1

Design of the Well-Tempered Aircraft

> Let no new improvement in flying and flying equipment pass us by.
>
> —Bill Boeing (1928)

> As our industry has matured . . . we have become increasingly enslaved to our data bases of past successful achievements. Increased competitive pressures and emphasis on control of rapidly escalating costs have combined to preclude the level of bold risks taking in exploring possible new configuration options that might offer some further increase in performance, etc., but for which no adequate data exist to aid development.
>
> —J.H. McMasters [57] (2005)

1.1 How Aircraft Design Developed

1.1.1 Evolution of Jetliners and Executive Aircraft

The second half of the twentieth century has been truly revolutionary. In particular, the period 1945–1960 produced some highly innovative projects which demonstrated that propulsion of transport aircraft by means of jet engines had become feasible. In combination with the appearance of the sweptback wing, this resulted in a jump in maximum cruising speeds from about 550 to more than 850 km/h (Figure 2.1). Having pioneered the B-47 swept-wing bomber, Boeing introduced its basic jet concept to the 367-80 tanker transport and later to the 707 passenger transport; see Figure 1.1(a). This concept proved successful and has been adopted for jetliners almost universally since the 1960s. When one realizes that in the early 1950s designers did not yet avail themselves of the advantage of electronic computers, it will be appreciated that this revolution in design technology was a monumental achievement.

Modern jetliners are mostly low-wing designs with two or four engines installed in nacelles mounted underneath and to the fore of the wing leading edge. It should not be concluded, however, that since the Boeing 707 little progress has been made in configuration design. An early example of an unusual mutation was the Sud-Est Caravelle, see Figure 1.1(b), the airliner that

Advanced Aircraft Design: Conceptual Design, Analysis and Optimization of Subsonic Civil Airplanes, First Edition. Egbert Torenbeek.

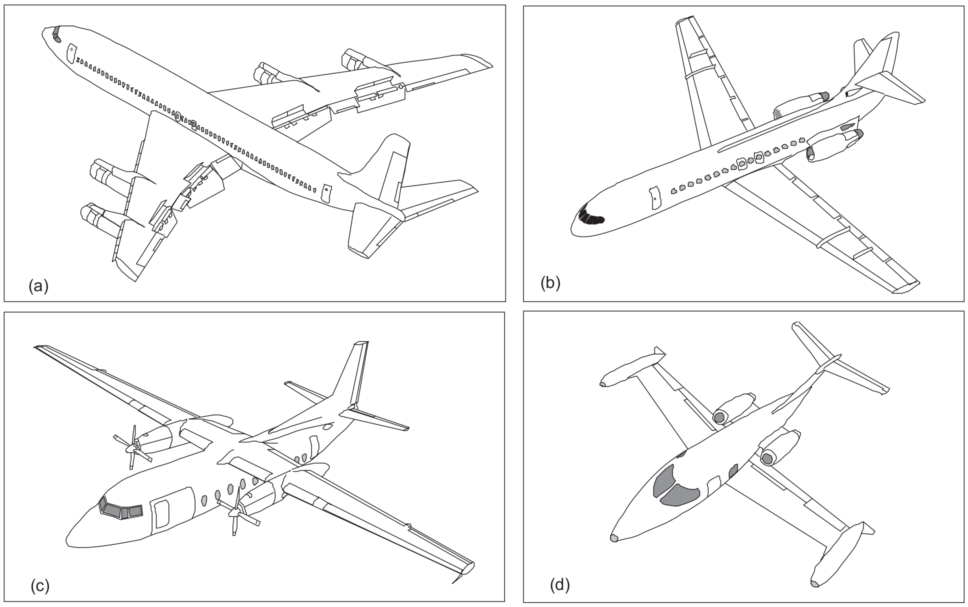

Figure 1.1 Prime examples of early post-WW II passenger aircraft. (a) Boeing 707 (1954): the first jet-powered airliner of US design. (b) Sud-Est Caravelle (1959): the first airliner with rear fuselage-mounted jet engines. (c) Fokker F 27 (1955): turboprop designed as a regional aircraft; still operational in 2012. (d) Gates Learjet 24B (1963): business jet designed in the early 1960s

pioneered jet engines attached to the rear fuselage. Even though this was a patented concept, several short-haul designs soon emerged with a similar layout and some of these were very successful. The introduction of bypass engines (∼1960) and large turbofans (∼1970) further improved the productivity and economy of jetliners. In combination with the strong worldwide economic expansion, this resulted in an unprecedented growth of air traffic and the almost complete extinction of competing modes of transportation over long distances, including the long-haul piston-powered and even the brand-new turboprop-powered propeller airliners.

Short-range jets initially suffered from poor low speed performances and high fuel expenditure. This market niche was filled by the four-engine Vickers Viscount and other turboprops designed in the 1950s. The twin-engine Fokker Friendship – see Figure 1.1(c) – had its Rolls-Royce Dart turboprop engines mounted to the high-set wing. This configuration was difficult to improve on and became the standard for similar propeller aircraft appearing later. Short-range turboprops have survived the twentieth century thanks to their excellent fuel economy and low operating costs. The idea of producing economy-size jets for large companies and wealthy individuals came around 1960. A prime example of a successful business jet was the Learjet depicted in Figure 1.1(d). Seating six in a slim fuselage (‘no-one walks about in a Cadillac’), it outperformed jetliners of its time in maximum speed. Learjet’s general arrangement, a low-wing design with engines attached to the rear fuselage and a high-set horizontal tail, has been adopted on most executive jets.

Since the introduction of the first jetliners, subsonic civil airplane technology development has advanced in an evolutionary way. During the time span between 1950 and 2000, considerable improvement has been accomplished in all technical areas, but none could be regarded as revolutionary. The basic properties of traditional designs – such as lift, drag, weight and flight performances – have become well understood. Computational methods supporting advanced design (AD) have steadily developed over a long period of time and a wealth of empirical evidence confirms their accuracy. Consequently, aircraft with a conventional layout can be developed with a high degree of confidence in the analysis. Though designing an innovative configuration will always be challenging from an engineering viewpoint, its application in an industrial project entails many challenges. This may lead to the situation that, after several years of costly configuration development, the project has to be terminated by a show stopper. It is also observed that airline management tends to avoid the uncertainties of an unusual general arrangement and prefers the purchase of a traditional configuration.

The conformity between modern airliners is not caused by the lack of conceptual creativity of designers; arguments supporting this statement can be found in publications such as [12] and [14]. In fact, several innovative designs proposed during the last decennia of the twentieth century have not been developed into a for-sale aircraft because airlines were reluctant to order them for non-technical reasons. The following projects serve as examples.

- The Boeing 7J7 project of the 1980s – Figure 1.2 (a) – was a 150-seat airliner in which new technologies were integrated: a fly-by-wire control system, unducted fan (UDF) engine technology, advanced system and flight deck technologies, and advanced aluminium alloys. The 7J7 did not find favour with the airlines mainly because the anticipated spike in fuel prices did not occur.
- Boeing's Sonic Cruiser – Figure 1.2 (b) – was designed to connect typical long-range city pairs at Mach 0.95 or above. In a business class layout for 100 seats it would attract passengers who would be willing to pay a fare premium to save several hours on long distance flights with increased comfort. The 300-seat version would be used for continental flights circumventing the large hubs. The Sonic Cruiser became the victim of the aftermath of the events following September 2001, when airlines began to re-evaluate their business models resulting in a

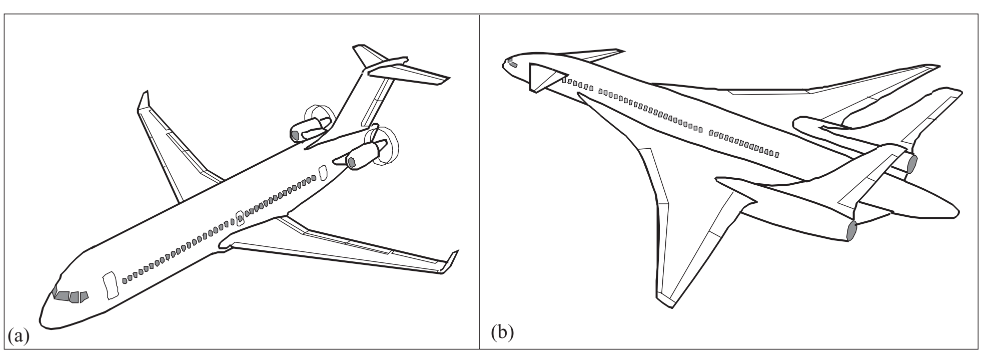

Figure 1.2 Boeing design projects which were not put into production. (a) 7J7 open rotor-powered narrow body airliner of the 1980s. (b) Sonic Cruiser long-range wide body Mach 0.95 airliner 1999–2002

preference for a more economical (slower) design which became the 787 [41]. The Sonic Cruiser was not developed into a for-sale product because potential customers would rather see its advanced technology developed for integration into an airplane optimized for lower Mach numbers.

1.1.2 A Framework for Advanced Design

The non-recurring costs of a commercial aircraft development programme are so enormous that even a relatively minor technical hiccup may be magnified into an unacceptable commercial risk. Consequently, a certain amount of conservatism is inherent in the development of civil aircraft design. In spite of this, conservatism in design is risky because it can lead to missed opportunities when maturing aerodynamic, structural and propulsive technologies are becoming available which find their best application in concepts different from the current dominant configuration.

In civil aircraft development programmes, far-reaching decisions concerning top level specifications, general arrangement, propulsion and enabling technologies are made before and during the concept finding and the conceptual design phases. The preliminary design phase is then entered during which the aircraft's characteristics are defined in more detail, initial assumptions are verified and the feasibility and risk level of the project are investigated. A year or more may elapse before management will decide to give the green light or withdraw from further development. The next phase consists of design verification (testing) and detail design during which major modifications of the basic configuration can be very labour-intensive and costly. Clearly, ESDU's trademark phrase, 'get it right the first time' is highly relevant for the initial aircraft system design process.

The observation has frequently been made that no more than a few percent of the pre-production costs are attributed by a few designers committing to a large fraction of total aircraft programme cost. In some cases this observation was made in favour of strengthening the advanced design capability of the aeronautical industry and/or the effort in academia to offer excellent aircraft design teaching. Although these arguments are fully justified, it is not always acknowledged that a large portion of aircraft programme costs is committed by merely specifying the need for the particular vehicle rather than by defining its technical and operational characteristics. If a new airplane has been developed for which no market exists, the project will be doomed to fail. The project design team cannot be blamed for a wrong go-ahead/exit decision and devoting more manpower to advanced design is not necessarily a panacea for avoiding misjudgement of the market. Although concept finding is not, in general, considered a part of the design project, it is at least as crucial to the success of a programme as the actual concept development phase.

1.1.3 Analytical Design Optimization

Since advanced design is highly relevant to the company's viability, one would expect that the discipline of design optimization has traditionally received a great deal of attention from the aeronautical community – in fact, this is not the case. Until the time of large-scale computer applications, only a few systematic efforts were made to develop a fundamental framework for non-intuitive decision-making. Most of these were small-scale programs initiated by individuals in research institutes and academia and their impact on the actual practice in design offices has not become entirely clear. Nevertheless, from the educational point of view, several approaches and trends from the past still deserve to be mentioned even though not all of them have received widespread recognition.

Early parametric surveys were made on a limited scale in the industry by experienced designers. Until the 1960s, efforts to include optimization in conceptual design were based on relatively simple methods with minimum take-off gross weight (TOGW) considered as the criterion for the figure of merit. The analytical approach to sizing and improving a design in the conceptual stage was discussed in 1948 by Cherry and Croshere Jr [19]. Though their methodology was based on experience with propeller airplanes, its systematic character appeared useful for jet aircraft as well. In 1958, G. Backhaus proposed a comprehensive (quasi-)analytical optimization of jet transports [20]. His article did not get the recognition it deserved, probably because it was published in German. Another pioneer of the analytical approach to concept optimization was D. Küchemann. During the 1960s, he and his co-workers at the Royal Aircraft Establishment in the UK developed analytical design methods of aircraft intended to fly over widely different ranges at different (subsonic, supersonic and hypersonic) speeds [21]. Part of this work was based on research in connection with the conception of Concorde and was compiled in a unique book [1]. The elegance and lucidity of Küchemann's analysis inspired the present author to initiate a systematic study of fundamental design considerations [27]; some of its results are included in the present book in a modified form. After the advent of computational design analysis and optimization technology in the 1970s, the (quasi-)analytical approach has appealed to only a few researchers; see, for example, W.H. Mason and B. Malone in [34, 35].

1.1.4 Computational Design Environment

During the first decennia after WWII, aircraft design was performed manually with the use of hand calculators and drawing boards. Despite the commercial success of several excellent airliners and business airplanes developed during this period, the 'paper method' is nowadays considered too labor-intensive and ineffective. Since the 1970s, the advancement of design technology changed fundamentally due to the availability of powerful computers and interactive graphics devices. Simultaneously, significant progress was made in the fields of computational engineering methods and numerical optimization, a trend set by early applications in astronautics and chemical engineering. The aeronautical community initially paid most attention to developing complex computer-based design synthesis programs such as those reported in [62] and [68]. Although automated design optimization has attracted much attention from research institutes such as NASA, reputed designers initially viewed these efforts with apprehension for reasons to be discussed in Chapter 2.

The penetration of ICT into all fields of aeronautics since 1980 has drastically changed the aircraft development scene. Whereas designs were traditionally almost exclusively produced by the aircraft company's design offices, reports presented at scientific conferences indicate that research institutions and universities have become new actors in the aircraft configuration design field. The remarkable expansion of multidisciplinary design optimization (MDO) and concurrent engineering methodologies have brought about a design climate change in aeronautics as well as in other engineering disciplines. Since the 1990s, the EU Framework Programs have stimulated the industry, research institutions and academia to cooperate in order to improve aircraft design technology. These efforts have resulted in improved possibilities for designers to gain insight into the impact of new technologies and concepts on the design quality in pre-competitive phases before excessive resources have to be committed.

With the intention of offering a fresh and practical approach, the present book emphasizes the fundamentals of aircraft conceptual design sizing and optimization. The treatment of advanced computational systems and the presentation of design data collections is considered to be outside its scope. Fortunately, those involved in design teaching, students and practising designers can avail themselves of an abundance of detailed guidelines for drawing up a conceptual aircraft design in excellent books quoted in the bibliography of this chapter. Several of these and other publications have been used to compile this overview. The author is also indebted to J. van Toor for his permission to quote freely from personal correspondence [43].

1.2 Concept Finding

> How an engineer generates good design concepts remains a mystery that researchers from engineering, computer and cognitive sciences are working together to unravel.
>
> —P. Raj [95]

1.2.1 Advanced Design

The essential transportation properties of a new aircraft type, its overall system concept, design data and detailed geometry are defined by the company's advanced design (AD) office which is responsible for the generation of aircraft concept proposals including the technical, technological, competitive and commercial aspects. Focussing on new product development, the AD team is active in the overall concept development and in defining its technical and operational properties. AD is a vital and essential part of product development and has a substantial influence on the company's competitiveness and effectiveness. Dependent on the internal organization, most of the AD tasks can be categorized into the following activities.

- Future projects. The prime task of a future projects team is carrying out pre-conceptual studies, conceptual design and proof of concept for a new ('clean sheet') design and making proposals for novel configurations. This complex activity has a highly multidisciplinary character which requires that individuals from functional groups such as flight physics, structures/materials and systems integration are involved in the AD process. The team must accomplish the projected task subject to boundary conditions such as top level requirements, certification rules, technical capabilities and economic environment of the company, customer operational aspects and other considerations.
- Tool development. Software tools for aircraft sizing, performance analysis, weight and cost prediction and optimization techniques are of vital importance for a successful design effort. Reflecting the expertise of the company, these tools are in general not available on the commercial market. The capability to investigate a wide variety of vehicles and alternative concepts requires the design tools to be continuously improved by making them more reliable and versatile and by incorporating and expanding design databases. Advanced designers will

also be active in merging new results from the (applied) research field with available methods and procedures. Chapter 11 illustrates how a design tool can be developed.

- Enabling technologies. Most of the company's R & D activities aim at applications with one of its (future) production programmes. AD identifies the required key technologies in accordance with the company's technology objectives and gives guidance in the development of new technologies enabling competitive products. Included activities are assessment of operational research and market analysis, and available manufacturing capabilities.
- Competition evaluation. The technical, technological and economical situation of the company's products is judged versus competing products and developments. This requires year-round exploration and modelling of competing airplanes under consideration by the same potential customers and creation of a well organized competition database.

In addition to these focussed activities, AD is responsible for highly constrained temporary tasks. These may entail, for instance, interaction with the company's sales department and with (potential) customers, external suppliers and partners. The engine selection process requires that regular contacts are made with engine manufacturers. During the validation and detailed design phases of an ongoing project, AD specifies and coordinates the peripheral activities carried out externally such as wind tunnel, structural and system testing. Another activity is developing proposals for upgrade programmes and future derivatives or modifications of the company's existing product line.

1.2.2 Pre-conceptual Studies

The starting point for any project development is an understanding of market requirements and answering the question why – rather than how – a new product will be developed. The underlying reason for any commercial aircraft programme is its ability to provide a profit to the company that designs and builds it as well as the customer that uses it. Reliable forecasts about the demand for new aircraft are obtained from continuously monitoring and assessing the advancements in aeronautical research and technology. The pre-conceptual study phase is intended to identify a product line within the company's capabilities that fits a potential market. This entails a complex process which ideally includes a dialogue between design, management, marketing and customer support. The pre-conceptual phase includes aircraft configuration trade studies identifying techniques and technology requirements suitable for integration into the new product. This is accomplished by initial aircraft sizing, engine matching, weight estimation and evolution of a family of aircraft with a given set of payload versus range combinations. At the end of the process, a management decision is expected for a selected configuration to be visualized in a provisional three view drawing.

Different terms exist for the pre-conceptual phase: companies may call it the pre-feasibility, concept finding or architectural phase. In fact, the notion of architecture refers to a transportation system – this could be an airline, a number of airlines or some other transportation service of which the future plane will be a constituent part – rather than to the characteristics of the aircraft itself. Pre-conceptual studies produce an agreed and binding set of definitions that will drive the design, generally known as top level requirements (TLRs). Together with airworthiness certification rules, these will form the principal framework of objectives and constraints for the following design phases, eventually leading to a new product development.

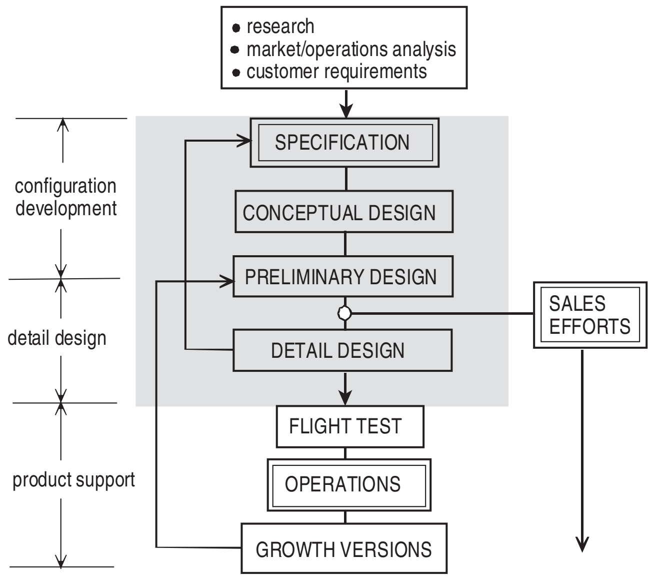

Figure 1.3 Schedule of the civil airplane development process [40]. Courtesy of J.H. McMasters

TLRs also include the criteria for a go-ahead or exit decision at the end of the product design phase. Although the concept finding phase may eventually lead to a new product, it is not usually considered as part of a design project; hence, concept finding entails a more continuous activity than project development.

Top level requirements identify characteristics that should not be subject to significant variations during project design since this could entail a violation of the transportation system architecture that has been identified as desirable for the new product. An illustration is the selection of the design cruise speed or Mach number. This parameter has a major impact on the aircraft geometry, propulsion, weight, operating costs, as well as on the way airline operations are carried out. Compared to a high cruise Mach number, a reduced speed is likely to result in a lighter aircraft structure, reduced installed engine power and less fuel consumption. But the low block speed may be detrimental to efficient and flexible operation, as well as commercial productivity.[1] Similar arguments apply to available field lengths for take-off and landing. Since these basic performance requirements are selected at the transportation system level, they should be considered as design constraints during conceptual sizing.

1.3 Product Development

The potential customer of a new airliner thinks that the life of a design begins with drawing up its requirements. However, advanced designers consider the conceptual design phase as the starting point of product development. The schedule of the development phases of a commercial or business airplane depicted in Figure 1.3 is helpful for understanding the design

[1] This rather complex selection problem must not be confused with mission performance analysis and optimization for an aircraft with given physical properties, a favoured, but not always properly treated topic of flight mechanics research (see Chapter 12).

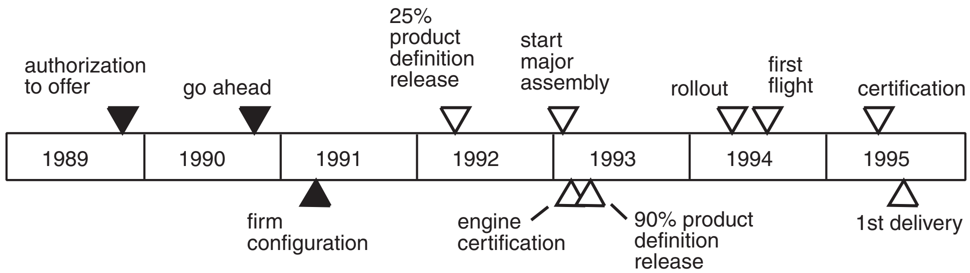

Figure 1.4 Boeing 777 project development milestones [36]

effort which is essential for a successful project. The complete process is subdivided into product design, manufacturing and testing phases. The product design process is broken down into conceptual design, preliminary design and detail design.

- Conceptual design encompasses sizing of the most promising overall aircraft concept and proof of its feasibility. Having a typical duration between 4 to 6 months for a business aircraft and 9 to 12 months for a mid-size airliner, conceptual design is characterized by cyclic design improvements and complexity increasing in time.
- The preliminary design phase aims at specifying the design concept at the main component level, sometimes including subsystem trades. Preliminary design typically lasts between 12 and 16 months.
- The detail design phase is entered when a management decision is taken to continue and give the project go-ahead.[2] This development phase is entered soon after the aircraft is committed to production and lasts between two and three years. The decision to freeze the configuration is taken early in the detail design phase when changes in the product definition are no longer appropriate.

As the aircraft goes through these phases, the level of detail and the confidence that the design will work are steadily increasing. For instance, during conceptual design, the interaction between major components such as fuselage frames, wing spars, fuel tanks, and landing gears is more important than their detailed geometry which materializes during preliminary design.

Aircraft manufacturers are active in different product lines in different markets and operate with different management methods; hence, the schedule and terminology discussed in this overview are far from universal. Dependent on the level of detail exerted in AD, the distinction between design phases is somewhat blurred, whereas some of the phases may overlap. Additional information on product development is given in the time schedule of well-defined events having the character of milestones. Figure 1.4 shows an example indicating major events such as programme go-ahead, configuration freeze, first flight, certification and first delivery. The

[2]The comparable term in system engineering terminology is full-scale development.

development time span between the first concept studies and certification is typically between three years for a light business aircraft and six years for a clean sheet wide body airliner. This illustrates why an aircraft must be conceived at least a decade ahead of the anticipated utilization period. Therefore, flexibility and extended duration have a strong impact on many application alternatives and the growth potential which a good design must have from its inception.

1.3.1 Concept Definition

The concept definition phase can be characterized as the highly creative and imaginative idea stage during which the component geometry, placement and connectivity of a future aircraft designed to fulfil the needs of a specific market are defined. Conceptual design also entails the development of a novel aircraft concept at an overall system level in competition with a more traditional layout. The objective is to explore a preferred configuration[3] to determine a layout which is technically superior and economically viable. This involves preliminary performance predictions and provision of three-dimensional electronic drawings with several cross-sections, an inboard profile showing the approximate placement and size of the major vehicle components. A weight and balance diagram provides another essential proof of concept.

There is an intimate relationship between the design objectives of an aircraft and the configuration concept capable of fulfilling these objectives. The overall concept describes a highly complex system which has to reach a compromise between contradicting requirements. Application of new technologies affecting all sub-systems is indispensable for economic success of the new product. The conceptual design phase is intended to generate a credible proposal of a feasible baseline design in order to convince management that it is worth the substantial resources required to develop and improve the design in further detail. Design tools are semi-empirical and low to medium fidelity methods used in trade-off studies and basic optimizations – most of the geometry is provisional. Validated design tools developed by the AD office are calibrated with statistical data bases, handbooks and historical trends, taking into account improvements expected from new technologies. The amount of data generated for a baseline design will be moderate and prediction errors are around 5%, typically.[4]

In an environment where designs are developed which fit into an existing product line, designers may investigate different fuselage cross-sections, wing positions and planforms, number and/or location of engines, empennage and undercarriage concepts. A few promising concepts are analyzed and selected for further study. Conceptual studies may also be carried out to investigate potential gains expected from new aerodynamic devices, structural concepts, materials and/or system technologies and/or an advanced engine concept. All of these features have a far-reaching effect when integrated into the design. Designers who are supposed to

[3] In the context of this chapter, the term configuration refers to the airplane's general arrangement, not to be confused with the same term used in flight mechanics defining operational parameters of a particular aircraft such as engine rating, flap and slat deflection angles, tailplane incidence, undercarriage position, etc.

[4] An error in the concept stage is defined as the difference between a predicted value and the established value of a parameter after completion and testing of the first aircraft. Since the certified aircraft will make its inauguration several years after concept definition, the detailed design has gone through many modifications. Hence, prediction errors are inaccuracies rather than mistakes.

explore a radical concept may consider an integrated configuration such as a blended wing body (BWB) or an all-wing aircraft (AWA) (Chapter 5). Less radical alternatives are a canard or three-surface aircraft, a twin-fuselage aircraft concept, a strut-braced or a nonplanar wing (Chapter 6). A detailed assessment of advantages and disadvantages must then be made by comparison with more conventional solutions. During all the stages of concept definition, the technical risks and costs of possible failure must be closely examined.[5]

Typical of concept design is its iterative character: primary components – wing, fuselage, nacelles, tailplane, landing gear, propulsion and other systems – are sized provisionally to result in a baseline design. Dependent on where improvements are desirable, the process may recycle to an earlier definition level at each point in time. A baseline design is not necessarily an optimized airplane and, for a traditional layout, the combined application of active constraints will normally give an adequate approximation to the best feasible design. If a novel solution is tried, the estimation of the aircraft effectiveness will be based in some areas on slender evidence and simple mathematical models. The best available model may then change rapidly with time and will probably be too crude to warrant rigorous treatment. In any case a comprehensive design optimization at the conceptual stage is of little value [66].

1.3.2 Preliminary Design

After selection of a baseline airplane concept, the design and analysis process will enter the preliminary design phase. As opposed to conceptual design which deals with the whole aircraft system, preliminary design aims at defining subsystems, making component trade-offs and optimization. Specialists from different functional groups contribute to this process of refining the initial vehicle concept – AD remains responsible for coordination. This team will (re)design the delivered baseline vehicle in sufficient detail to carry out supporting analysis and specify peripheral testing programmes but not with enough detail to specify each sub-assembly. Information to establish the programme feasibility is generated by means of sophisticated computational aerodynamical, mechanical and structural analysis, prediction of the economics and expected market penetration. Preliminary design can be characterized as setting goals for the extensive efforts to be made in the downstream detail design phase. Typical subjects are categorized as follows:

- Design definition. The baseline design team is committed to elaborate detailed analysis and sensitivity studies, with the aim of developing the best feasible configuration. This includes finding a balance between required volumes, main dimensions, weight distribution and engine performances. Details of the aircraft geometry, aerodynamic properties, structural loads and deformations and flying qualities have to be settled.
- Design validation. The predicted characteristics of the preferred configuration are verified by high-fidelity supporting analysis, simulations and test data. This becomes the final step of the preliminary design cycles.

[5] It is often said that 'In aircraft design one never gets a free lunch.' This statement applies in particular to conceptual design where it may be interpreted as follows: 'The greater the promise, the higher the risk of show stopper.'

A detailed analysis is usually made to determine the sensitivity of the configuration to technology inputs, performance objectives and design constraints. This makes sense since during preliminary design there still exists considerable freedom for refinements and improvements through optimization of variables such as detailed wing design, engine thrust, location of the power plant and empennage design. These trade studies have a widespread effect on most areas of the design and must therefore be carried out with scrutiny using high-fidelity analysis. Particular attention will be paid to the following issues:

- Detailed volumetric sizing and mass breakdown, centre of gravity (CG) location and loading restrictions, and moments of inertia, resulting in a considerable expansion of the design database.
- Definition of the aerodynamic shape of lifting surfaces, including high-lift devices, using computational fluid dynamics (CFD) methods and wind tunnel testing.
- Layout and sizing of main mechanical and structural concepts, aero-elastic analysis by means of finite element methods (FEM), and structural testing.
- Layout of the basic flight control system and control surfaces and devices, including prediction of flying qualities.
- Drawing up the specifications for buy-out components to be subcontracted to suppliers. This concerns the power plant (engines, propellers, nacelles) and other major aircraft systems such as the auxiliary power plant, environmental control, fuel system, hydraulic system, electrical system and avionics.
- Economic analysis in terms of operating costs. Commercial prospects are then predicted by means of economic analysis and a market penetration model.
- Analysis of environmental issues such as internal/external noise and engine emissions.

All activities are based on standards of the selected airworthiness codes and regulations as the primary measure for acceptance of design solutions. The scope and depth of the physics-based analysis and the fidelity of the computational models are increased to such a level that the impact on aircraft performance and cost of proposals to modify the baseline configuration can be quantified. Although CFD and FEM codes provide high-fidelity results, computer simulations cannot always be relied on for an accurate prediction of operational properties. Design validation will therefore require extensive wind tunnel testing[6] and testing of structural models to ensure that achieved performances will be no more than a few percent off the requirements.

Whereas the engineers involved in conceptual design generally belong to AD, specialists from various functional disciplines become involved when the preliminary design stage is entered. From then on the approach to be taken relies heavily on system engineering techniques. This phase may span a year or more with a team of dozens up to hundreds of engineers working in a multidisciplinary environment. The amount of detailed data generated is substantial, prediction errors should amount to no more than few percent. The end product is an optimized and verified airplane configuration resulting in the technical description of prototypes to be tested and the type specification of the aircraft. When the design project is

[6] A future addition to the presently available (high-cost) wind tunnel testing technology could be the use of free flying sub-scale models referred to as robot vehicle flight testing [56].

sufficiently mature, it may get an authorization to be offered for sale with written (contractually binding) guarantees on cost and performance. When market prospects appear to be promising, management authorizes the project go-ahead. In view of the high costs incurred by major configuration changes during the following design stage, this decision brings the iterative design cycle to an end by freezing the configuration.

1.3.3 Detail Design

The pieces of hardware that will actually be built and installed in the airframe are conceived during the detail design phase which is entered after the aircraft is committed to production. The objective of detail design is to specify the geometry of all components and plan their manufacturing processes. This encompasses drawing up instructions for the production department and the development of a careful plan for assembling the aircraft. Throughout this activity, drawings are progressively released for production. Results are complete production descriptions and specifications of all structures, systems and subsystems. Compared to preliminary design, detail design is much more labour-intensive and far more staff are involved. The participation of AD is restricted to coordinating measures to be taken when detail design appears to have an effect on the technical specifications. A typical example is when a significant empty weight growth has to be addressed by a weight reduction programme. After completion of the detail design phase, the manufacturing of components begins, followed by the final assembly of one or more flight-test vehicles, roll-out, first flight, flight testing, and certification. In the case of an all-new civil airplane development, the completion of the airworthiness certification process and first delivery to the customer will occur some five to eight years after the initial design efforts (Figure 1.4).

1.4 Baseline Design in a Nutshell

This book focusses on the conceptual and preliminary design definition rather than on the design validation and detail design. Although the described sizing procedure for conceiving a baseline design of a civil jet airplane is by no means a standard process, it contains a set of essential activity clusters. Conceptual design is a continuous iterative process that begins with an initialization of a few major characteristics to be discussed in Chapter 2. The following bird's eye view of a baseline design sizing process describes the logical order of activities visualized in Figure 1.5 leading to a converged design in as few iterations as possible. The result is a non-optimized but feasible jetliner design which complies with TLRs – the sizing process of a turboprop airplane is similar although sizing relationships are different. The diagram indicates an inner loop for satisfying payload/range and high speed performance requirements and an outer loop for making sure that low-speed properties comply with TLRs and other constraints. This approach is in the interests of an efficient iteration process but does not necessarily lead to the best feasible design. The next steps are optimization and trade-off studies as discussed in later sections.

1.4.1 Baseline Sizing

A baseline design is materialized in the form of a fairly comprehensive definition of its basic geometry, using a computer assisted design (CAD) system. Defining the geometry by

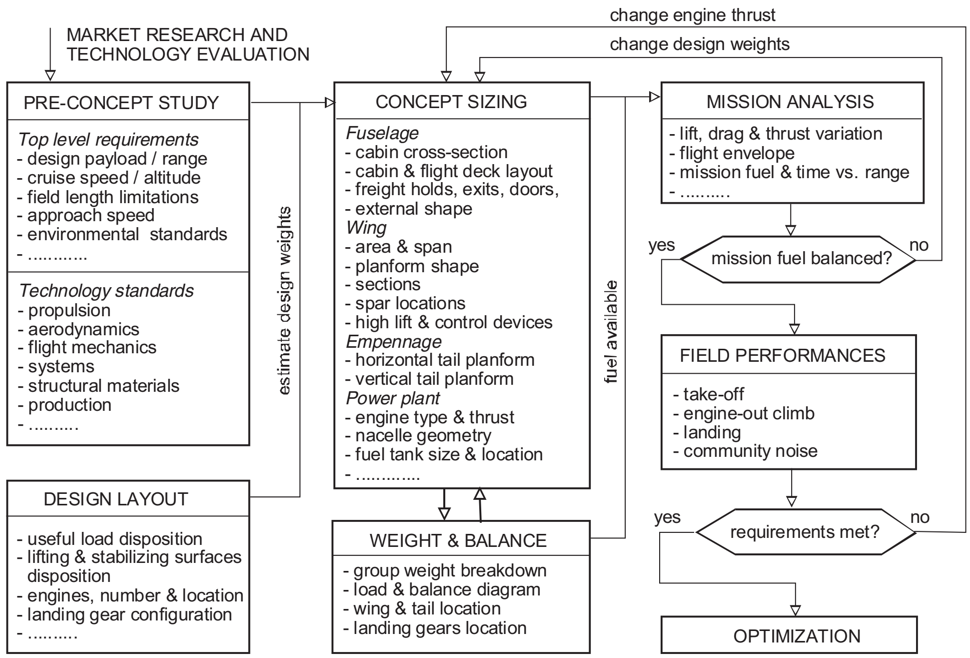

Figure 1.5 Schematic outline of a jetliner baseline design process

a parametric description helps the designer to predict the variation of mass distribution and aerodynamic properties due to variation of independent design variables such as wing area and aspect ratio, engine power or thrust, and empennage size. Figure 1.5 illustrates that initial 'guesstimates' are made of several important design characteristics.

- Design weights. Payload, fuel weight and take-off and landing gross weights corresponding to the design mission are estimated together with initial values of the empty weight and the zero fuel weight; see Chapter 2.
- Total take-off thrust and number of engines to be installed.
- Wing loading; that is, the maximum TOGW per unit of wing area.

These characteristics are revised as soon as more detailed design information becomes available. For designs with a conventional general arrangement, they are probably based on statistics, using input from the TLRs and data from similar existing or projected aircraft. For more innovative concepts, relevant publications on applied research should have been studied before starting the actual sizing.

For passenger aircraft and freighters with a traditional layout, the first geometric element to be conceived is typically a pressure cabin cross-section and floor planform, based on the specified transport function and comfort standards. Passenger cabin layout is based on selection of items such as number of passenger decks, number of seats abreast in a basic cross-section, seat pitch and number of seat rows for several accommodation standards, width and height of aisles and overhead bins, and allocation of restrooms and galleys. Pressure cabin dimensions are obtained by combining typical seating arrangements with (a) location and size of passenger and servicing entrance/exit doors and emergency exits; (b) flight deck geometry, entrance door and escape hatches; and (c) luggage/cargo hold geometry and loading/unloading hatches. Addition of a cabin wall with realistic thickness, fuselage nose and tail shapes results in a three-dimensional definition of the basic external fuselage shape. For airliners this is normally a streamlined hull with a cylindrical mid-section enclosing the contents arranged with good accessability inside the smallest possible skin. Cabin volume, floor area, and fuselage skin area are basic input for aerodynamic and weight prediction. In order to obtain an arrangement that is flexible enough to suit an airliner family concept, it may be necessary to repeat the fuselage sizing process for a future derivative or a freighter version.

The wing is the second main component to be sized. Wing geometry has to be matched to the performance requirements and is defined in terms of several parameters used in flight performance analysis. Prominent parameters of a lifting surface are the gross planform area, the span or the aspect ratio, the taper ratio, the thickness/chord ratio at the root and the tip, and the angle of sweep of the quarter-chord line. It is also desirable to specify a standard for aerodynamic wing design, such as supercritical or laminar flow technology. However, variation along the section shape and incidence along the span are the subject of downstream aerodynamic wing design (Chapter 10).

1.4.2 Power Plant

Figure 1.5 relates to the case that candidate engine types are under development. Each of the following options will lead to design processes that are different in the details.

- One option could be that a new aircraft design or a variant of an existing type is considered in response to the availability of a new engine type. In this case, installed engine performances and geometry are specified in detail by the engine manufacturer. In the interest of minimum project development costs, the basic properties of the existing aircraft are retained as much as possible, leading to a modest airframe modification. In this situation there is little or no opportunity for optimization.
- In order to match the engine to an existing airframe, its thrust is scaled up or down by means of a procedure known as engine rubberizing. A baseline engine is then characterized by its installed take-off thrust. Variations of engine performances with altitude and speed are described by generalized characteristics such as thrust as a fraction of take-off thrust – the thrust lapse rate – and specific fuel consumption (SFC) or overall efficiency of the engine. Scaling relationships for engine size and weight are derived from the engine manufacturer's information. Rubberizing includes the effects on the engine's installation characteristics which means that nacelles are scaled up or down so that performance losses due to nacelle drag and power off-takes are properly taken into account.
- A far more complicated situation occurs when different engine cycles are studied, for example, for investigating the effects of turbofan bypass ratio variation. This requires a thermodynamic cycle analysis for computing engine performances as well as prediction of engine plus nacelle geometry and weight, all of these in relation to the bypass ratio and the take-off thrust. It goes without saying that the various scaling rules should be drawn up in cooperation with the engine manufacturer's project design office.

The decision of where and how engines are attached to the airframe constitutes one of the most essential choices of layout design (Chapter 3).

1.4.3 Weight and Balance

The allowable variation of the useful load and its location determines the aircraft's loading flexibility. This is restricted by the allowable centre of gravity (CG) travel which in turn relates to the amount of (inherent or artificial) stability required for the configuration. The horizontal tail size is obtained from longitudinal stability and control requirements in combination with load and balance computations. For a given wing position relative to the fuselage and horizontal tail size/location, the following results are derived:

- Empty weights of major assemblies and their CG location, airplane CG location and moments of inertia about the three body axes. Some of these are be based on analysis, others are obtained from statistical information, using initial design weight estimates and design geometry.
- Envelopes of loaded aircraft fore and aft CG locations versus GW corresponding to likely combinations of payload and fuel.
- Allowable fore and aft CG locations for several important flight conditions derived from stability and control requirements, known as aerodynamic limits.

The required and allowable CG envelopes versus GW form the load and balance envelope which gives a tool for making sure that the operationally required CG range always fits within the aerodynamic limits. If that is not the case, measures have to be taken to obtain a balanced aircraft: (a) by relocating the wing relative to the fuselage; (b) by changing the wing sweep angle; (c) by relocating system components or operating items; or (d) by increasing the horizontal tail size. If these measures do not help, loading restrictions may be necessary – an undesirable situation. Vertical tail size follows from required directional stability, lateral control after engine failure and coping with cross-wind during the landing. When the airplane appears to be safely flyable in all practical conditions, the main landing gear elements are sized and arranged relative to the CG range so that the aircraft can be manoeuvred safely on the ground. Having located the landing gears, the designer may have to make another iteration of the CG envelope and/or horizontal tail sizing. The balancing process is thus highly iterative.

1.4.4 Structure

Part and parcel of the geometric development are the conception of a provisional structural configuration and distribution of the following system elements:

- Topology and major components of the cabin structure such as major fuselage frames where the wing, tail surfaces and engine pylons are attached, longerons, with pressure bulkheads, doors and hatches and pylons of fuselage-mounted engines.
- Principal structural elements of the wing: skin/stringer panels, spars and ribs, fixed leading and trailing edge structures, high lift devices, flight controls and their supports. Also specified are pylons of wing-mounted engines, landing gears and their attachments, and wheel wells.
- Basic structure of the empennage and its attachment to the fuselage body, taking into account provisions for flight controls and stabilizer incidence adjustment.

Size and location of major systems hardware such as the auxiliary power unit (APU) and the environmental control unit (ECU) are indicated to make sure that they can be fitted inside the available structure.

1.4.5 Performance Analysis

Aerodynamic and engine characteristics can be predicted as soon as the baseline design geometry is defined. First, lift and drag coefficients in the en-route configuration are computed as a function of the angle of attack and Mach number. Second, engine thrust and fuel consumption as a function of the altitude and Mach number are determined for several climb and cruise ratings. Before analyzing a flight profile, it is useful to check that the available thrust matches the drag at the desired cruise conditions. If that is not the case, the engines are scaled up or down in thrust and dimensions and part of the sizing loop is repeated, as indicated in Figure 1.5.

The objective of mission analysis is to compute the amount of fuel burned, distance travelled and time elapsed during each flight segment and during the complete flight from the airfield of departure to the destination. The flight profile of a civil aircraft (Figure 1.6) is composed of the segments take-off, climb and acceleration, cruise, descent, approach, aborted landing and diversion to an alternate airfield. The intention is to make sure that, when taking off, the required mission fuel is available to fly the design payload over the required distance, after which there remains sufficient reserve fuel to make a holding flight and divert to an alternate field. If a mission analysis is carried out after computation of the MTOW, it is mostly found that the range is not exactly equal to the design range specified in the TLRs. The next sizing iteration is then started as indicated in Figure 1.5. In principle, all design weights, many empty weight components and the amount of fuel have to be revised and the mission analysis is repeated until the weight distribution is balanced with the required range.

Aircraft handling and performances while taxying, taking off from and landing on the airfield, and in low-speed flight are primarily affected by take-off and landing weights, the number of engines and their forward and reverse thrust, wing area and planform shape, aerodynamic properties of high-lift and drag modulation devices, and landing gear braking capacity. The distance that a civil aircraft requires to make a safe continued or aborted take-off after failure of an engine during the take-off run is referred to as the balanced field length (BFL). This distance must not be longer than the available runway length. Moreover, it has to be verified that minimum climb-out performances can be attained in case the flight is continued

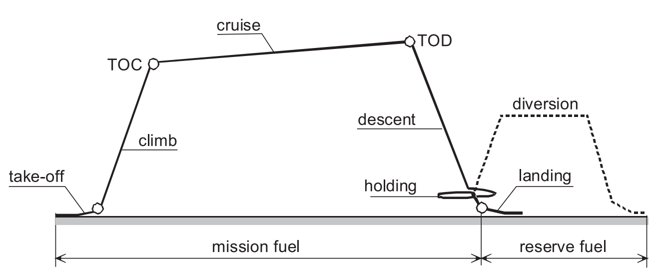

Figure 1.6 Typical flight profile

after engine failure. In commercial flights, a take-off is seldom complicated by engine failure – nevertheless, the pilot makes a flight schedule based on the case of an inoperative engine. Since in this situation low drag is most important, the high lift devices will not be deflected to their maximum extent. Climb performance lower limits apply during approach and landing as well, however, a higher lift coefficient is available compared to the take-off. Since for medium- and long-range (subsonic) aircraft the landing GW is significantly lower than the take-off GW, the approach and landing requirements are not often critical. The opposite is true for short-range aircraft for which – dependent on the deceleration due to aerodynamic drag devices, lift spoilers and wheel brakes – the approach speed and available landing distance often dictate the landing wing loading.

1.4.6 Closing the Loop

It is likely that at this stage one or more performances are inadequate and appropriate measures have to be taken. For example, if the BFL required is satisfactory but climb-out performance after engine failure is inadequate, one might consider increasing the wing span for the same area, that is, an increased aspect ratio. If both performances are unsatisfactory and cannot be improved by aerodynamic means such as more sophisticated high-lift devices, the take-off thrust may be inadequate. The final outcome of the iterations should be a certifiable baseline design which satisfies the requirements and constraints. Geometric details laid down in a three-view drawing and an inboard profile are augmented by more detailed information such as illustrated in Figure 1.7. In the case that all requirements in the TLRs are satisfied and the project can be continued, the baseline design becomes the subject of detailed analysis and verification during the preliminary design phase. If, even after reasonable modifications of the baseline aircraft, certain requirements cannot be met, the conclusion must be that the available technology for a successful project is lacking. This may lead to accepting (minor) changes in the TLRs or cancellation of the project.

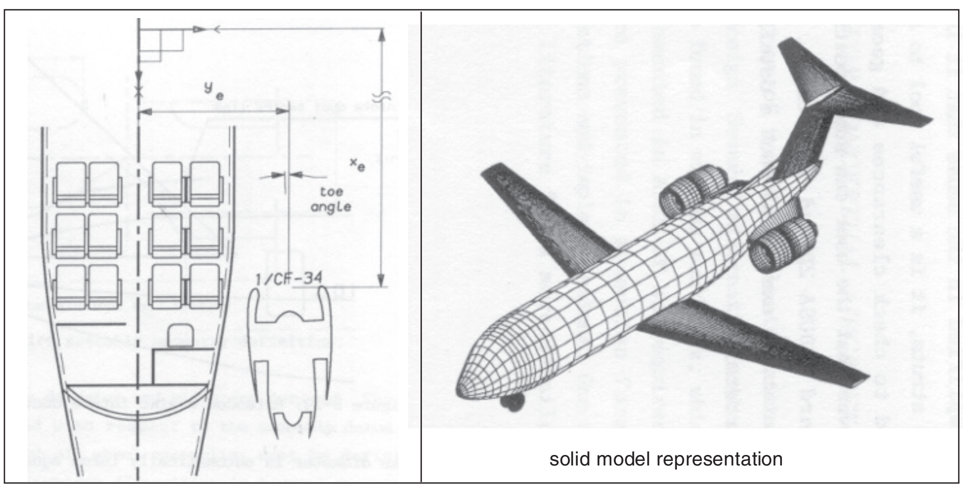

Figure 1.7 Airliner concept generated by a CAD and analysis system [84]

1.5 Automated Design Synthesis

Conceptual design tools used by aircraft manufacturers are not available on the software market since they contain sensitive information reflecting the expertise of the company. However, automated design synthesis (ADS) systems have been developed by consultancy firms, research institutes and academia. Automated design systems emphasize optimization rather than sizing. Although synthesis programs are used primarily for sizing a baseline design, they can be useful for other tasks as well. For example, figures of merit (FOMs) for evaluating the importance of design variables are operational/commercial performance and cost. Comparing the characteristics of aircraft optimized for different FOMs is a complex but revealing activity that can be carried out only with a ADS system. Investigations of unconventional concepts, technology trade-off studies between alternate designs and weight-related studies are almost invariably made by applications of ADS programs. And, last but not least, synthesis programs are useful for validating and improving drag and weight prediction tools.

1.5.1 Computational Systems Requirements

The aim of a high-fidelity design analysis is to obtain more credible predictions in the interest of reducing development risk. However, a comprehensive synthesis program is used in various stages of the design process and should therefore have the capability to provide computations with different levels of prediction accuracy. Low fidelity methods are used in the early conceptual phase to derive simple but statistically validated predictions based on only a small number of essential inputs. As the vehicle definition becomes more detailed, the fidelity of design tools increases. Accordingly, aerodynamic analysis ranges from (semi-)empirical handbook methods through several levels of computational complexity to interpretations of wind tunnel data. Other technical disciplines have similar levels. High fidelity analysis requires a detailed input which is not available until the preliminary design phase is entered. Internal and external geometry – in particular, the volumetric disposition and wetted areas – are essential inputs to the ADS program, and shape optimization requires that the geometry can be parameterized. This requires simplification by ignoring details such as small fairings between major components, wing leading and trailing edge extensions and kinks. The internal geometry is schematized by considering large structures to be built from generic components, such as the primary and secondary wing structure, the fuselage shell, floors, bulkheads and secondary structures.

ADS systems must be flexible enough to allow the design problem structure to be defined according to the designer's needs. They are usually highly modular so that the functions to be performed are clearly separated and can be assembled to perform various sequences of computations, depending on the problem. Each individual module provides the intermediate data from a particular technical discipline, thus forming the input of other modules as well as the geometric definitions needed for vehicle (component) definition. These modules should be verified prior to integration with other modules. Modularity leads to obtaining a more transparent design procedure since it simplifies data transfer and identification of errors during program development. A control program is used to exercise the individual modules and to coordinate data transfer to other modules. This set-up is required in order to ensure that in each stage of an iteration the definition of the vehicle as a system remains unambiguous and consistent. A correct problem structure is at least as important as the accuracy of the analysis methods used. Accordingly, a great deal of thinking and arranging of equations are required before the computations can be made. In contrast to many publications which emphasize the mathematical treatment of optimization, the designer's activity is a blend of interactive graphics manipulation and visualization, computation and organization of data flow. In an efficient integrated program the selection of the appropriate levels of computational fidelity and the preferred search strategy remain under the designer's control.

1.5.2 Examples

Synthesis programs contain simplified vehicle descriptions and merely mimic the process by humans to accomplish the design and analysis solutions provided by statistics and calculator-based methods from handbooks. The primary objective of the synthesis process is to carry out a trade-off between basic design parameters and characteristics that will warrant a more detailed study. In particular, wing size and engine power or thrust are primary candidates for trade-off. Computerized synthesis is a complex activity which integrates the contributions of various disciplines involved illustrated in Figure 7.8. A practical engineering approach requires a large computer program connecting the inputs and outputs of each discipline. The final result is a combined answer indicating the overall feasibility of the project.

Figure 1.8 shows schematically the principal lines of data flow of an early – but still representative – ADS program structure [62]. Analysis programs are modularized by discipline, the sequence of calculations is controlled by a separate module. Via the performance and economic evaluations block, design objectives are initially introduced as input into the program flow. Part of the concepts introduced into the modules is technology state-of-the-art information.

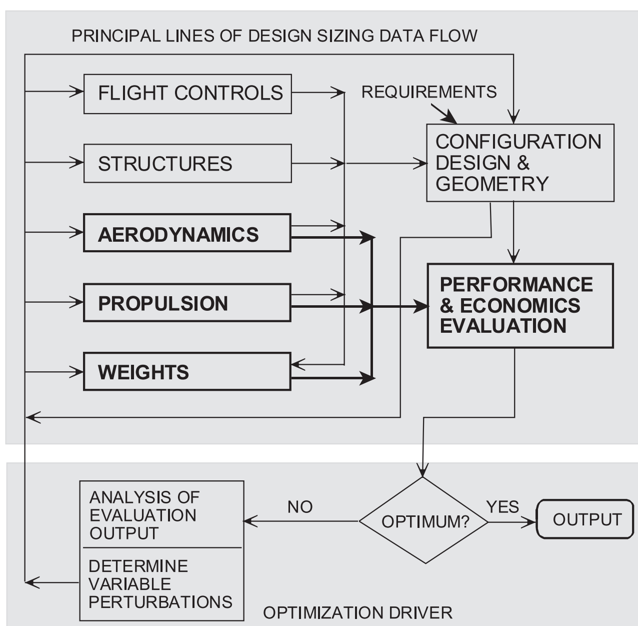

Figure 1.8 Schematic sizing and optimization data flow of a design synthesis program [62]

In aerodynamics this could be the sophistication of airfoil and high lift technology. Structural concepts' state of the art includes the degree of composite materials application in primary structures. Propulsion technology defines the gas generator compressor pressure and temperature levels and the bypass ratio. And in flight controls the degree of artificial stability is a typical concept for reducing tailplane size, drag and weight. Note that in Figure 1.8 the output from the disciplinary modules as well as the configuration design eventually goes to the performance and evaluation block. Some of the paths are direct, others are indirect via weights and configuration design. Flight systems, structures, aerodynamics and propulsion all feed weights as well as configuration design. However, since drag, thrust and aircraft weight are the only force vectors necessary for performance evaluation, the aerodynamics, propulsion and weight blocks are sufficient to deliver the data input. The design converges after several iterations and the outcome of the process is an evaluation of the design by the performance module. The user will then decide to accept the outcome or to continue the process through variations in the design. For this purpose, modern synthesis programs have a separate optimization driver containing a suite of algorithms to choose from.

Major design organizations are developing their own ADS programs. Commercially available programs developed by consulting companies are mostly based on handbooks [102] whereas several programs exist in the public domain using a similar approach as shown in Figure 1.8. Systems developed by NASA institutes are available in the public domain [75, 91, 96], systems developed in academia are reported in [80, 83, 89, 98]. Automated systems have proved effective for designing airplanes within the prescribed domain – some of them have been continuously improved and have become highly trusted. New approaches based on object-oriented and knowledge based engineering (KBE) may be particularly promising for developing sizing tools to study unusual air vehicle concepts [94, 100, 103].

1.5.3 Parametric Surveys

The traditional approach to conceptual sizing and optimization is to carry out parametric surveys by solving the system of equations for a few – typically, not more than five – selection variables defining the design space (Chapter 7). The most relevant properties of the evaluated designs are presented for inspection in tables and/or carpet plots [39] such as Figure 1.9. It should be noted that every combination of wing area and engine thrust represents a provisional but complete aircraft design for which the weight breakdown has been computed or interpolated. Since many of these designs do not comply with all TLRs, constraints are added to indicate the feasible region of the design space. The baseline design complies with all requirements, although a lower MTOW is obtained by selecting a larger wing area and a slightly smaller engine. Quasi-analytical methods for obtaining parametric surveys are derived and illustrated in Chapters 8 to 10.

Parametric surveys are rooted in the industrial approach, where they are considered valuable since the designer can make maximum use of experience and keeps complete control over decisions. These surveys accept relatively simple programming techniques such as spreadsheet methods adaptable to the situation [86]. This approach has the advantages that an *a priori* choice of a single FOM is not required and sensitivity to less-than-optimum design conditions remains visible; hence, maximum use is made of calculated results. The number of design variations and modifications can be selected in accordance with the time budget available.

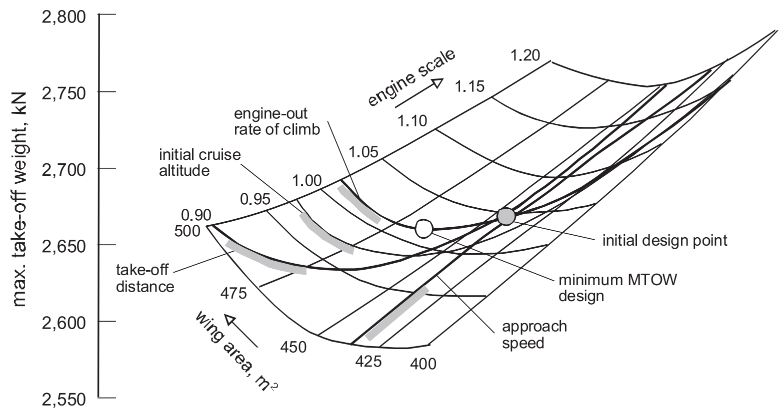

Figure 1.9 Carpet plot depicting results of a parametric survey. Wing loading and engine thrust are design variables, MTOW is the figure of merit

If the overall concept is within the designer's experience, parametric investigations may be helpful in optimization work although this pragmatic approach may not be entirely satisfactory for the following reasons.

- Due to the restricted number of selection variables, there is no guarantee that the solution represents the 'real optimum'.
- The method is practical for a small number of selection variables. The designer may resist increasing the design space since the addition of more variables will increase the amount of computation by an order of magnitude.
- The majority of the analyzed configurations are used for the purpose of the parametric study only and are discarded afterwards whereas small changes in the TLRs may make all previous results obsolete.

1.6 Technology Assessment

The challenge for conceptual designers active in an AD office is to strike a balance between the pros and cons of enabling technologies that are considered mature for application. They have to make an assessment of economic benefits, effects on safety, cabin comfort, reliability, maintainability, and environmental compatibility. The aim is to identify and select the most cost-effective breakthrough technical innovations and to find out whether they can be developed in time, and whether their integration into the aircraft system requires a departure from the conventional aircraft configuration. A long list of potential innovations can be made – the more radical of these tend to be achievable only with considerable development effort, costs and risk. However, using advanced technologies may drive up operating cost and degrade operational flexibility, maintainability or even passenger appeal. Assessment of emerging technologies must take into account possible program development risks. The enormous costs of developing jetliners are justified only when potential customers can be convinced that the new product will outperform existing types in its category both technically and economically.

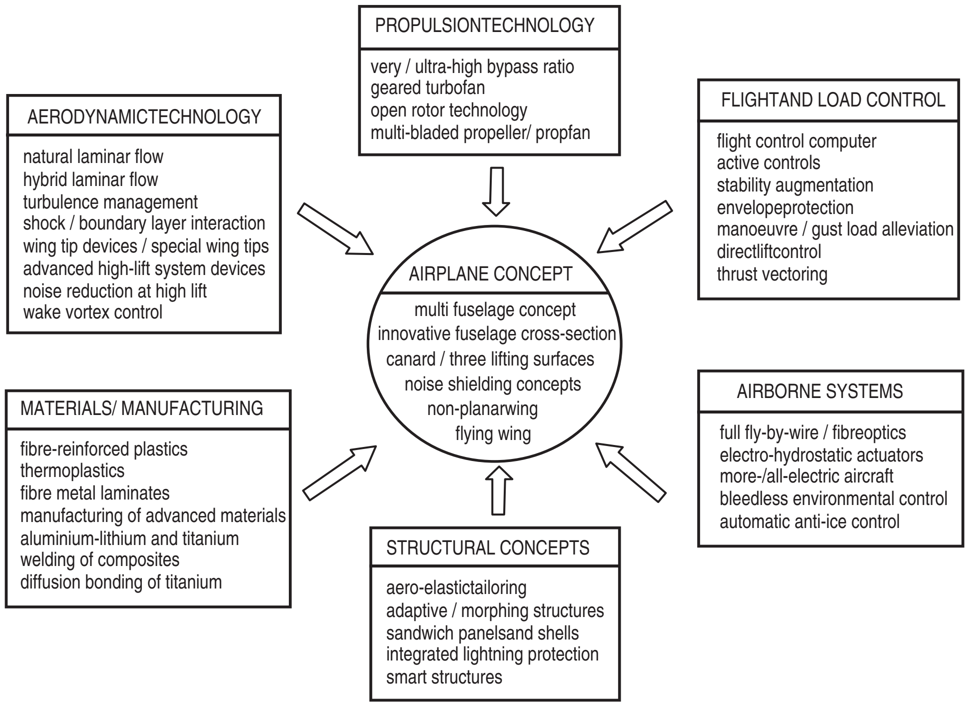

Figure 1.10 Overview of disciplines and enabling technologies

In general, this requires the introduction of an advanced but sufficiently mature technology standard in several design disciplines. Accordingly, conceptual design studies are frequently initiated to assess how the application of new technology will affect future designs rather than to develop a new aircraft development project. Disregarding the appearance of a new engine generation, the largest impact on operating economics is due to the accumulative effect of several relatively small advancements. Improvements in new airplane designs have therefore traditionally been evolutionary rather than revolutionary.

Conceptual design studies are based on choices from the most promising advancements in the state of the art; see Figure 1.10. For a particular project more alternatives can be added, other topics may already have been eliminated beforehand. Chapters 3 and 4 are dedicated to identifying improvements of aerodynamic and propulsive efficiencies. Specific technologies with a large impact on the overall airplane layout are treated extensively in Chapters 5 and 6. Factors driving the design of airliners are relevant to some extent for business aircraft design as well:

- Propulsion. Turbofans of the next generation of civil aircraft are expected to have an ultra-high bypass ratio and geared turbofans. A more radical concept is open rotor engine technology in the form of contra-rotating propfans or unducted fans. Integration into the airframe of these new engine concepts may require an innovative overall airplane concept. Turboprops for high speeds will drive multi-bladed crescent-shaped propellers.

- Airplane configurations. Evolutionary development of airliners may result in different concepts emphasizing low-cost transportation, improved cabin comfort, reduced atmospheric contamination and external noise. Radical concepts such as integrated configurations, non-planar wings, all-wing aircraft and propulsion by hydrogen fueleld engines require major investments in research and development.
- High-speed aerodynamics. Small airliners and business aircraft with a small wing leading edge sweep may achieve areas of natural laminar flow (NLF). Laminar flow control (LFC) by suction of the boundary layer through a porous skin is a potentially powerful fuel saver. Winglets and sheared tips reduce induced drag by up to 15%.
- Low-speed aerodynamics. Airplanes with stringent airfield performances require advanced high-lift devices. Options are variable camber, full-span flaps and powered lift by means of externally blown flaps or engines blowing over the wing. Reduction of aerodynamic flap/slat noise and manipulation of trailing vortices can have a favourable effect on air traffic management (ATM) and environmental compatibility.
- Flight control systems. Flight envelope protection and stability augmentation are accommodated by a flight control computer and active controls. Manoeuvre and gust load alleviation are considered additional provisions for saving structural weight and improving comfort. Direct lift control and/or thrust vectoring can be considered for unusual configurations to improve their controllability.
- Airborne systems. Except for very light aircraft, fly-by-wire has become the standard for airliners and business jets – fibre optics may be considered in the future. More-electric aircraft enable environmental and automatic icing control without making use of engine bleed air and simplify the auxiliary power unit.
- Materials and manufacturing. Composites are becoming increasingly dominant with applications of fibre-reinforced plastics in primary and secondary structures. Fibre metal laminates are applied in fatigue-sensitive areas and secondary structures. Aluminium-lithium alloys replace the traditional 5000 series, leading to about 10% weight reduction.
- Structural concepts. Affordable composite fuselages are becoming an option for many airliners and business jets. Lightning protection is required for all exposed composite structures. Aero-elastic tailoring is applied to avoid divergence or flutter and may be considered to enable a forward swept or very high aspect ratio wing. A morphing wing structure adapts the shape of high-lift devices off-design flight conditions.

Conceptual designers base their judgement concerning new technologies on experience and on how much credibility they attach to innovations, taking into account that airlines are often more conservative than airframe manufacturers. Neither of them do want to be involved in a high-risk technology leading to unexpected development, certification and maintenance costs. In this respect a (seemingly radical) technology such as active LFC is considered suspect even though its aerodynamic and operational feasibility has been demonstrated in R & T programs in the US and in Europe. Conceptual design technological standards are specified in relation to the operational profile and the time of introduction into service of the new type. For example, long-range airliners are usually large and cruise at high speeds – they require more advanced technology than regional aircraft spending more time at low altitudes and speeds. The preference for a particular technology will also be affected by the company's capabilities to incorporate them into their manufacturing processes. Although innovations generated by technological research are continuously reported worldwide, application in actual design practice can only be justified after a study of all aspects associated with their integration into the aircraft and its production process.

1.7 Structure of the Optimization Problem

The structure of an optimization problem is essential to make its results credible. This section is intended to stimulate the (inexperienced) advanced designer to avoid unrealistic results of a complex aircraft system optimization. Reference is made to Chapter 7 for the terminology used and more background information.

1.7.1 Analysis Versus Synthesis

It is useful to make a clear distinction between design analysis and synthesis. This is illustrated by showing the differences between performance analysis of a specified design and sizing a design for specified performance.

- Flight performance analysis applies to an aircraft (design) that is fully defined in terms of geometry, weight distribution, aerodynamic characteristics and propulsion system properties. The underlying physics – mainly flight mechanics and dynamics – is mono-disciplinary and the solution is fully determined. Validated programs based on substantial experience are available to assist the analyst. For instance, cruise performance analysis is a matter of routine although Chapter 12 demonstrates that for cruising at a transonic Mach number, this can be more complicated than is usually thought.
- Synthesizing an aircraft design that has to comply 'in an optimum fashion' with a specified set of TLRs. The designers' task is to find a satisfactory compromise between conflicting requirements which may lead to an indeterminate problem. The underlying physics originate from many interacting – but to a large extent fundamentally unrelated – aeronautical disciplines and the set of equations does not always have a unique solution. Although at first sight the freedom to select the independent design variables may seem overwhelming, constraints reduce the dimensionality of the design space. Guidelines based on statistics can be useful when choosing selection variables if a suitable objective function cannot be quantified, although these 'rules of a thumb' may be reliable only for configurations that are not too different from existing ones.

A practical example is selecting the preferable cruise altitude. The best initial cruise condition of an operational aircraft with given gross weight is readily obtained from performance analysis – it is usually defined as the altitude where the fuel consumption per distance travelled is minimal. For an aircraft taking off with its MTOW, this optimum is probably constrained by the available cruise thrust. On the other hand, the sizing problem is to find the definition of a design that yields the most economical performance by computing the effects on the cruise altitude of varying wing geometry and installed thrust. In the latter case, the designer has to cope with the following challenges:

- The sensitivity of dependent design variables (lift, drag, gross weight, initial cruise altitude) to variation in independent design variables (wing geometry and installed thrust) must be established.

- A criterion must be found defining 'the best aircraft' within the set of design constraints.
- A choice has to be made of representative conditions – in particular, payload and range – for which operational and economics characteristics are evaluated. This is often referred to as the design condition.

In principle, this problem definition determines the solution of the aircraft system optimization. However, even the basic task of defining the best cruise altitude must not be underestimated, whereas the problem of determining an optimum cruise Mach number is a challenging task. For both examples, the case of a given (operational) aircraft is fairly easy if not trivial, but computing the best design cruise Mach number of a clean-sheet design is extremely complicated, if not impossible. In both examples, the conceptual designer may decide that a maximum payload or a long-range condition is most important and that an all-out optimization does not have a high priority. Using the quasi-analytical approach discussed in Chapters 8 to 10 may then be preferable.

1.7.2 Problem Classification

In accordance with the structure of the aircraft system optimization problem and the previous considerations, the ground rules and the computational approach discussed in this book are clarified according to one of the following options.

1. Optimizing flight conditions for a given airframe-cum-engine combination. The problem is to derive a mission profile resulting in minimum fuel burn, flight duration or direct operating costs (DOC). This is basically an optimal control problem occurring in design studies as well as mission analysis of existing aircraft. Depending on the design phase (conceptual or preliminary), the solution may be simplified by accepting approximations, resulting in a closed-form equation for the mission fuel required to fly a given range or the range obtainable with a given mission fuel. Treated in Chapter 12, these subjects form essential elements of the aircraft sizing process.
2. Determining the optimum airframe properties for specified engines. This is a typical conceptual design exercise of matching the airframe to engines selected a priori in an optimum fashion. Wing geometry is then the primary candidate for a highly constrained optimization. A similar situation occurs if a new engine technology becomes available for installation in an existing aircraft (family). The aircraft's commercial value may then be enhanced by increasing the payload versus range capabilities, preferably with minor modifications of the airframe.
3. Finding the best combination of the airframe and a given number of engines. Selection of the engines and their position relative to the airframe has far-reaching consequences. In order to find the best match during the conceptual stage, basic airframe properties are varied and engine properties are scaled by rubberizing the engines. The final selection is likely to be made during preliminary or detailed design. Chapter 9 deals with the subject of engine and airframe matching and derives a FOM for initial engine selection.

This book focusses on how conclusions can be obtained and interpreted with regard to optimum conditions by means of a quasi-analytical approach. To this end, the problem is simplified to such an extent that the objective function is differentiable so that (closed form) analytical solutions are obtained. The emphasis is initially on unconstrained optima which are easily obtained by means of classical theory of local optima. These optima are interesting because they identify the ultimate design quality achievable for a given generic task – moving a payload over a given distance. Although practical considerations associated with technological limits may degrade this 'well-tempered aircraft design' into an unfeasible solution, the penalty to be paid for the best feasible solution becomes explicit by comparing it with the unconstrained optimum. The analytical approach may also give useful information on the sensitivity of a design to small changes in the TLRs and technological parameters.

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