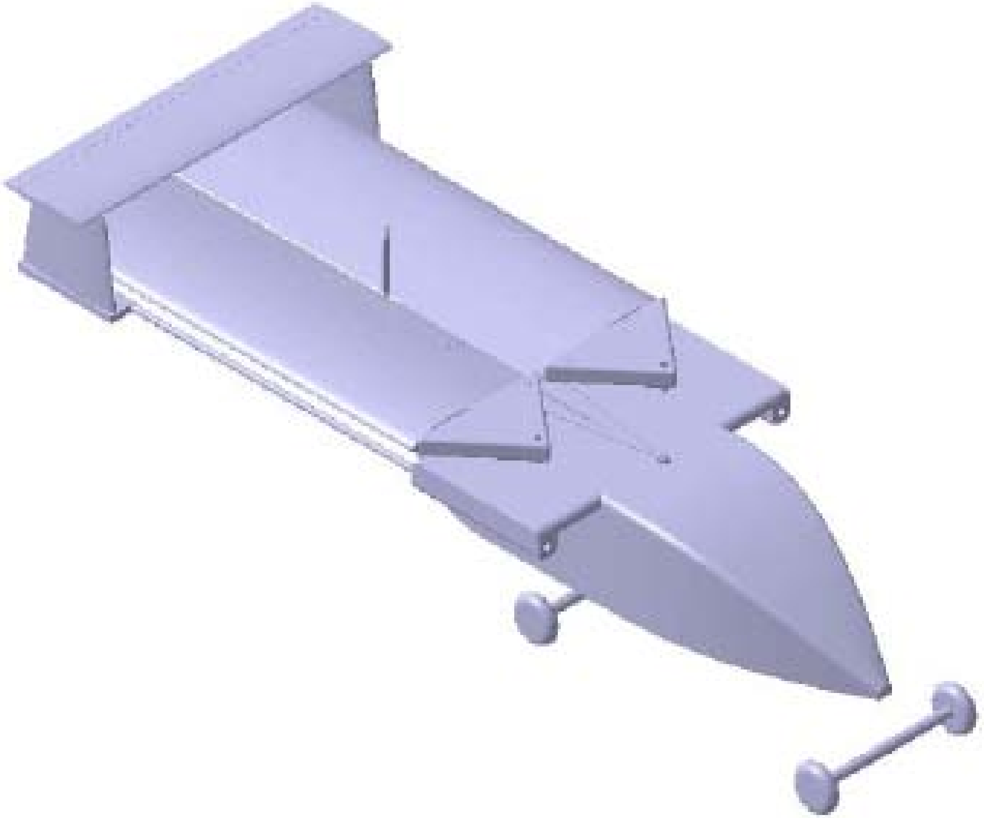
Design and Development Phase



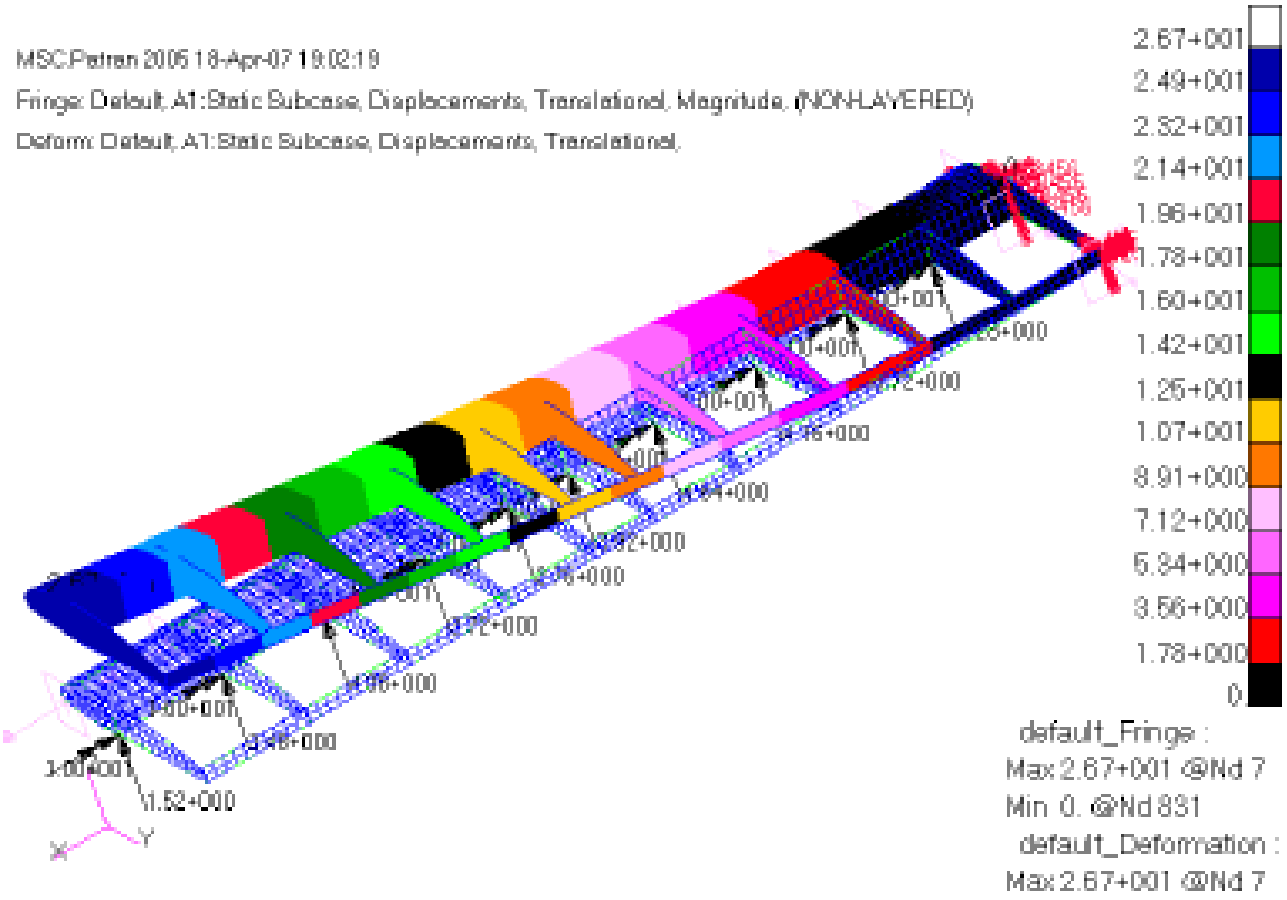
EPUAV project covers all the phases !

The output of Conceptual Design

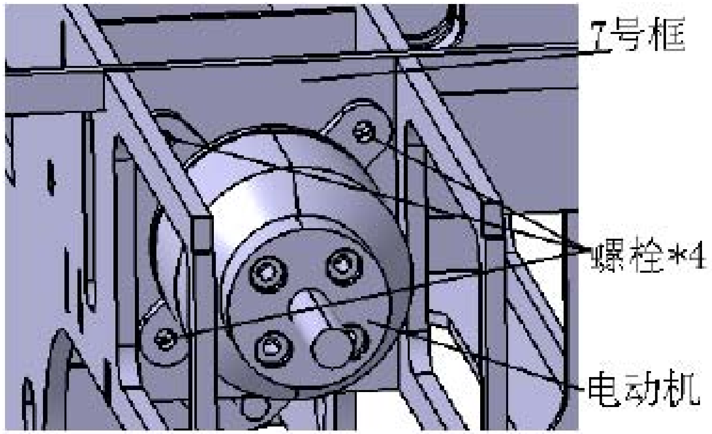


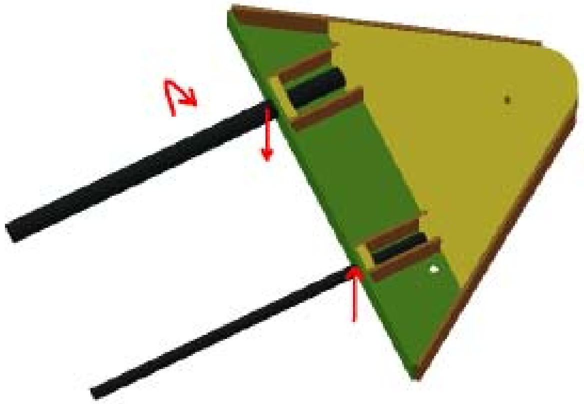


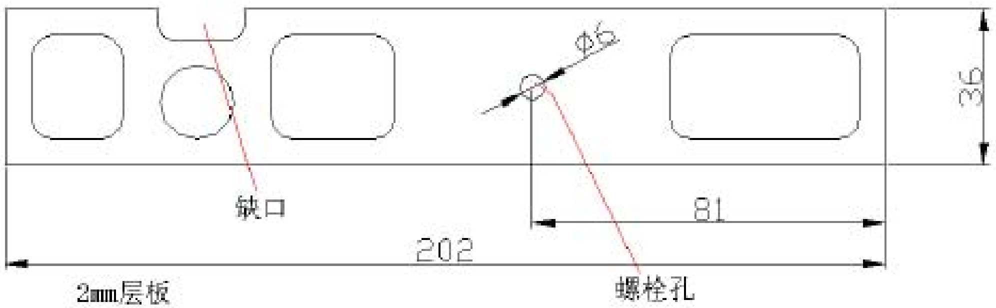
The output of Preliminary Design

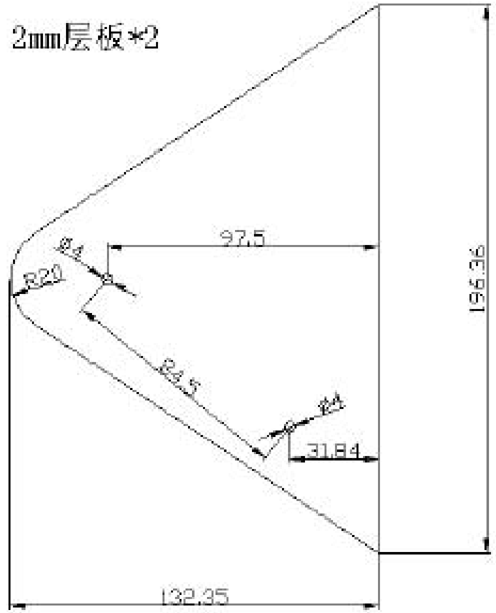


The output of Detailed Design

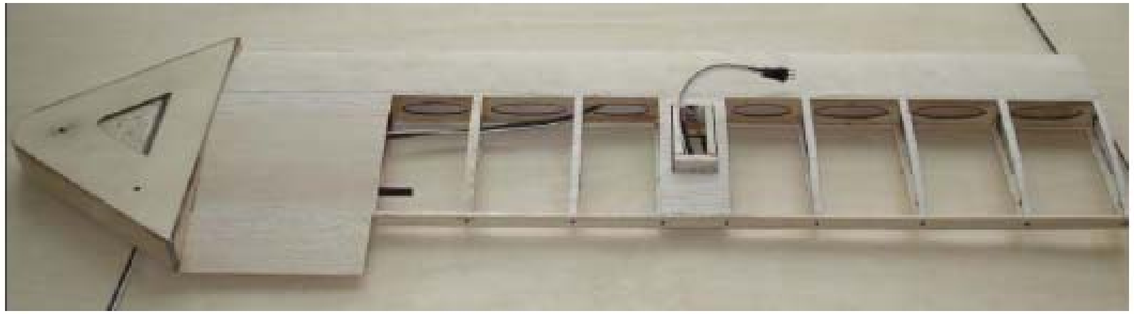


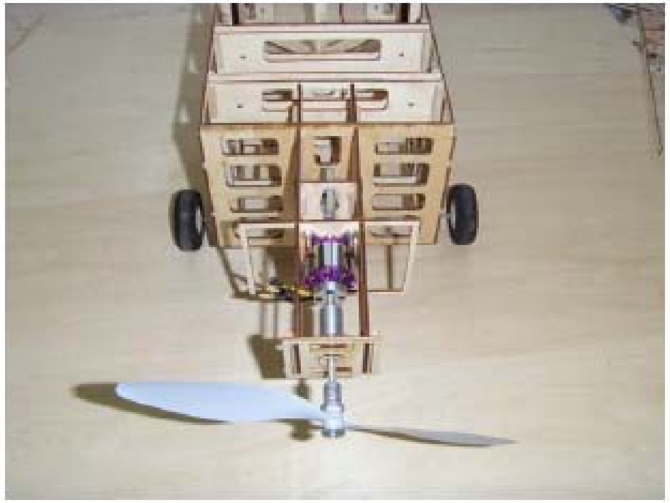






The output of Fabrication





The output of Fabrication

The Flight Test

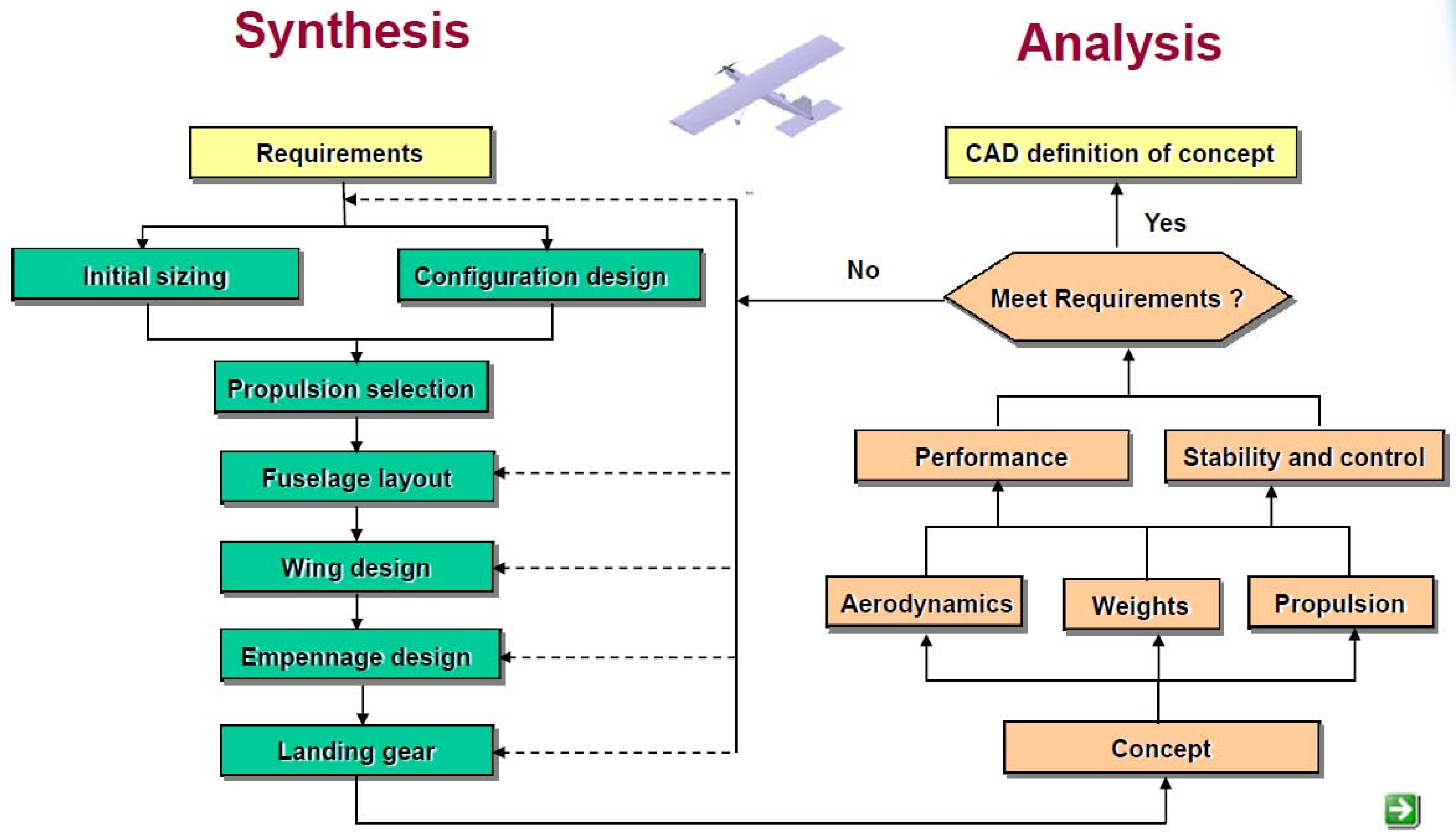
BASIC REQUIREMENTS

- Performance
  - Endurance $T \geq 10$ (min)
  - Maximum level flight speed $V_{max} \geq 18$ (m /s)
  - Stall speed $V_{min} \leq 10$ (m /s)
  - Takeoff distance (ground run) $S_{to} \leq 20$ (m)
  - Gross weight $W_{to} \leq 2.6$ (kg)
  - Payload $W_{PL} \geq 0.5$ (kg)
- Operation requirements
  - Wing span ≤ 2.0 (m)
  - Fuselage length ≤ 1.8 (m)

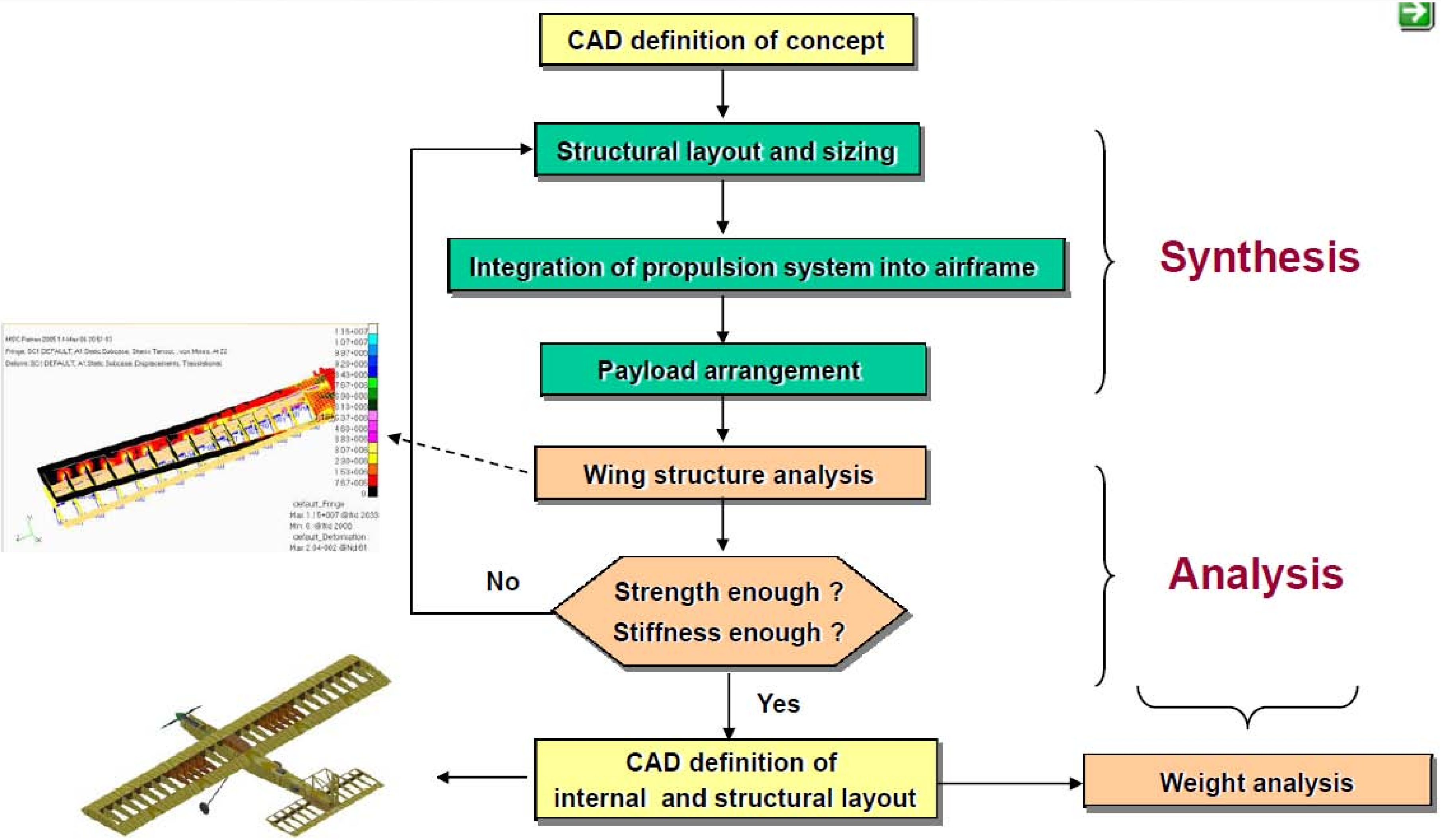
BASIC REQUIREMENTS

- Propulsion
  - One Motor
  - Battery: Li
  - Propeller
  - Speed controller
- Costs
  - Airframe material cost ≤ 2000 （yuan）

CONCEPTUAL DESIGN



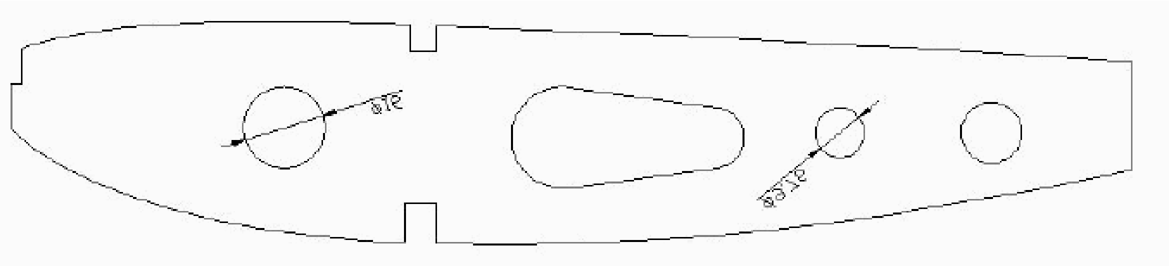
PRELIMINARY DESIGN

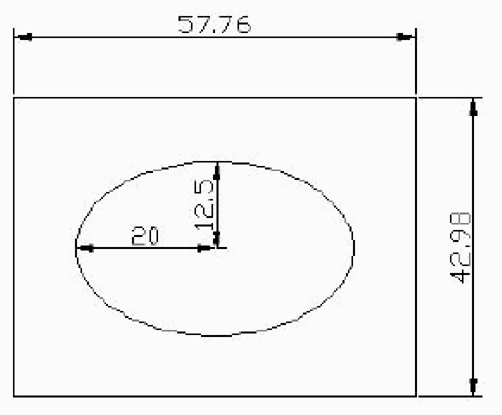


DETAILED DESIGN

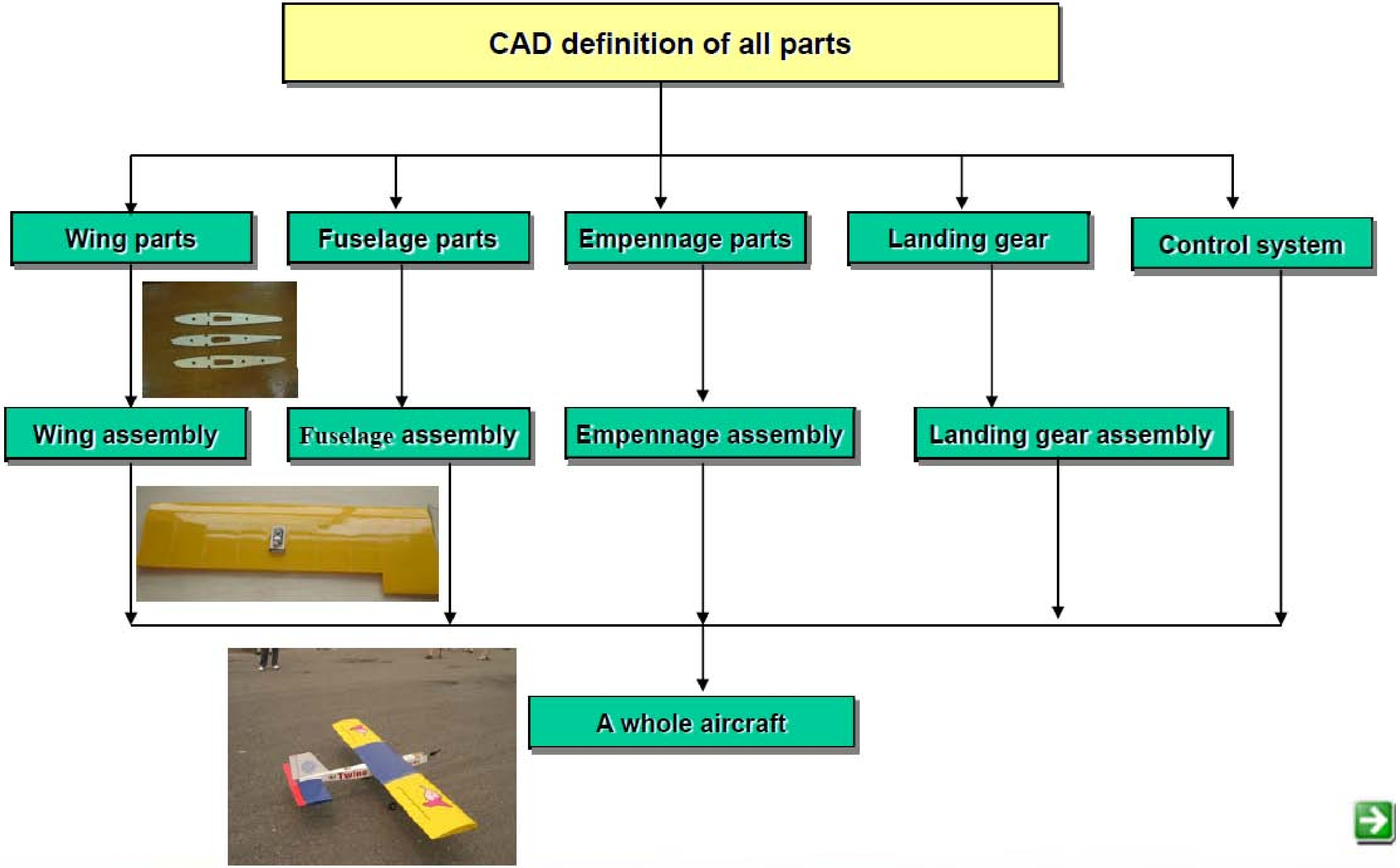
CAD definition of internal and structural layout

- Wing parts
- Fuselage parts
- Empennage parts
- Landing gear
- Control system





FABRICATION



SUMMARY

Phase	Tasks	Tools	Due	Outputs
Conceptual Design	Synthesis Configuration/wing design/ fuselage/empennage/landing gear/ Analysis Aerodynamics / Propulsion / weights / performances/ stability	Historical data Statistical formula CATIA Xfoil AVL	Oct. 23	CAD definition of conceptual design Documents on feasibility
Preliminary Design	Internal / structural layout structural analysis	CATIA, PATRAN	Nov. 13	Layout CAD definition and analysis report
Detail Design	Parts design Tests of airframe structures and control systems	CATIA AutoCAD Test tools	Dec.27	Drawings of all parts Control system
Fabrication	Parts fabrication Assembly	Cutting machine Other tools	Dec . 19	Product
Tests	Ground tests Air tests	Controller	Dec . 23	Video of flight tests
Document	Final presentation by team Design report	Powerpoint Word	Dec .29	Design report