Modern Aircraft Design Techniques

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1. Introduction to Aircraft Design

This chapter describes transport aircraft design. We discuss the key issues facing aircraft designers followed by a review of the physical principles underlying aircraft design. Next we discuss some of the considerations and requirements that designers must satisfy, and the configuration options available to the designer. Finally we describe the airplane design process in some detail and illustrate the process with some examples. The modern commercial transport airplane is a highly integrated system. Thus, the designer has to have an understanding of a number of aspects of engineering, the economics of air transport and the regulatory issues.

Large transports are currently manufactured by two fiercely competitive companies: Boeing in the US, and Airbus in Europe. Smaller "regional jets" are manufactured by several companies, with the key manufacturers being Bombardier of Canada and Embraer of Brazil. Any new airplane designs must offer an advantage over the products currently produced by these manufacturers (known as "airframers"). Key characteristics of current designs can be found in the annual issue of *Aviation Week and Space Technology* called the "Sourcebook".[1] The other standard reference is *Jane's All the Worlds Aircraft*.[2] An electronic Appendix to the book by Jenkinson, Simpkin and Rhodes[3] provides an especially complete summary. Also, essentially all new transport aircraft use turbofan engines for propulsion, although there are a number of smaller turboprop airplanes currently in service.

In picking the basis for a new aircraft design, the manufacturer defines the airplane in terms of range, payload, cruise speed and takeoff and landing distance. These are selected based on marketing studies and in consultation with potential customers. Two examples of decisions that need to be made are aircraft size and speed. The air traffic system operates near saturation. The hub and spoke system means that many passengers take several flights to get to their destination. Often this involves a regional jet carrying from 50-70 passengers to a major hub, and then taking a much larger airplane to their destination. They may even have to transfer once again to a small airplane to get to their final destination. From an airport operations standpoint, this is inefficient. Compounding the problem, the small regional jets require the same airspace resources as a large plane carrying perhaps ten times the number of passengers. Thus the designer needs to decide what size is best for both large and small passenger transports. At one time United Airlines operated two sections of a flight between Denver and Washington's Dulles Airport using Wide-Body aircraft. Frequently, both aircraft were completely full. Thus there is a need for even larger aircraft from the airspace operations viewpoint even though it may not be desirable on the basis of the operation of a single plane. Based on the system demands, Airbus has chosen to develop a very large airplane, the A380. Alternately, Boeing predicts that the current hub and spoke system will be partially replaced with more point-to-point operations, leading to the major market for new aircraft being about the size of B767. They reached this conclusion based on the experience of the North Atlantic routes, where B747s have been replaced with more frequent flights using the smaller B767s.

Another consideration is speed. Designers select the cruise speed in terms of the Mach number, M, the speed of the plane relative to the speed of sound. Because the drag of the airplane rises rapidly as shock waves start to emerge in the flow over the airplane, the economical speed for a particular configuration is limited by the extra drag produced by these shock waves. The speed where the drag starts to increase rapidly is known as the drag divergence Mach number, M_{DD}. Depending on the configuration shape, the drag divergence Mach number may occur between $M = 0.76$ and $M = 0.88$. It is extremely difficult to design an airplane to fly economically at faster speeds, as evidenced by the decision to withdraw the Concorde from service. Numerous supersonic transport design studies since the introduction of the Concorde have failed to produce a viable successor. In addition to the aerodynamic penalties, the sonic boom restriction for supersonic flight over land and the difficulty of achieving low enough noise around airports (so-called community noise) makes the challenge especially severe.

The choice of design characteristics in terms of size and speed is at least as important as the detailed execution of the design. Selecting the right combination of performance and payload characteristics is known as the “you bet your company” decision. The small number of manufacturers building commercial transports today provides the proof of this statement.

The starting point for any vehicle system design work is to have information about current systems. In this chapter we will use fifteen recent transports as examples of current designs. We have divided them into three categories, narrow body transports, which have a single aisle, wide-body aircraft, which have two aisles, and regional jets, which are small narrow body aircraft. Table 1 provides a summary of the key characteristics of these airplanes. The values shown are the design values, and the range and payload, and associated takeoff and landing distances can vary significantly. Detailed performance data can be found for Boeing airplanes on their web site: www.boeing.com. Other airframers may provide similar information.

While this section provides an overview, numerous books have been written on airplane design. Two books emphasizing commercial transport design are by Jenkinson, Simpkin and Rhodes[3] in the UK and Schaufele in the U.S.[4] Simpkin had a long career at Rolls Royce, and that book includes excellent insight into propulsion system considerations. Schaufele was involved in numerous Douglas Aircraft Company transport programs. Two other key design books are by Raymer[5] and Roskam (an eight volume set).[6]

Table 1. Key Current Transport Aircraft

Aircraft	TOGW (lb)	Empty Weight (lb)	Wingspan, ft.	No. of Pass.	Range (nm)	Cruise Mach	Takeoff Distance (ft)	Landing Distance (ft)
Narrow Body								
A320-200	169,800	92,000	111.8	150	3,500	0.78	5,900	4,800
B717-200	121,000	68,500	93.3	106	2,371	0.76	5,750	5,000
B737-600	143,500	81,000	112.6	110	3,511	0.782	5,900	4,400
B757-300	273,000	141,690	124.8	243	3,908	0.80	8,650	5,750
Wide Body								
A330-300	513,670	274,650	197.8	440	6,450	0.82	8,700	5,873
A340-500	811,300	376,800	208.2	375	9,960	0.83	10,450	6,601
A380-800	1,234,600	611,000	261.8	555	9,200	0.85	9,350	6,200
B747-400	875,000	398,800	211.4	416	8,356	0.85	9,950	7,150
B747-400ER	911,000	406,900	211.4	416	8,828	0.85	10,900	7,150
B767-300	345,000	196,000	156.1	218	5,450	0.80	7,550	5,200
B777-300	660,000	342,900	199.9	368	6,854	0.84	12,150	6,050
B777-300ER	750,000	372,800	212.6	365	8,258	0.84	10,700	6,300
Regional Jets								
CRJ200(ER)	51,000	30,500	69.7	50	1,895	0.74	5,800	4,850
CRJ700(ER)	75,000	43,500	76.3	70	2,284	0.78	5,500	4,850
ERJ135ER	41,888	25,069	65.8	37	1,530	0.76	5,052	4,363
ERJ145ER	54,415	26,270	65.8	50	1,220	0.76	5,839	4,495

2. Essential Physics and Technology of Aircraft Flight

Aircraft fly by exploiting the laws of nature. Essentially, lift produced by the wing has to equal the weight of the airplane, and the thrust of the engines must counter the drag. The goal is to use physics principles to achieve efficient flight. A successful design requires the careful integration of a number of different disciplines. To understand the basic issues we need to establish the terminology and fundamentals associated with the key flight disciplines. These include:

- aerodynamics
- propulsion
- control and stability
- structures/materials
- avionics and systems

The book by Shevell[7] describes these disciplines as related to airplane design, together with a description of methods used to compute airplane performance.

To understand how to balance these technologies, designers use weight. The lightest airplane that does the job is considered the best. The real metric should be some form of cost, but this is difficult to estimate. Traditionally, designers have used weight as a surrogate for cost. For designs using similar technology and sophistication, the lightest airplane costs least. One airplane designer said that airplanes were like hamburger, you buy them by the pound. A study carried out at Boeing[8] showed that an airplane designed to do a given mission at minimum takeoff weight was a good design for a wide range of operating conditions compared to an airplane designed for minimum fuel use or minimum empty weight.

We can break the weight of the airplane up into various components. For our purposes, we will consider the weight to be:

$$W_{TO} = W_{empty} + W_{fuel} + W_{payload} \tag{1}$$

where W_{TO} is the takeoff weight, W_{empty} is the empty weight, mainly the structure and the propulsion system, W_{fuel} is the fuel weight, and $W_{payload}$ is the payload weight, which for commercial transports is passengers and freight. Very crudely, W_{empty} is related to the cost to build the airplane, and W_{fuel} is the cost to operate the airplane. The benefit of a new technology is assessed by examining its effect on weight.

Weight is critically important in aircraft design. This example illustrates why. If

$$W_{TO} = W_{struct} + W_{prop} + W_{fuel} + \underbrace{W_{payload} + W_{systems}}_{W_{fixed}}$$

$$= W_{TO}\left(\frac{W_{struct}}{W_{TO}} + \frac{W_{prop}}{W_{TO}} + \frac{W_{fuel}}{W_{TO}}\right) + W_{fixed}$$

$$or: \left[1 - \left(\frac{W_{struct}}{W_{TO}} + \frac{W_{prop}}{W_{TO}} + \frac{W_{fuel}}{W_{TO}}\right)\right] W_{TO} = W_{fixed}$$

$$and$$

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

Using weight fractions, which is a typical way to view the design, the structural fraction could be 0.25, the propulsion fraction 0.1, and the fuel fraction 0.40. Thus:

$$W_{TO} = \frac{W_{fixed}}{(1 - 0.75)} = 4 \cdot W_{fixed}$$

Here 4 is the *growth factor*, so that for each pound of increased fixed weight, the airplane weight increases by four pounds to fly the same distance. Also, note that the denominator could approach zero if the problem is too difficult. This is an essential issue for aerospace systems. Weight control and its accurate estimation in design are very important.

The weight will be found for the airplane carrying the design payload over the design range. To connect the range and payload to the weight, we use the equation for the range known as the Brequet range equation:

$$R = \frac{V(L/D)}{sfc}\ln\left(\frac{W_i}{W_f}\right) \tag{2}$$

In this equation R is the range of the airplane (usually given in the design requirement), V is the airplane speed, L is the lift of the airplane (assumed equal to the weight of the airplane, W) and D is the drag. Since the weight of the plane varies as fuel is used, the values inside the log term correspond to the initial weight, W_i, and the final weight W_f. The specific fuel consumption, *sfc*, is the fuel used per pound of thrust per hour. The aerodynamic efficiency is measured by the lift to drag ratio, L/D, the propulsive efficiency is given by the *sfc*, and the structural efficiency is given by the empty weight of the plane as a fraction of the takeoff weight.

Aerodynamics

The airplane must generate enough lift to support its weight, with a low drag so that the L/D ratio is “high”. For a long-range transport this ratio should approach 20. The lift also has to be distributed around the center of gravity so that the longitudinal (pitching) moment about the center of gravity can be set to zero through the use of controls without causing extra drag. This requirement is referred to as “trim”. Extra drag arising from this requirement is “trim drag”.

Drag arises from two primary sources, the viscosity of the air causes friction on the surface exposed to the airstream. This “wetted” area should be held to a minimum. To account for other drag associated with surface irregularities, the drag includes contributions from the various antennas, fairings and manufacturing gaps. Taken together, this drag is generally known as the parasite drag. The other major contribution to drag arises from the physics of the generation of lift, and is thus known as drag due to lift. When the wing generates lift, the flowfield is deflected down, causing an induced angle over the wing. This induced angle leads to an induced drag. The size of the induced angle depends on the spanloading of the wing, and can be reduced if the span of the wing is large. The other contribution to drag arises due to the presence of shock waves. Shock waves start to appear as the plane's speed approaches the speed of sound, and the sudden increase in drag once caused an engineer to describe this "drag rise" as a "sound barrier".

To quantify the aerodynamic characteristics, designers present the aerodynamic characteristics in coefficient form, removing most of the size effects and making the speed effects more clear. Typical coefficients are the lift, drag and pitching moment coefficients, which are:

$$C_L = \frac{L}{\frac{1}{2}\rho_\infty V^2 S_{ref}}, \qquad C_D = \frac{D}{\frac{1}{2}\rho_\infty V^2 S_{ref}}, \qquad C_m = \frac{M}{\frac{1}{2}\rho_\infty V^2 \bar{c} S_{ref}} \tag{3}$$

where *L*, *D* and *M* are the lift, drag and pitching moment respectively. These values are normalized by the dynamic pressure, *q*, and a reference area, S_{ref} and length scale, *c*, as appropriate. The dynamic pressure is defined as $q = \frac{1}{2}\rho_\infty V^2$. Here ρ_∞ is the atmospheric density at the flight altitude. The subscript infinity refers to the freestream values. One other nondimensional quantity also frequently arises, know as the aspect ratio, $AR = b^2/S_{ref}$.

In particular, the drag coefficient is given approximately as a function of lift coefficient by the relation

$$C_D = C_{D_0} + \frac{C_L^2}{\pi ARE} \tag{4}$$

where C_{D_0} is the parasite drag and the second term is the drag due to lift term mentioned above. *E* is the airplane efficiency factor, usually around 0.9. Many variations on this formula are available, and in particular, when the airplane starts to approach the speed of sound and wave drag starts to arise, the formula needs to include an extra term, $C_{D_{wave}}(M, C_L)$. Assuming wave drag is small, and that the airplane is designed to avoid flow separation at its maximum efficiency, the drag relation given above can be used to find the maximum value of *L*/*D* (which occurs when the parasite and induced drag are equal) and the corresponding C_L:

$$\left(\frac{L}{D}\right)_{\max} = \frac{1}{2}\sqrt{\frac{\pi A R E}{C_{D_0}}} \qquad (5)$$

and

$$C_L\Big)_{L/D_{\max}} = \sqrt{\pi A R E C_{D_0}} \qquad (6)$$

These relations show the importance of streamlining to achieve a low C_{D_0}. They also seem to suggest that the aspect ratio should be large. However, the coefficient form is misleading here, and the way to reduce the induced drag is actually best shown by the dimensional form:

$$D_i = \frac{1}{q\pi E}\left(\frac{W}{b}\right)^2, \qquad (7)$$

where *b* is the span of the wing, and we’ve assumed that the weight, *W*, equals the lift, *L*.

Finally, to delay the onset of drag arising from the presence of shock waves, the wings are swept. We will present a table below containing the values of wing sweep for current transports.

The other critical aspect of aerodynamic design is the ability to generate a high enough lift coefficient to be able to land at an acceptable speed. This is characterized by the value of $C_{L_{\max}}$ for a particular configuration. The so-called stalling speed of the airplane is the slowest possible speed at which the airplane can sustain level flight, and can be found using the definition of the lift coefficient as:

$$V_{stall} = \sqrt{\frac{2(W/S)}{\rho C_{L_{\max}}}}, \qquad (8)$$

and to achieve a low stall speed we need either a low wing loading, *W/S*, or a high $C_{L_{\max}}$. Typically, an efficient wing loading for cruise leads to a requirement for a high value of $C_{L_{\max}}$, meaning that high-lift systems are required. High lift systems consist of leading and trailing edge devices such as single-, double-, and even triple- slotted flaps on the rear of the wing, and possibly slats on the leading edge of the wing. The higher the lift requirement, the more complicated and costly the high lift system has to be. In any event, mechanical high lift systems have a $C_{L_{\max}}$ limit of about 3. Table 2 provides an example of the $C_{L_{\max}}$ values for various Boeing airplanes. These values were cited in a paper by Brune and McMasters,[9] A good recent survey of high lift systems and design methodology has been put together by van Dam.[10]

Table 2. Values of C_{Lmax} for some Boeing airplanes.

Model	**CLmax**	**Device Type**
B-47/B-52	1.8	Single slotted Fowler flap
367-80/KC-135	1.78	Double slotted flap
707-320/E-3A	2.2	Double slotted flap and Kreuger Leading edge flap
727	2.79	variable camber Kreuger and tripl slotted flap
747/E-4A	2.45	Variable camber Kreuger and triple slotted flap
767	2.45	Slot and single slotted flap

Propulsion

Virtually all modern transport aircraft use high bypass ratio turbofan engines. These engines are much quieter and more fuel efficient than the original turbojet engines. The turbofan engine has a core flow that passes through a compressor, then enters the combustor and drives a turbine. This is known as the hot airstream. The turbine also drives a compressor that accelerates a large mass of air that doesn’t pass through the combustor, and is know as the cold flow. The ratio of the cold air to the hot air is the bypass ratio. From an airplane design standpoint, the key considerations are the engine weight per pound of thrust and the fuel consumption.

$$W_{eng} = \frac{T}{\left(T/W\right)_{eng}} \tag{9}$$

where the engine thrust is given by T. Typical values of the T/W of a high bypass ratio engine are around 6-7. The fuel flow is given as:

$$sfc = \frac{\dot{w}_f}{T} \tag{10}$$

where $\dot{w}_f$ is the fuel flow in pounds per hour, and the thrust is given in pounds. Thus the units for *sfc* are “per hour”. There can be some confusion in units because the *sfc* is sometimes described as a mass flow. But in the US the quoted values of *sfc* are as a weight flow. Table 3 provides the characteristics of the engine used in the aircraft listed in Table 1.

Values for thrust and fuel flow of an engine are quoted for sea-level static conditions. Both the maximum thrust and fuel flow vary with speed and altitude. In general the thrust decreases with altitude, and with speed at seal level, but remains roughly constant with speed at altitude. The *sfc* increases with speed, and decreases with altitude. Examples of the variations can be found in Appendix E of Raymer’s aircraft design book.[5] More details on engines related to airplane design can be found in the book by Cumpsty.[11]

Control and stability

Safety plays a key role in defining the requirements for ensuring that the airplane is controllable in all flight conditions. Stability of the motion is obtained either through the basic airframe stability characteristics or by the use of an electronic control system providing apparent stability to the pilot or autopilot. Originally airplane controls used simple cable systems to move the surfaces. When airplanes became large and fast the control forces using these types of controls became too large for the pilots to be able to move surfaces, and hydraulic systems were incorporated. Now some airplanes are using electric actuation. Traditionally controls are required to pitch, roll and yaw the airplane. Pitch stability is provided by the horizontal stabilizer, which has an elevator for control. Similarly, directional stability is provided by the vertical stabilizer, which incorporated a rudder for directional control. Roll control is provided by ailerons, which are located on the wing of the airplane. In some cases one control surface may be required to perform several functions, and in some cases multiple surface are used simultaneously to achieve the desired control. A good reference for control and stability is available in Nelson's book.[12]

Critical situations defining the size of the required controls include engine out conditions, crosswind takeoff and landing, and roll response. Longitudinal control requirements are dictated by the ability to rotate the airplane nose up at takeoff and generate enough lift when the airplane slows down to land. These conditions have to be met under all flight and center of gravity location conditions.

Table 3. Engines for Current Transport Aircraft

Aircraft	Engine	Thrust (lbs)	Weight (lbs)	sfc	T/Weng
Narrow Body					
A320-200	IAE V2527-A5	26,500	5,230	0.36	5.1
B717-200	RR BR 715	21,000	4,597	0.37	4.6
B737-600	CFM56-7B	20,600	5,234	0.36	3.9
B757-300	PW 2040	41,700	7,300	0.345	5.7
Wide Body					
A330-300	Trent 768	71,100	10,467	0.56	6.8
A340-500	Trent 553	53,000	10,660	0.54	5.0
A380-800	Trent 970	70,000	-	0.51	-
B747-400	GE CF6-80C2	58,000	9,790	0.323	5.9
B747-400ER	GE CF6-80C2	58,000	9,790	0.323	5.9
B767-300	GE CF6-80C2	58,100	9,790	0.317	5.9
B777-300	RR Trent 892	95,000	13,100	0.56	7.25
B777-300ER	GE90-115	115,000	18,260	-	6.3
Regional Jets					
CRJ200(ER)	GE CF34-3B1	9,220	1,670	0.346	5.5
CRJ700(ER)	GE CF34-8C1	13,790	2,350	0.37	5.9
ERJ135ER	AE3007-A3	8,917	1,586	0.63	5.6
ERJ145ER	AE3007-A1/1	8,917	1,586	0.63	5.6

Structures/Materials

Aluminum has been the primary material used in commercial transports. However, composite materials have now reached a stage of development that allows them to be widely used, providing the required strength at a much lighter weight. The structure is designed for an extremely wide range of loads, including taxiing and ground handling (bump, touchdown, etc.) and flight loads for both sustained maneuvers and gusts.

Typically, transport aircraft consist of a constant cross section pressurized fuselage that is essentially round, and a wing that is essentially a cantilever beam. The constant cross section of the fuselage allows the airplane to be stretched to various sizes by adding additional frames, some in front of, and some behind the wing to allow the plane to be properly balanced. However, if the airplane becomes too long, then the tail will scrape on the ground when the airplane rotates for takeoff. The wing typically consists of spars running along the length of the wing, and ribs running between the front and back of the wing. The wing is designed so that fuel is carried between the front and rear spars. Fuel is also carried in the fuselage where the wing carry-through structure is located. Carrying fuel in the wing, as well as the wing support of pylon-mounted engines helps reduce the structural weight required by counteracting the load due to the wing lift. Because the wing is a type of cantilever beam, the wing weight is reduced by increasing the depth of the beam, which increases the so-called thickness-to-chord ratio, *t/c*. This increases the aerodynamic drag. Thus the proper choice of *t/c* requires a system-level tradeoff. An excellent book illustrating the structural design of transport aircraft is by Niu.[13]

Avionics and systems

Modern aircraft incorporate many sophisticated systems to allow them to operate efficiently and safely. The electronic systems are constantly changing, and current periodicals such as

Aviation Week should be read to find out about the latest trends. The survey by Keyton[14] provides an excellent overview of the electronics systems used on transports. Advances in the various systems allowed modern transports airplanes to use two-man crews. Fielding's book[15] has a good summary of the systems used on transport aircraft. The basic systems are:

Avionics systems

- Communications
- Navigation
- Radar
- Auto-pilot
- Flight control system

Other Systems

- Air conditioning and pressurization
- Anti-icing
- Electrical power system
- Hydraulic system
- Fuel system
- APU, the auxiliary power unit
- Landing gear

Each of these systems, listed in a single line, are associated with entire companies dedicated to providing safe, economical components for the aircraft industry.

3. Transport Aircraft Design Considerations and Requirements

The current environment and key issues for aircraft designers

In addition to the overall selection of the number of passengers and design range, described above, the designer has to consider a number of other issues. One of the key issues has been the selection of the seat width and distance between seats, the pitch. The seating arrangements are closely associated with the choice of the fuselage diameter. This has been a key design issue since the selection of the fuselage diameter for the DC-8 and B-707s, the first modern jet transports. This can be a key selling point of the aircraft. For example, currently Boeing uses the same fuselage diameter for its 737 and 757 transports: 148 inches. The comparable Airbus product, the A320, uses a fuselage diameter of 155 inches. Because of the details of the interior arrangements, both companies argue that they have superior passenger comfort. Typically in economy class the aisles are 18 inches wide and economy class seats are approximately 17.5 to 19 inches wide, depending on how they are measured (whether to consider the armrest). In general, the wider the aircraft the more options are available, and the airlines can select the seating arrangement.

The distance between rows, known as the pitch, can be selected by the airline, and is not as critical in the design process. Airplanes can be lengthened, or shortened, relatively cheaply. The fuselage diameter essentially cannot be changed once the airplane goes into production. Typically the pitch for economy class is 30 inches, and increases for business and first class seating.

Emergency exits, which are dictated by regulatory agencies, overhead bins and lavatories are also key considerations. In addition, access for service vehicles has to be considered. In some cases you must include enough ground clearance that carts can pass underneath the airplane.

In addition to passengers, transport airlines depend on freight for a significant portion of their revenue. Thus the room for baggage and freight also requires attention. There are a number of standardized shipping containers, and the fuselage must be designed to accommodate them. The most common container is known as an LD-3. These can be fit two abreast in a B777. The LD-3 is 64 inches high and 60.4 inches deep. The cross section is 79 inches wide at the top and 61.5 inches wide at the bottom, the edge being clipped off at approximately a 45 degree angle to allow it to fit efficiently within the near circular fuselage cross-section. This container has a volume of 158 cubic feet, and can carry up to 2830 pounds.

The modern transports turn out to have about the “right” volume available as a natural consequence of the near-circular cylindrical fuselage and the single passenger deck seating. Regional jets, which have a smaller fuselage diameters frequently can’t fit all the passenger luggage in the plane, and when you are told that “the baggage didn’t make the flight”, it probably actually means it didn’t fit on the plane. Considering large double-deck transports, a similar problem exists, and some of the main deck may be required to be used for baggage and freight.

Details of passenger cabin layout are generally available from the manufacturer’s website. Boeing and Embraer are particularly good. Texts such as Jenkinson, et al[3] provide more details.

Regulatory Requirements

The aircraft designer has to accommodate numerous requirements. Safety is of paramount importance, and is associated with numerous regulatory considerations. Environmental considerations are also important, with noise and emissions becoming increasingly critical, especially in Europe. In addition, security has become an important consideration. These requirements arise independently of the aircraft economics, passenger comfort, and performance characteristics of the introduction of a successful new airplane.

In the US, the FAA must certify aircraft. The requirements are given in Federal Airworthiness Regulations (FARs). In Europe the regulations are Joint Airworthiness Requirements (JARs). Commercial aircraft are generally governed by:

- Regulatory design requirements
    - FAR Pt 25: the design of the aircraft,
    - FAR Pt 121: the operation of the aircraft
    - FAR Pt 36: noise requirements
    - Security
    - Airport requirements
    - Icing
    - ETOPS: extended range Twin-engine Operations

An airplane design has to be consistent with the airports it is expected to use. Details of airport design for different size airplanes can be found in the book by Ashford and Wright.[16] Table 4 defines the basic characteristics. The FAA sets standards and defines airplanes within six categories, related to the airplane wingspan. A key consideration for new large airplanes is the maximum wingspan on the Class VI airport of 262 feet, the so-called “80 meter gatebox” limit. The new Airbus A380, listed, table 1 is constrained in span to meet this requirement. Because we have shown that the wingspan is a key to low induced drag, it is clear that the A380 will be sacrificing aerodynamic efficiency to meet this requirement.

Table 4. FAA Airplane Design Groups for Geometric Design of Airports.

Airplane Design Group	Wingspan, ft.	Runway width, ft.	Runway centerline to taxiway centerline, ft.
I	up to 49	100	400
II	49 - 79	100	400
III	79 - 118	100	400
IV	118 - 171	150	400
V	171 - 197	150	varies
VI	197 - 262	200	600

Another issue for airplane designers is the thickness of the runway required. If too much weight is place on a tire, the runway may be damaged. Thus you see fuselage-mounted gears on B747s, and the B-777 has a six wheel bogy instead of the usual 4-wheel bogy. This general area is known as flotation analysis. because of the weight concentrated on each tire, the pavement thickness requirements can be considerable. The DC-10 makes the greatest demands on pavements. Typically it might require asphalt pavements of around 30 inch thickness, and concrete pavements to be 13 inches thick. An overview of langing gear design issues is available in the report by Chai and Mason.[17]

4. Vehicle Options: driving concepts – what does it look like?

The basic configuration arrangement

The current typical external configuration of both large and small commercial transport airplanes is similar, having evolved from the configuration originally chosen by Boeing for the Boeing B-47 medium range bomber shortly after World War II. This configuration arose following the development of the jet engine by Frank Whittle in Britain and Hans von Ohain in Germany, which allowed for a significant increase in speed.[18] The discovery of the German aerodynamics development work on swept wings to delay a the rapid increase in drag with speed during World War II was incorporated into several new jet engine designs, such as the B-47, immediately after the war. Finally, Boeing engineers found that jet engines could be placed on pylons below the wing without excessive drag. This defined the classic commercial transport configuration. The technical evolution of the commercial transport has been described by Cook,[19] who was an active participant. A broader view of the development including business, financial and political aspects of commercial transports has been given by Irving.[20] The other key source of insight into the development of these configurations is by Loftin.[21]

So where do we start when considering the layout of an airplane? In general, form follows function. We decide on candidate configurations based on what the airplane is supposed to do. Generally, this starts with a decision on the type of payload and the "mission" the airplane is supposed to carry out with this payload. This is expressed generally in terms of

- What does it carry?
- How far does it go?
- How fast is it supposed to fly?
- What are the field requirements? (how short is the runway?)
- Are there any maneuvering and/or acceleration requirements?

Another consideration is the specific safety-related requirements that must be satisfied. As described above, for commercial aircraft this means satisfying the Federal Air Regulations (FARs) and JARs for Europe. Satisfying these requirements defines the takeoff and landing distances, engine-out performance requirements, noise limits, icing performance, and emergency evacuation among many others.

With this start, the designer develops a concept architecture and shape that responds to the *mission*. At the outset, the following list describes the considerations associated with defining a configuration concept. At this stage we begin to see that configuration design resembles putting a puzzle together. These components all have to be completely integrated.

Configuration Concept:

- Lifting surface arrangement
- Control surface(s) location
- Propulsion system selection
- Payload
- Landing Gear

The components listed above must be coordinated in such a fashion that the airplane satisfies the requirements given in the following list. The configuration designer works to satisfy these requirements with input from the various team members. To be successful the following criteria must be met.

Good Aircraft

- Aerodynamically efficient, including propulsion integration (streamlining!)
- Must balance near stability level for minimum drag
- Landing gear must be located relative to *cg* to allow rotation at takeoff
- Adequate control authority must be available throughout the flight envelope
- Design to build easily (cheaply) and have low maintenance costs
- Today, commercial airplanes must be quiet and nonpolluting

Two books do an especially good job of covering the aerodynamic layout issues. The first is by Ray Whitford[22], and the second by Abzug and Larrabee[23]. In both cases the titles are slightly misleading. Further discussion of configuration options can be found in the books by Raymer[5] and Roskam.[6]

We can translate these desirable properties into specific aerodynamic characteristics. Essentially, they can be given as:

Design for Performance

- Reduce minimum drag:
  - Minimize the wetted area to reduce skin friction
  - Streamline to reduce flow separation (pressure drag)
  - Distribute area smoothly, especially for supersonic a/c (area ruling)
  - Consider laminar flow
  - Emphasize clean design/manufacture with few protuberances, steps or gaps
- Reduce drag due to lift:
  - Maximize span (must be traded against wing weight)
  - Tailor spanload to get good span *e*, (twist)
  - Distribute lifting load longitudinally to reduce wave drag due to lift (a supersonic requirement, note R.T. Jones' oblique wing idea)
  - Camber as well as twist to integrate airfoil, maintain good 2D characteristics
- Key constraints:
  - At cruise: buffet and overspeed constraints on the wing
  - Adequate high lift for field performance (simpler is cheaper)
  - Alpha tailscrape, $C_{L\alpha}$ goes down with sweep, *AR*

Design for Handling Qualities

- Adequate control power is essential
  - Nose up pitching moment for stable vehicles
  - Nose down pitching moment for unstable vehicles
  - Yawing moment, especially for flying wings and fighters at Hi-α
  - Consider the full range of *cg*'s.
- Implies: must balance the configuration around the *cg* properly

FAA and Military Requirements

- Safety: for the aerodynamic configuration this means safe flying qualities
  - FAR Part 25 and some of Part 121 for commercial transports
  - MIL STD 1797 for military airplanes

- Noise: community noise, FAR Part 36, no sonic booms over land
  (High *L/D* in the takeoff configuration reduces thrust requirements,
  makes plane quieter)

To start considering the various configuration concepts, we use the successful transonic commercial transport as a starting point. This configuration is mature. New commercial transports have almost uniformly adopted this configuration and variations are minor. An interesting comparison of two different transport configuration development philosophies is available in the papers describing the development of the original Douglas DC-9[24] and Boeing 737[25] designs. Advances in performance and reduction in cost are currently obtained by improvements in the contributing technologies. After we establish the baseline, we will examine other configuration component concepts that are often considered. We give a summary of the major options. Many, many other innovations have been tried, and we make no attempt to be comprehensive.

The Boeing 747 layout is shown in Figure 1. It meets the criteria cited above. The cylindrical fuselage carries the passengers and freight. The payload is distributed around the *cg*. Longitudinal stability and control power comes from the horizontal tail and elevator, which has a very useful moment arm. The vertical tail provides directional stability, using the rudder for directional control. The swept wing/fuselage/landing gear setup allows the wing to provide its lift near the center of gravity and positions the landing gear so that the airplane can rotate at takeoff speed and also provides for adequate rotation without scraping the tail (approximately 10% of the weight is carried by the nose gear). The wing has a number of high lift devices. This arrangement also results in low trimmed drag. The engines are located on pylons below the wing. This arrangement allows the engine weight to counteract the wing lift, reducing the wing root bending moment, resulting in a lighter wing. This engine location can also be designed so that there is essentially no adverse aerodynamic interference.

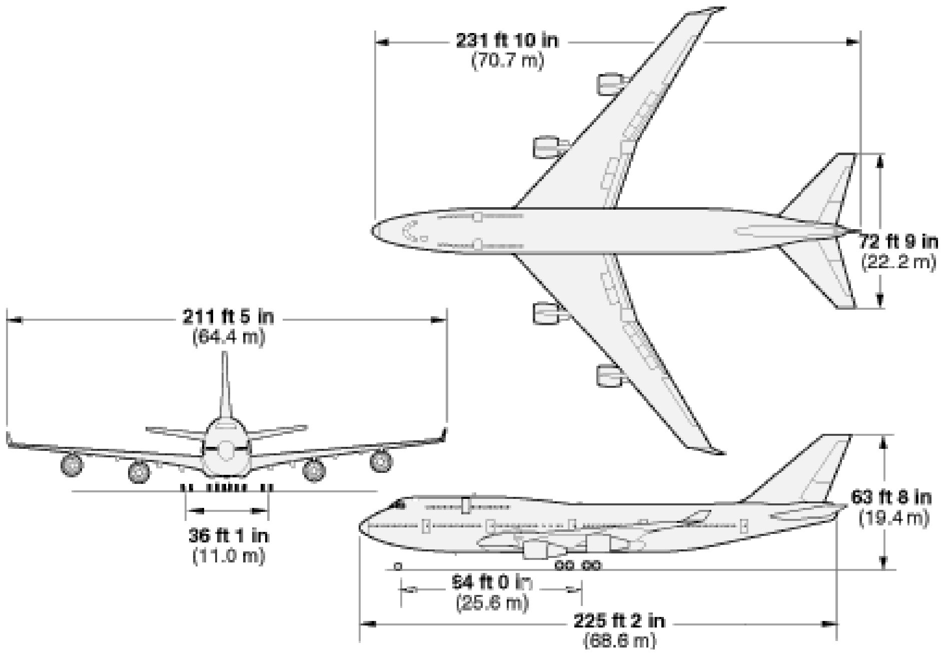

Figure 1. The classic commercial transport, the Boeing 747 (www.boeing.com)

Configuration Architecture Options

Many another arrangements are possible, and here we list a few typical examples. All require attention to detail to achieve the claimed benefits.

- *forward swept wings*: reduced drag for severe transonic maneuvering conditions
- *canards*: possibly safety, also possibly reduced trim drag and supersonic flight
- *flying wings*: elimination of wetted area by eliminating fuselage and tail surfaces
- *three-surface configurations*: trim over wide *cg* range
- *slender wings*: supersonic flight
- *variable sweep wings*: good low speed, low altitude penetration, and supersonic flight
- *winglets*: reduced induced drag without span increase

Improvements to current designs can occur in two ways. One way is to retain the classic configuration, and improve the component technologies. This has been the recent choice for new aircraft, which are mainly derivatives of existing aircraft, using refined technology, *e.g.,* improved aerodynamics, propulsion and materials. The other possibility for improved designs is to look for another arrangement.

Because of the long evolution of the current transport configuration, the hope is that it is possible to obtain significantly improved aircraft through new configuration concepts. Studies looking at other configurations as a means of obtaining an aircraft that costs less to build and operate are being conducted. Two concepts have received attention recently. One integrates the wing and the fuselage into a blended wing body concept,[26] a second uses strut bracing to allow for increased wingspan without increasing the wing weight.[27]

The Blended Wing Body

The Blended –Wing-Body concept (BWB) combines the fuselage and wing into a concept that offers the potential of obtaining the aerodynamic advantages of the flying wing while providing the volume required for commercial transportation. Figure 2 shows the concept. Although this configuration offers the potential for a large increase in *L/D* and an associated large reduction in fuel use and maximum take-off gross weight (TOGW). The major overview was given by Robert Liebeck,[26] who predicted that the BWB has an 18% reduction in TOGW and 32% in fuel burn per seat compared to the proposed A380-700.

Because the BWB does not have large moment arms for generating control moments, and also requires a non-traditional passenger compartment, the design is more difficult than traditional designs, and requires the use of multidisciplinary design optimization methods to obtain the predicted benefits.[28] Recently the concept has been shown to be able to provide a significant speed advantage over current commercial transports.[29] Because of the advantages of this concept, it has been studied by other design groups.

Figure 2. The Blended Wing Body Concept (courtesy Boeing)

The Strut-Braced Wing

Werner Pfenninger suggested the strut-braced wing concept around 1954. His motivation was actually associated with the need to reduce the induced drag to balance his work in reducing parasite drag by using active laminar flow control to maintain laminar flow and reduce skin friction drag. Since the maximum *L*/*D* occurs when the induced and parasite drag are equal, the induced drag had to be reduced also. The key issues are:

- Once again, the tight coupling between structures and aerodynamics requires the use of MDO to make it work
- The strut allows a thinner wing without a weight penalty and also a higher aspect ratio, and less induced drag
- Reduced *t*/*c* allows less sweep without a wave drag penalty

- Reduced sweep leads to *even lower* wing weight
- Reduced sweep allows for some natural laminar flow and thus reduced skin friction drag

The benefits of this concept are similar to the benefits cited above for the BWB configuration. The advantage of this concept is that it doesn't have to be used on a large airplane. The key issue is the need to provide a mechanism to relieve the compression load on the strut under negative *g* loads. Work on this concept was done at Virginia Tech.[27,30] Figure 3 shows the result of a joint Virginia Tech – Lockheed Martin study.

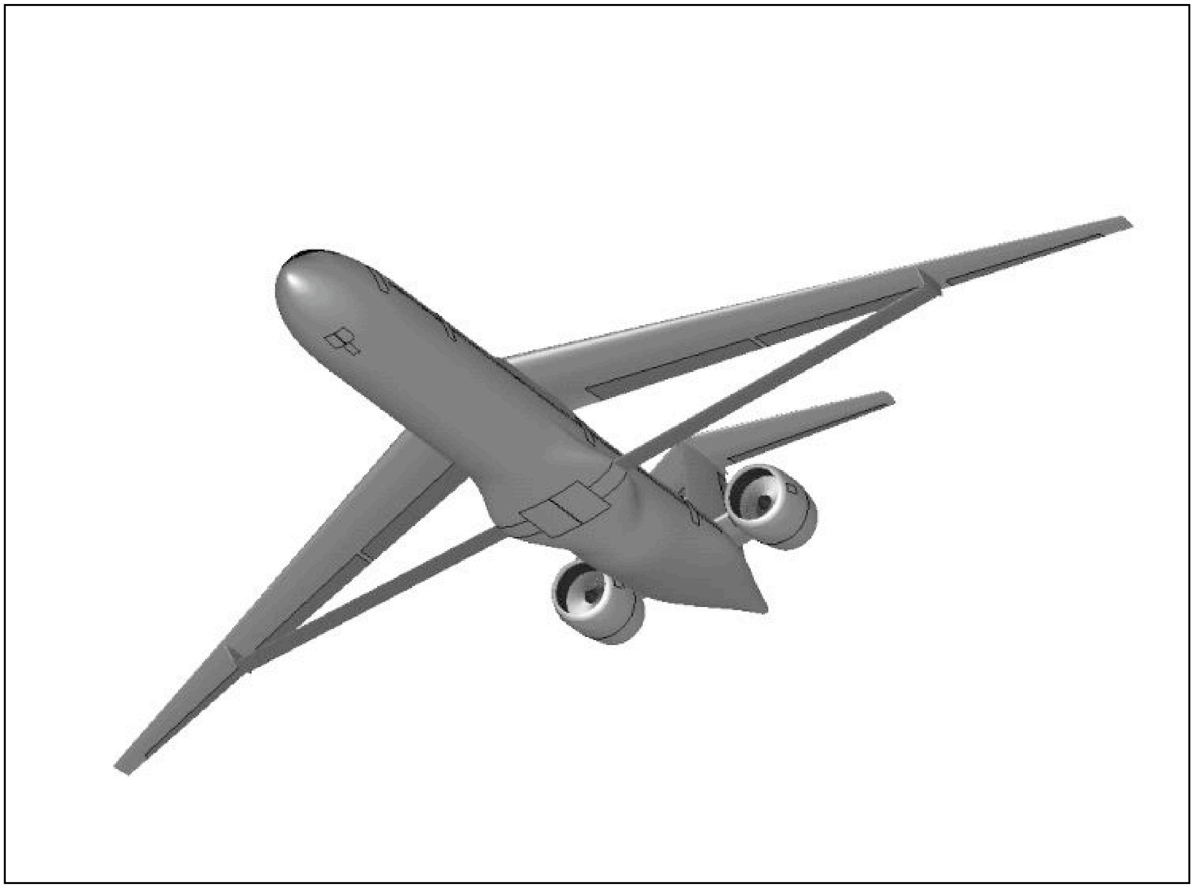

Figure 3. The Strut-Braced Wing Concept

There are numerous options for the shape of the aircraft. Other possibilities exist, and there is plenty of room for imagination. See Whitford[22] for further discussion of configuration options.

5. Vehicle Sizing – how big is it?

Once a specific concept is selected, the next task is to determine how big the airplane is, which essentially means how much it weighs. Typically, for a given set of technologies the maximum takeoff gross weight is used as a surrogate for cost. The lighter the airplane, the less it costs, both to buy and operate. Some procedures are available to estimate the size of the airplane. This provides a starting point for more detailed design and sizing, and is a critical element of the design. The initial "back-of-the-envelope" sizing is done using a database of existing aircraft, and developing an airplane that can carry the required fuel and passengers to do the desired mission. This usually means acquiring data similar to the data presented in Tables 1 and 2, and doing some preliminary analysis to obtain an idea of the wing area required in terms of the wing loading, *W/S*, and the thrust to weight ratio, *T/W*, as shown in Table 5.

Table 5. Derived Characteristics of Current Transport Aircraft

Aircraft	TOGW (lb)	Empty Weight (lb)	Wing area, sq. ft.	Sweep (quarter chord)	Aspect Ratio	W/S	W/b	T/W
Narrow Body								
A320-200	169,800	92,000	1,320	25.0	9.47	129	1,519	0.312
B717-200	121,000	68,500	1,001	24.5	8.70	121	1,297	0.347
B737-600	143,500	81,000	1,341	25.0	9.45	107	1,274	0.287
B757-300	273,000	141,690	1,951	25.0	7.98	140	2,188	0.305
Wide Body								
A330-300	513,670	274,650	3,890	30.0	10.06	132	2,597	0.272
A340-500	811,300	376,800	4,707	30.0	9.21	172	3,897	0.261
A380-800	1,234,600	611,000	9,095	33.5	7.54	136	4,716	0.227
B747-400	875,000	398,800	5,650	37.5	7.91	155	4,139	0.265
B747-400ER	911,000	406,900	5,650	37.5	7.91	161	4,309	0.255
B767-300	345,000	196,000	3,050	31.5	7.99	113	2,210	0.337
B777-300	660,000	342,900	4,605	31.6	8.68	143	3,302	0.278
B777-300ER	750,000	372,800	4,694	31.6	9.63	160	3,528	0.307
Regional Jets								
CRJ200(ER)	51,000	30,500	520	26.0	9.34	98	732	0.36
CRJ700(ER)	75,000	43,500	739	26.8	7.88	102	983	0.37
ERJ135ER	41,888	25,069	551	20.3	7.86	76	637	0.43
ERJ145ER	54,415	26,270	551	20.3	7.86	82	690	0.39

Following Nicolai,[31] consider the *TOGW*, called here W_{TO}, to be:

$$W_{TO} = W_{fuel} + W_{fixed} + W_{empty} \tag{11}$$

where the fixed weight includes a non-expendable part, which consists of the crew and equipment, and an expendable part, which consists of the passengers and baggage or freight. W_{empty} includes all weights except the fixed weight and the fuel. The question becomes: for a given (assumed) TOGW, is the weight left enough to build an airplane when we subtract the fuel and payload? We state this question in mathematical terms by equating the available and required empty weight:

$$WEmptyAvail = WEmpty\mathrm{Re}qd \tag{12}$$

where *WEmptyReqd* comes from the following relation:

$$WEmpty\mathrm{Re}qd = KS \cdot A \cdot TOGW^{B} \tag{13}$$

and *KS* is a structural technology factor, and *A* and *B* come from the data gathered from information in Table 5. Now, the difference between the takeoff and landing weight is due to fuel used (the mission fuel). Figure 4 shows how this relation is found from the data. Note that KS is very powerful, and should not be much less than one without a very good reason.

Next we define the mission in terms of segments, and compute the fuel used for each segment. Figure 5 defines the segments used in a typical sizing program. Note that the mission is often defined in terms of a radius (an obvious military heritage). Transport designers simply use one half of the desired range as the radius. At this level of sizing, reserve fuel is included as an additional range, often taken to be 500 nm. To use the least fuel, the airplane should be operated at its best cruise Mach number (BCM), and it best cruise altitude (BCA). Often, air traffic control or weather conditions may prevent being able to fly at these conditions in actual operation.

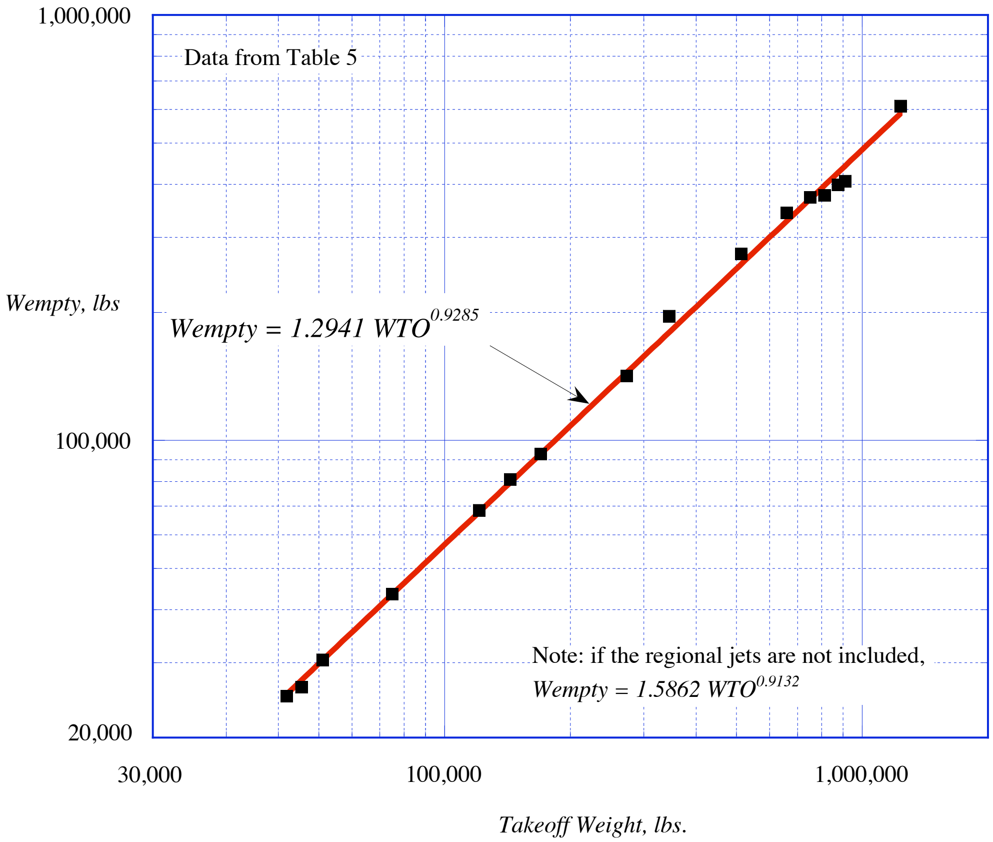

Figure 4. Relationship between empty weight and takeoff weight for the airplanes in Table 5.

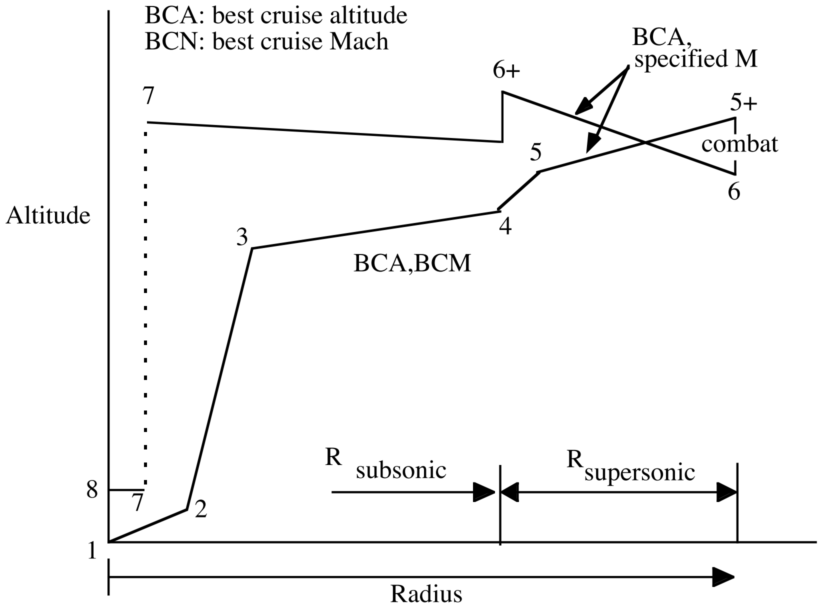

Figure 5. Mission definition

Mission segment definitions for Figure 5

1-2	engine start and takeoff
2-3	accelerate to subsonic cruise velocity and altitude
3-4	subsonic cruise out
4-5	accel to high speed (supersonic) dash/cruise
5-5+	supersonic cruise out
	combat (use fuel, expend weapons)
6-6+	supersonic cruise back
6+ -7	subsonic cruise back
7-8	loiter
8	land

To get the empty weight available, compute the fuel fraction for each mission segment. For the fuel fraction required for the range, invert the Brequet range equation given above:

$$\frac{W_{i+1}}{W_i} = e^{-\frac{R\cdot sfc}{V(L/D)}} \tag{14}$$

and for loiter:

$$\frac{W_{i+1}}{W_i} = e^{-\frac{R\cdot sfc}{(L/D)}} \tag{15}$$

the values of the cruise *L*/*D* and *sfc* have to be estimated, and the velocity for best range also has to be estimated, so it takes some experience to obtain these values. Note that this approach can also be used to establish the values of *L*/*D* and *sfc* required to perform a desired mission at a desired weight. Values for takeoff and climb are typically estimated, and can be computed for more accuracy. However, for a transport aircraft, the range requirement tends to dominate the fuel fraction calculation, with the rest of the fuel fractions being near unity. Therefore, we compute the mission weight fraction as:

$$\frac{W_{final}}{W_{TO}} = \frac{W_8}{W_1} = \underbrace{\frac{W_2}{W_1}\cdot\frac{W_3}{W_2}\cdot\frac{W_4}{W_3}\cdots\frac{W_8}{W_7}}_{\text{fuel fraction for each segment}} \tag{16}$$

and solve for the fuel weight in Eq.(16) as:

$$\begin{aligned} W_{fuel} &= \left(1 + \frac{W_{\substack{reserve\\fuel}}}{W_{TO}} + \frac{W_{\substack{trapped\\fuel}}}{W_{TO}}\right)\left(1 - \frac{W_8}{W_1}\right)W_{TO} \\ &= \left(1 + \frac{W_{\substack{reserve\\fuel}}}{W_{TO}} + \frac{W_{\substack{trapped\\fuel}}}{W_{TO}}\right)\left(W_{TO} - W_{landing}\right) \end{aligned} \qquad (17)$$

so that we can compute *WEmptyAvail* from:

$$W_{EmptyAvail} = W_{TO} - W_{fuel} - W_{fixed}. \qquad (18)$$

The value of W_{TO} that solves the problem is the one for which $W_{EmptyAvail}$ is equal to the value of $W_{EmptyReqd}$ which comes from the statistical representation for this class of aircraft. An iterative procedure is often used to find this value. The results of this estimate are used as a starting point for the design using more detailed analysis. A small program that makes these calculations is available on the web.[32]

We illustrate this approach with an example, also from Nicolai.[31] The example is for a C-5. In this case we pick:

Range: 6000 nm
Payload: 100,000 lb
sfc: 0.60 @ $M = 0.8$, $h = 36{,}000$ ft altitude
$L/D = 17$.

Figure 6 shows how the empty and available weight relations intersect, defining the weight of the airplane, which is in reasonable agreement with a C-5A. Note that as the requirements become more severe the lines will start to become parallel, the intersection weight will increase, and the uncertainty will increase because of the shallow intersection.

The author's students have used this approach to model many commercial transport aircraft and it has worked well, establishing a baseline size very nearly equal to existing aircraft and providing a means of studying the impact of advanced technology on the aircraft size.

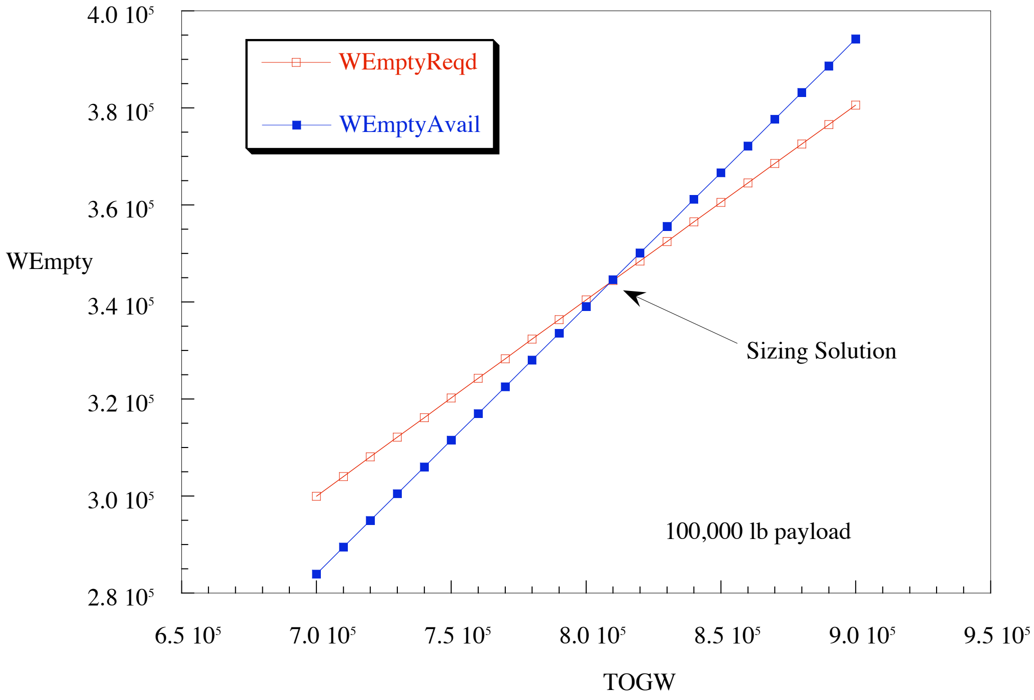

Figure 6. Illustration of sizing results using Nicolai's back of the envelope method.

Once the weight is estimated, the engine size and wing size are picked considering constraints on the design. Typical constraints include the takeoff and landing distances and the cruise condition. Takeoff and landing distance include allowances for problems. The takeoff distance is computed such that in case of engine failure at the decision speed the airplane can either stop or continue the takeoff safely, and includes the distance required to clear a 35 ft. obstacle. The landing distance is quoted including a 50 ft. obstacle, and is includes an additional runway distance. Other constraints that may affect the design include the missed approach condition, the second segment climb (the ability to climb if an engine fails at a prescribed rate between 35 and 400 ft altitude), and the top of climb rate of climb. The book by Jenkinson, Simpkins and Rhodes[3] has an excellent discussion of these constraints for transport aircraft. Figure 7 shows a notional constraint diagram for *T*/*W* and *W*/*S*. Typically, the engines of long range airplanes are sized by the top of climb requirement and the engines of twin-engine airplanes are sized by the second segment climb requirement.[3]

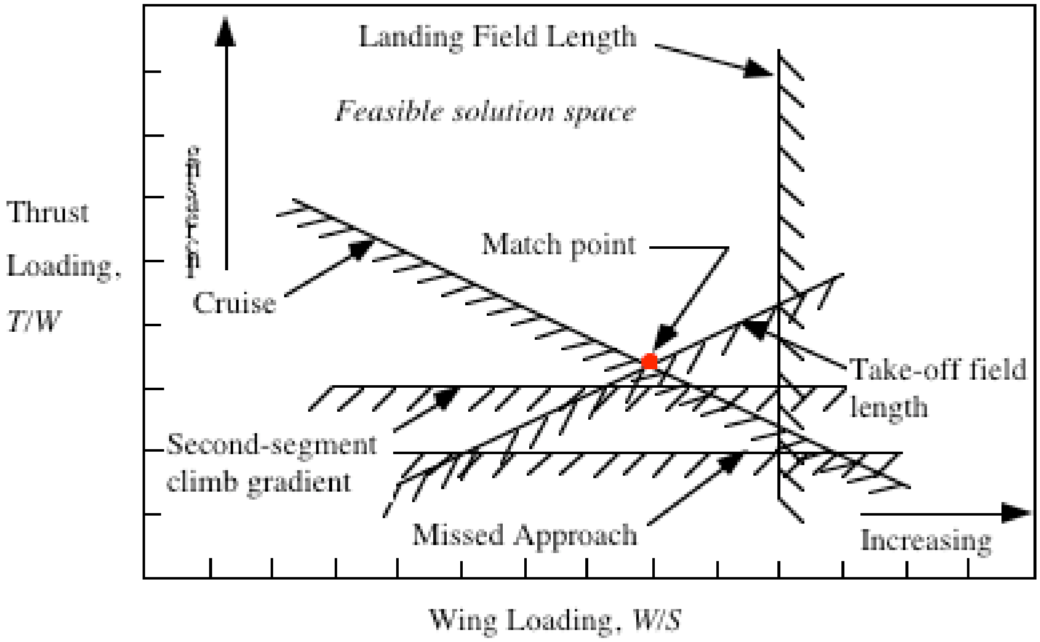

Figure 7. Typical constraint diagram, after Loftin.[21]

6. Current typical design process.

The airplane design process is fairly well established. It starts with a conceptual stage, where a few engineers use the sizing approaches slightly more elaborate than the one described above to investigate new concepts. Engine manufacturers also provide information on new engine possibilities or respond to requests from the airframer. If the design looks promising it progresses to the next stage: preliminary design. At this point the characteristics of the airplane are defined and offered to customers. Since the manufacturer cannot afford to build the airplane without a customer, various performance guarantees are made, even though the airplane has not been built yet. This is risky. If the guarantees are too conservative you lose the sale to the competition. If the guarantees are too optimistic, a heavy penalty will be incurred.

If the airplane is actually going to be built, it progresses to detail design. The following from John McMasters of Boeing, describes the progression.

• *Conceptual Design (1% of the people):*

- competing concepts evaluated	What drives the design?
- performance goals established	Will it work/meet req't?
- preferred concept selected	What does it look like?

• *Preliminary Design (9% of the people):*

- refined sizing of preferred concept	Start using big codes
- design examined/establish confidence	Do some wind tunnel tests
- some changed allowed	Make actual cost estimate (you bet your company)

• *Detail Design (90% of the people):*

- final detail design	Certification process
- drawings released	Component/systems tests
- detailed performance	Manufacturing(earlier now)
- only “tweaking” of design allowed	Flight control system design

7. MDO – the modern computational design approach

With the increase of computer power, new methods for carrying out the design of the aircraft have been developed. In particular, the interest is in using high fidelity computational simulations of the various disciplines at the very early stages of the design process. The desire is to use the high fidelity analyses with numerical optimization tools to produce better designs. Here the high quality analysis and optimization can have an important affect on the airplane design early in the design cycle. Currently, high fidelity analyses are used only after the configuration shape has been “frozen”. At that point it is extremely difficult to make significant changes. If the best tools can be used early, risk will be reduced and the design time reduced. Recent efforts have also focused on means of using large scale parallel processing to reduce the design cycle time. These various elements, taken all together, are generally known as Multidisciplinary Design Optimization, or MDO. One collection of papers has been published as a book on the subject,[33] and there is a major conference on MDO every other year sponsored by the AIAA, ISSMO and other societies. Perhaps the best survey of our view of MDO for aircraft design is summarized in the paper by Giunta, et al.[34] We will outline the MDO process and issues based on these and other recent publications.

Our current view of MDO is that high-fidelity codes can’t be directly coupled into one major program. There are several reasons. Even with advanced computing the computer resources required are too large to perform an optimization with a large number of design variables. For 30 or so design variables, with perhaps one hundred constraints, hundreds of thousands of analysis of the high fidelity codes are required. In addition, the results of the analyses are invariably noisy,[35] so that gradient-based optimizers have difficulty in producing meaningful results. In addition to the artificial noise causing trouble, the design space is non-convex, and many local optima exist.[36] Finally, the software integration issues are complex, and it is unlikely that major computational aerodynamic and structures codes can be combined. Thus innovative methods are required to incorporate MDO into the early stages of airplane design.

Instead of a brute-force approach, MDO should be performed using surrogates for the high-fidelity analyses. This means that for each design problem, a design space should be constructed which uses a parametric model of the airplane in terms of design variables such as wing span and chords, etc. The ranges of values of these design variable are defined, and a data base of analyses for combinations of the design variables should be constructed. Because the number of combinations will quickly become extremely large, design of experiments theory will need to be used to reduce the number of cases that need to be computed. Because these cases can be evaluated independently of each other, this process can exploit coarse grain parallel computing to speed the process. Once the database is constructed, it must be interpolated. In statistical jargon this means constructing a response surface approximation. Typically, second order polynomials are used. This process automatically filters out the noise from the analyses of the different designs. These polynomials are then used in the optimization process in place of the actual high-fidelity codes. This allows for repeated investigations of the design space with an affordable computational cost. A more thorough explanation of how to use advanced aerodynamics methods in MDO, including examples of trades between aerodynamics and structures, has been presented by Mason, et al.[37]

Current issues of interest in MDO also include the consideration of the effects of uncertainty of computed results and efficient geometric representation of aircraft. MDO is an active research area, and will be a key to improving future aircraft design.

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