1

Aircraft Design Fundamentals

1.1 Introduction to Design

Aircraft design is essentially a branch of engineering design. Design is primarily an analytical process which is usually accompanied by drawing/drafting. Design contains its own body of knowledge, independent of the science-based analysis tools usually coupled with it. Design is a more advanced version of a problem-solving technique that many people use routinely. Design is exciting, challenging, satisfying, and rewarding. The general procedure for solving a mathematical problem is straightforward. Design is much more subjective, there is rarely a single "correct" answer. The world of design involves many challenges, uncertainties, ambiguities, and inconsistencies. This chapter is intended to familiarize the reader with the basic fundamentals and overall process of design. This book has been written primarily to provide the basic tools and concepts required to create an optimum/efficient aircraft design that will meet the necessary design requirements.

A very basic and simplified model of a design process is shown schematically in Figure 1.1. In general, a design process includes three major operations: analysis, synthesis, and evaluation. Analysis is the process of predicting the performance or behavior of a design candidate. Evaluation is the process of performance calculation and comparing the predicted performance of each feasible design candidate to determine the deficiencies. The noun synthesis refers to a combination of two or more entities that together form something new. In this text, synthesis is employed interchangeably with design. Hence, synthesis is defined as the creative process of putting known things together into new and more useful combinations. Synthesis is the vehicle of the design, with evaluation being its compass. The candidate designs that fail to satisfy (partially or completely) the requirements are reiterated. That is new values, features, characteristics, or parameters are determined during synthesis operation. The redesigned candidate is reanalyzed again for compliance with the design requirements. This iterative process is continued until the design requirements are met. A design process requires both integration and iteration, invoking a process that coordinates synthesis, analysis, and evaluation. These three operations must be integrated and applied iteratively and continuously throughout the lifecycle of the design.

Aircraft Design: A Systems Engineering Approach, First Edition. Mohammad H. Sadraey.

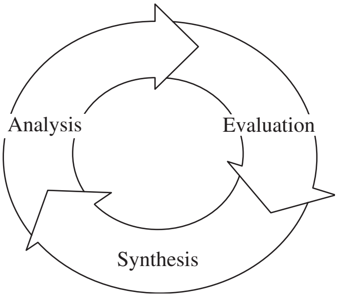

Figure 1.1 Interrelationship between synthesis, analysis, and evaluation

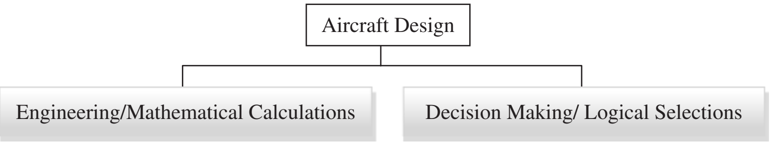

Figure 1.2 Two main groups of design activities in aircraft design

A design operation often involves two activities: (i) problem solving through mathematical calculations and (ii) choosing a preferred one among alternatives (Figure 1.2). The first activity is performed in Chapters 4–12 in designing various aircraft components. The second design activity is in general a decision-making process. The fundamentals of decision making are reviewed in Section 1.4; and employed entirely in aircraft conceptual design (Chapter 3). In addition, there are various decision-making processes in aircraft components design (e.g., wing design, tail design, and propulsion system design), as will be discussed in several chapters. The major components that comprise a conventional aircraft are wing, fuselage, horizontal tail, vertical tail, engine, landing gear, and equipment. The decision-making process plays a significant role in the configuration design of these primary components.

The traditional engineering education is structured to emphasize mathematics, physical sciences, and engineering sciences. The problem is the lack of sufficient concentration on design and creativity. Creative thinking and its attitudes are essential to design success. Producing a new design requires an ability to be creative and overcome strong barriers. To address this significant issue a new organization, CDIO,[1] was established in the late 1990s. The CDIO initiative is defined to be an innovative educational framework for producing the next generation of engineers. The framework provides students with an education stressing engineering fundamentals set within the context of conceiving/designing/implementing/operating real-world systems and products. This textbook has been written with a strong emphasis on creativity, and the freedom of the designer to go beyond current aircraft designs.

[1] www.cdio.org.

Throughout this text, various techniques for generating creative design alternatives are introduced. An effective approach in creative design as a source of new ideas is *brainstorming*. Brainstorming is a structured group-oriented technique for conceiving design alternatives. It consists of a group of individuals letting their imaginations run wild, but in accordance with central procedural rules. The ultimate goal is that the group members will inspire and support each other. The outcome is that the group will be able to conceptualize design alternatives that are more elegant than those the individuals could have achieved independently. In order to encourage members to describe their ideas, even totally impractical ones, a crucial brainstorming rule is that no criticism of individuals or ideas is permitted. The emphasis is on generating as many ideas and concepts as possible, without worrying about their validity. Rectifying, organizing, and combining the ideas suggested in a brainstorming session is performed out of the group meeting. The brainstorming technique is mainly applicable at the conceptual design phase (see Chapters 2 and 3).

In general, aircraft design requires the participation of six (Figure 1.3) fundamental disciplines: (i) flight dynamics, (ii) aerodynamics, (iii) propulsion, (iv) aero-structure, (v) management skills, and (vi) engineering design. The first four items are primary expertise areas of aeronautical engineering. This text has no particular chapters on any of these four topics; so the reader is expected to be familiar with the fundamentals, concepts, technical terms, and engineering techniques in such areas. Management is defined [1] as coordinating work activities so that they are completed efficiently and effectively with and through other people. An aircraft designer needs to be equipped with managerial skills and act as a manager throughout the design process. This topic is not covered in this text; however, a few aspects of management – such as project planning and decision making – are reviewed in this chapter (Sections 1.3 and 1.4).

Finally, engineering design [2–4] is at the heart of the design process and is assumed as the sixth discipline necessary for design of an air vehicle. Section 1.2 briefly examines various aspects of engineering design. It must be noted that aircraft engineering design has its own science, concepts, fundamentals, technical terms, and techniques. Chapters 3–12 all address various aspects of designing aircraft components as well as introducing aircraft design procedures.

This chapter will first examine the engineering design profession. Next, design project planning is addressed and tools such as Gantt charts are introduced. Then the principle of decision making, a very significant section of any design process, is presented. Feasibility study is also discussed in Section 1.5. Finally, the tort of negligence will be described to warn aircraft design engineers to take the utmost care in order to prevent liability.

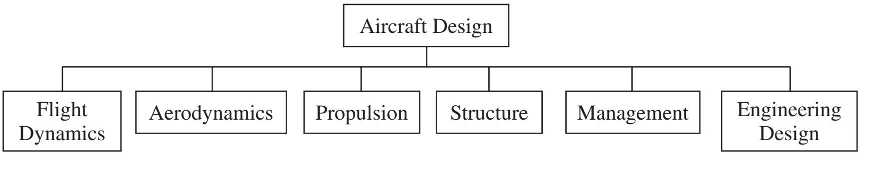

Figure 1.3 Aircraft design required tools and expertise

1.2 Engineering Design

Aircraft design is essentially a branch of engineering design. Design is the culmination of all engineering activities, embodying engineering operations and analysis as tools to achieve design objectives. Many engineering professors find it more difficult to teach design than to teach traditional engineering science-based analytical topics. Every undergraduate engineering curriculum has a design component, although the extent and structure of that component may vary widely. Engineering design fundamentals are common to all engineering disciplines – aeronautical, mechanical, electrical, civil, and computer. Engineering design is a methodical approach to dealing with a particular class of large and complex projects. Engineering design provides the design engineer with a realistic design process. Design is the central activity of the engineering profession, and it is concerned with approaches and management as well as design techniques and tools. In this section, the fundamentals of engineering design as well as the definitions of a few technical terms are presented.

There is a clear distinction between classical mathematics and science problem-solving techniques, and design operation. There is inherently a beauty embedded in the design process which is usually felt after the design output is created. The mathematics and science problems have three main features: (i) the problems are well-posed in a compact form, (ii) the solutions to each problem are unique and compact, and (iii) the problems have an identifiable closure. However, a real-world engineering design problem does not share these characteristics. In fact, engineering design problems are usually poorly posed, do not have a unique solution, and are also open-ended. The Accreditation Board of Engineering and Technology (ABET) [5] defines engineering design as follows:

> Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process (often iterative), in which the basic sciences and mathematics and engineering sciences are applied to convert resources optimally to meet a stated objectives. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation.

Just as the ABET statement is only one of many definitions of engineering design, there are several approaches to describing how design is done. This text formalizes the ABET description into a simplified step-by-step model of the design process based on a systems engineering approach [6]. A very basic block diagram of the design process is shown in Figure 1.4. It represents the road from customer need to design output, including feedback based on evaluation. The problem formulation is discussed in this section, and project

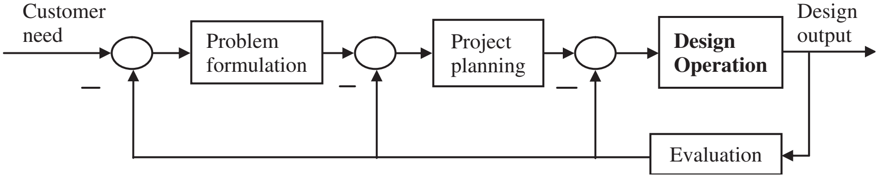

Figure 1.4 Engineering design block diagram

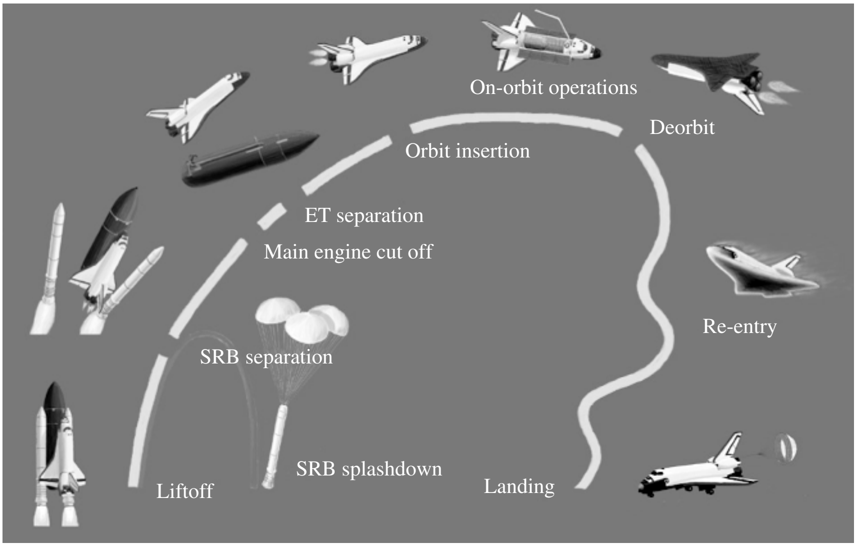

Figure 1.5 The original Space Shuttle concept and mission profile. Reproduced from permission of NASA

planning is examined in Section 1.4. A large part of this text is on design operations, including Chapters 3–12.

The evaluation not only influences the design operation, but most of the time may affect problem formulation and project planning. A clear current example is the Space Shuttle, which started in 1981 but retired in 2011. After more than 30 years of successful operations (135 space missions), the National Aeronautics and Space Administration (NASA) figured out that the current design concept is not viable. Besides economic factors, two reasons that forced NASA to re-engineer the Space Shuttle (Figure 1.5) are the disasters that happened in 1986 and 2003. On January 28, 1986 Space Shuttle Challenger broke apart, just 73 seconds into its flight, leading to the deaths of its seven crew members. On February 1, 2003, shortly before it was scheduled to conclude its 28th mission, Space Shuttle Columbia disintegrated over Texas during re-entry into the Earth's atmosphere, resulting in the death of all seven crew members. Until another US launch vehicle is ready, crews will travel to and from the International Space Station aboard Russian Soyuz spacecraft or possibly a future American commercial spacecraft.

After the need is clearly defined, the designer has to turn his/her attention to describing how he/she envisions meeting the need. This fundamental step requires achieving a delicate balance between establishing the general scope of the design efforts, and avoiding being so specific that opportunities are unnecessarily narrowed for creative design solutions. Problem formulation includes recognizing the need, identifying the customer, market assessment, defining the problem, functional analysis, and establishing design requirements. A problem statement needs to be constructed in such a way that it consists of three components: goal, objectives, and constraints (Figure 1.6).

A **goal** statement is a brief, general, and ideal response to the need statement. The need describes the current, unsatisfactory situation, while the goal describes the ideal future

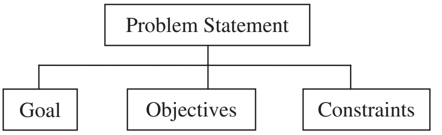

Figure 1.6 Three elements of a problem statement

condition to which we aspire in order to improve on the situation described by the need. The goal is defined by describing the current situation that is unsatisfactory. Hence the goal is to improve the current situation to a higher level. The goal is generally so ideal that it could never be accomplished. The goal is usually revised through a process called benchmarking. **Benchmarking** involves explicitly comparing your design to that of the competitor which does the best job in terms of satisfying customer requirements.

The **objectives** are quantifiable expectations of performance which identify those performance characteristics of a design that are of most interest to the customer. In addition, the objectives must include a description of conditions under which a design must perform. In the lifecycle, the objective is to specify the *whats* and not the *hows*; that is, *what* needs to be accomplished versus *how* it is to be done. When the operating conditions are specified, the designer is able to evaluate the performance of different design options under comparable conditions. Each of the objectives must be defined using words that convey the desirable aspect of performance. The term "performance specification" is often a synonym for objectives. However, the term "design specification" refers to the detailed description of the completed design, including all dimensions, material properties, weight, and fabrication instructions.

Restrictions of function or form are called **constraints**; they limit our freedom to design. Constraints define the permissible conditions of design features and the permissible range of the design and performance parameters. They are features that all design must have in order to be eligible for consideration. Most engineering design projects essentially include a variety of realistic constraints, such as economic factors, safety, reliability, aesthetics, ethics, and social impacts. For instance, the height of the new system cannot exceed 1.4 m; or its mass may not exceed 3.6 kg; or it must operate year-round during cold and hot days.

The value-free descriptors associated with each objective are referred to as **criteria**. For instance, an objective for a design is that it must be "inexpensive." The criterion associated with this objective is "cost." The criteria are quantified using the same bases for measurement and the same unit as their corresponding objectives. In other words, the criteria are more compact ways of identifying objectives. Table 1.1 demonstrates a number of typical design objectives and related criteria to design a vehicle.

Fundamentally, design products are developed and created to satisfy needs and wants and provide utility to the customer. The customer's needs have to be translated into **design requirements** through goal and objectives. Design requirements mainly include customer requirements plus engineering requirements. The customer requirements refer to objectives as articulated by the customer or client. The engineering requirements refer to the design and performance parameters that can contribute to achieving the customer requirements.

Table 1.1 Typical design objectives and related criteria for a vehicle design project

No.	Objective	Basis for measurement	Criterion	Units
1	Inexpensive in market	Unit manufacturing cost	Manufacturing cost	Dollar
2	Inexpensive in operation	Fuel consumption per kilometer	Operating cost	l/km
3	Light	Total weight	Weight	N
4	Small size	Geometry	Dimensions	m
5	Fast	Speed of operation	Performance	km/h
6	Maintainable	Man-hours to maintain	Maintainability	Man-hour
7	Producible	Required technology for manufacturing	Manufacturability	–
8	Recyclable	Amount of hazardous or non-recyclable materials	Disposability	kg
9	Maneuverable	Turn radius	Maneuverability	m
10	Comfortable	Ergonomic standards	Human factor	–
11	Airworthiness	Safety standards	Safety	–
12	No human casualty in operation	Level of injury to passengers in a mishap	Crashworthiness	–

Figure 1.7 illustrates conceptually the status of various design features during the design process. It indicates that there will be a large commitment in terms of configuration, manufacturing technology, and maintenance techniques at the early stages of a design program. In addition, it is at this point that major decisions are made and product-specific knowledge is limited. Moreover, it is estimated that about 70% of the projected lifecycle cost for a given product can be committed based on engineering design and management decisions during the early stages of design. As the design progresses, changes to the design get harder and harder. Therefore, the impact of a decision at the early stages of a design program is more profound than a decision at the later stages. Hence, it is crucial to be highly confident about any decision a designer makes at the conceptual design phase.

The cost of aircraft design is about 1% of the total lifecycle cost; however, this 1% determines the other 99%. Furthermore, the design cost is about 20% of the production (acquisition) cost. Thus, any necessary investment in design team members is worth it. Most aircraft manufacturers do not make any profit in the first couple of years of production, in the hope that in the future, they will make money. The large aircraft manufacturers get back their money after about 10 years; after that, they will make a profit. In the past, there were a few examples where aircraft manufacturers were bankrupted and only resurrected by government through long-term loans.

Wind-tunnel testing costs from 200 US$/hour for GA (General Aviation) small aircraft to 5000 US$/hour for large transport aircraft. The design and fabrication of some

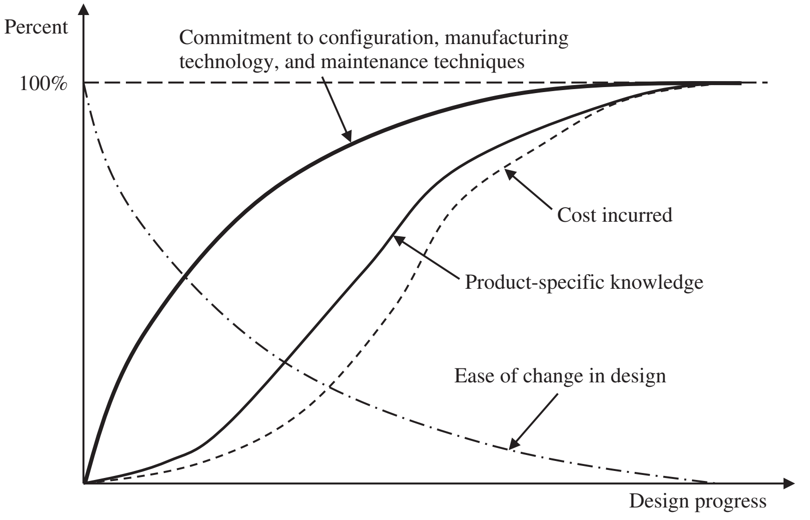

Figure 1.7 Status of various design features during the design process

aircraft – such as supersonic transport aircraft Aerospatiale-BAC Concorde (Figures 7.24 and 11.15) – was a great achievement, but when the international market does not purchase it, the production has to be stopped.

1.3 Design Project Planning

In order for a design project schedule to be effective, it is necessary to have some procedure for monitoring progress; and in a broader sense for encouraging personnel to progress. An effective general form of project management control device is the Gantt chart. It presents a project overview which is almost immediately understandable to non-systems personnel; hence it has great value as a means of informing management of project status. A Gantt chart has three main features:

1. It informs the manager and chief designer of what tasks are assigned and who has been assigned them.
2. It indicates the estimated dates on which tasks are assumed to start and end, and represents graphically the estimated ration of the task.
3. It indicates the actual dates on which tasks were started and completed and pictures this information.

Like many other planning/management tools, Gantt charts provide the manager/chief designer with an early warning if some jobs will not be completed on schedule and/or if others are ahead of schedule. Gantt charts are also helpful in that they present graphically immediate feedback regarding estimates of personnel skill and job complexity. Table 1.2 illustrates a typical Gantt chart for the design of a light single-seat aircraft in the form of a combined bar/milestone chart. Such a chart provides the chief designer with

Table 1.2 A typical Gantt chart for the design of a light single-seat aircraft

Job/task		Week/month/year					
Job	Task	January 2013	February 2013	March 2013	April 2013	May 2013	June 2013
Problem definition	Identification of design requirements						
	Feasibility analysis						
Conceptual design	Configuration design						
	Conceptual design review						
Preliminary design	Calculations						
	Preliminary design review						
Detail design	Wing design						
	Tail design						
	Fuselage design						
	Propulsion system						
	Landing gear						
	Equipment/ subsystems						
	Integration						
	Wind-tunnel testing						
	Weight distribution						
	Performance/stability analysis						
	Control surfaces design						
	Evaluation and test review						
Flight testing	Production of prototype						
	Flight tests						
Critical design review	Critical design review						
Certification	Certification						

Figure 1.8 Airbus A-380, the newest Airbus production. Reproduced from permission of Anne Deus

a scheduling method and enables him/her to rapidly track and assess the design activities on a weekly/monthly basis. An aircraft project such as Airbus A-380 (Figure 1.8) will not be successful without design project planning.

A preferred method of scheduling is through the use of program networks [2] such as the program evaluation and review technique (PERT) and the critical path method (CPM). The application of network scheduling is appropriate for both small- and large-scale design projects and is of particular value for a system development where there are several interdependencies. The definitions of new terms in Table 1.2, such as preliminary design and critical design review, and their associated techniques are addressed in Chapter 2.

1.4 Decision Making

First and foremost, it must be emphasized that any engineering selection must be supported by logical and scientific reasoning and analysis. The designer is not expected to select a configuration just because he/she likes it. There must be sufficient evidence and reasons which prove that the current selection is the best.

The main challenge in decision making is that there are usually multiple criteria along with a risk associated with each one. In this section, a few techniques and tools for aiding decision making under complex conditions are introduced. However, in most design projects there are stages where there are several acceptable design alternatives and the designer has to select only one of them. In such cases, there are no straightforward governing equations to be solved mathematically. Thus, the only way to reach the solution is to choose from a list of design options. There are frequently many circumstances in which there are multiple solutions for a design problem but one option does not clearly dominate the others in all areas of comparison.

A simple example is a transportation design problem where a designer is required to design a vehicle to transfer one person from one city to another. It is assumed that the two cities are both seaports and located at a distance of 300 km. The design solution alternatives are bicycle, motorbike, automobile, train, bus, ship, and aircraft. A traveler may select to travel using any of these vehicles. Three common criteria in most engineering design projects are: (i) cost, (ii) performance, and (iii) safety (and reliability). Table 1.3 shows a typical comparison of these design options and the ranking of each alternative.

Table 1.3 A typical multi-criteria decision-making problem (1 is the most desirable)

No.	Design option (vehicle)	Criteria		
		Cost (of operation)	Safety	Performance (maximum speed)
1	Bicycle	1	1	7
2	Motorbike	2	7	3
3	Automobile	5	6	4
4	Bus	3	5	5
5	Train	4	3	2
6	Ship	6	4	6
7	Aircraft	7	2	1

As the ranking illustrates, no one option clearly ranks first with respect to all three criteria to dominate the other six alternatives.

If the designer cares only for the cost of operation and safety, he/she has to select the bicycle, but if the only criterion was travel speed, the aircraft would be chosen as the vehicle. The bicycle is often the slowest vehicle; however it is the cheapest way to travel. In contrast, the aircraft does the best job in terms of speed (fastest to travel), but it is usually the most expensive option. It is evident that, for a typical traveler and designer, all the criteria matter. Thus, the question is how to come up with the best decision and the optimum vehicle. This example (Table 1.3) represents a typical multi-criteria decision-making problem that a design engineer frequently faces in a typical engineering design project. After the type of vehicle is selected, the calculations begin to determine geometry and other engineering characteristics.

A designer must recognize the importance of making the best decision and the adverse consequences of making a poor decision. In the majority of design cases, the best decision is the right decision, and a poor decision is the wrong one. The right decision implies design success, while a wrong decision results in a failure of the design. As the level of design problem complexity and sophistication increases in a particular situation, a more sophisticated approach is needed.

The approach for making the best decision to select/determine the best alternative is to take five steps, as follows.

- **Step 1**. Specify all the alternatives to be included in the exercise. Try to generate as many design concepts as possible using the brainstorming technique. However, given the resources required to include and consider all alternatives, you need to give considerable thought to reducing the alternatives to a manageable number.
- **Step 2**. The second step in selecting the best design is to identify and establish the criteria (e.g., Table 1.1). These criteria serve later as the guidelines for developing the options. Some design references employ the term "figures of merit" instead of criteria.

- **Step 3**. The next step is to define the metrics. The metrics are defined as a shorthand way of referring to the criteria performance measures and their units. Metrics are the tool to overcome a non-comparable complex situation (e.g., comparing apples and oranges) by establishing a common evaluation scale and mapping each criterion's metric onto this scale. A simple evaluation scale is to map each criterion as either excellent, adequate, or poor. So, each design option may be rated with respect to each criterion using this common scale. A better and more quantifiable scale is a numerical scale, as demonstrated in Table 1.4. Typical metrics for measuring performance of an aircraft are maximum speed, take-off run, rate-of-climb, range, endurance, turn radius, turn rate, and ceiling.
- **Step 4**. The fourth step is to deal with criteria that have unequal significance. A designer should not frequently treat all criteria as being equally important. The designer must try to ascertain how important each requirement (i.e., criterion) is to the customer. The simplest approach is to assign numerical weights to each criterion (or even at a metrics level) to indicate its importance relative to other criteria. These weights ideally reflect the designer's judgment of relative importance. Judgment as to whether one design alternative is superior to another may be highly dependent on the values and preferences of the evaluator. In some cases, the designer has no way other than relying on personal "feelings" and "judgments" for the basis of the numerical weights. As a starting point, you may pair up each criterion with every other criterion one at a time and judge which of the items in each pair is more important than the other. The weights may later be normalized (i.e., mathematically convert each number to a fraction of 1) in order to make them easier to compare.

  A prerequisite to identifying the weight of each criterion is prioritization. Table 3.6 demonstrates the priorities of various aircraft designers against 10 design criteria. When the number of criteria is small, this task is straightforward. For large and complex systems, a systems engineering approach must be employed (Chapter 2). A cookbook method is no substitute for experience and sound professional judgment in what is inherently a subjective process. Reference [2] describes a higher-level approach which is referred to as the analytical hierarchy process (AHP) method; it is worth considering for sophisticated systems.
- **Step 5**. Select the alternative which gains the highest numerical value. It is expected that the output of the decision-making process will yield the most desirable result.

  The designer may conduct the decision-making process by developing a software package to minimize or maximize a specific index. In case there are uncertainties in evaluating criteria, a sophisticated robust decision rule should attempt to incorporate the uncertainties into the decision-making process. One of the difficulties of dealing with uncertainties is coming up with the probabilities of the uncertain parameters and factors. This is best performed in a process referred to as "sensitivity analysis."

1.5 Feasibility Analysis

In the early stages of design and by employing brainstorming, a few promising concepts are suggested which seem consistent with the scheduling and available resources. Prior to committing resources and personnel to the detail design phase, an important design activity – feasibility analysis – must be performed. There are a number of phases through

Table 1.4 Common scale and criteria metrics and three examples

No.	Common scale		Criteria metrics		
	Preferred level	Value	Example 1: length (m)	Example 2: maximum speed (km/h)	Example 3: mass (kg)
1	Perfect	10	35	60	500
2	Excellent	9	29.1	52	550
3	Very good	8	25.7	41	620
4	Good	7	21.4	32	680
5	Satisfactory	6	18.4	27	740
6	Adequate	5	16.6	21	790
7	Tolerable	4	12.7	17	830
8	Poor	3	8.4	17	910
9	Very poor	2	6.7	14	960
10	Inadequate	1	4.3	10	1020
11	Useless	0	2.5	7	1100

which the system design and development process must invariably pass. Foremost among them is the identification of the customer-related need and, from that, the determination of what the system is to do. This is followed by a feasibility study to discover potential technical solutions, and the determination of system requirements.

It is at this early stage in the lifecycle that major decisions are made relative to adapting a specific design approach and technology application, which have a great impact on the lifecycle cost of a product. At this phase, the designer addresses the fundamental question of whether to proceed with the selected concept. It is evident that there is no benefit or future in spending any more time and resources attempting to achieve an unrealistic objective. Some revolutionary concepts initially seem attractive but when it comes to the reality, they are found to be too imaginary. Feasibility study distinguishes between a creative design concept and an imaginary idea. Feasibility evaluation determines the degree to which each concept alternative satisfies the design criteria.

In the feasibility analysis, the answers to the following two questions are sought:

1. Are the goals achievable, are the objectives realistic, or can the design requirements be met?
2. Is the current design concept feasible?

If the answer to the first question is no, the design goal and objectives, and hence the design requirements, must be changed. Then, no matter what the source of the design requirements – either direct customer order or market analysis – they must be changed (Figure 1.9). When the answer to the second question is negative, a new concept must be selected. Finding the answers to these questions is not always easy. To determine the answers other professionals beside design engineers – such as financial experts or manufacturing engineers – must often be involved in the feasibility study. The feasibility

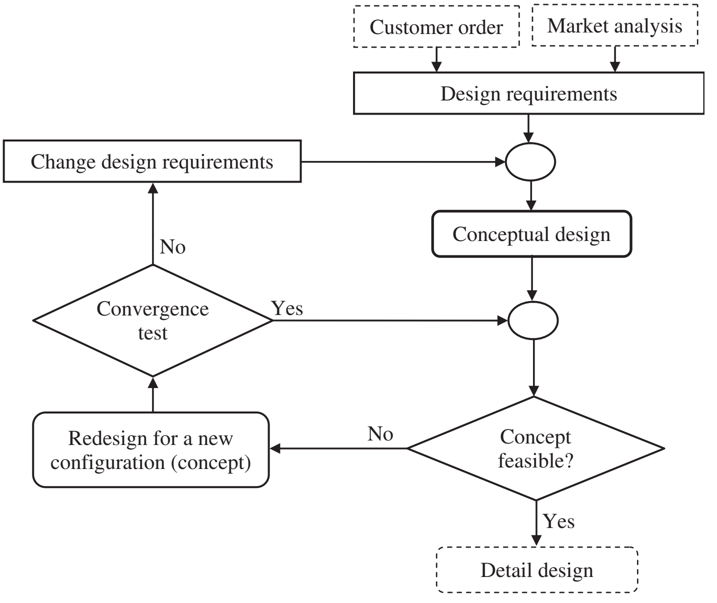

Figure 1.9 Feasibility analysis process

analysis will refine the design requirements and narrow down the initial promising design concepts to a few feasible ones. It is at this stage that uncertainties are identified.

When several concepts are analyzed and the convergency test illustrates that none of the promising concepts are feasible, the customer is informed that the objectives are not achievable within the current limits of science and technology. At this time, it is recommended that the customer reduces the level of his/her expectations. In contrast, the results of a feasibility study will significantly impact the operational characteristics of the product and its design for producibility, supportability, disposability, and detectability. The selection and application of a given technology or given materials has reliability and maintainability implications, will influence manufacturing operations, and will affect the product operating cost.

For instance, Boeing 787 Dreamliner (Figure 1.10) is the first commercial transport aircraft with full composite structure. The composite materials may have reduced the aircraft

Figure 1.10 Boeing 787 Dreamliner. Reproduced from permission of A J Best

weight, but will certainly influence the reliability, maintenance, and entire lifecycle. All these considerations should be dealt with during the feasibility study before a commitment is made to pursue extensive design activities. The systems engineering approach has a systematic view of feasibility analysis. Thus, a primary objective of systems engineering is to ensure the proper coordination and timely integration of all systems elements (and the activities associated with each) from the beginning. The systems engineering approach is introduced in Chapter 2.

1.6 Tort of Negligence

The issue of legal liability is crucial to an aircraft design engineer. Liability is basically part of the system of civil law. In civil law, the issue is not one of innocence or guilt; it is a question of who is at fault in a dispute, or who violated an agreement, or who failed to fulfill obligations. Liability law belongs to that branch of civil law known as torts. The area of tort law known as negligence involves harm caused by carelessness, not intentional harm. Negligence is a failure to exercise the care that a reasonably prudent person would exercise in like circumstances. Designers and manufacturers who sell their products to the public face many uncertainties regarding the legal ramifications of their actions. Design engineers and manufacturers are responsible and liable for harm done by their product or design to a customer or third party. Thus a designer has the responsibility to act in a careful and prudent manner. The negligence is applied to a designer when the product was defective or a design created a concealed danger.

Thousands of disasters have occurred throughout aviation history, for a great number of which the designers (not the pilots) have been responsible. Disasters include aircraft crashes, mishaps, and accidents. In all of these cases, harm (bodily or financially) has been done to a customer or to the public. The primary source of such incidents is the designer's carelessness in design, error in calculations, or lack of prediction of the future. In the area of accident prediction, Murphy's Law applies which states:

> If any event can happen, it will happen; or anything that can go wrong will go wrong.

For instance, one application of this law relates to liquid containers. The direct application of the law is as follows: every system in an aircraft which carries a liquid will **leak**. An aircraft with an air-breathing engine carries fuel and a passenger aircraft carries water. Thus, the aircraft designer must avoid installing electrical wiring and avionic systems in the belly, below the toilet or liquid container or fuel tank. Reference [7] describes a number of war stories based on actual events that happened in the design and development of aircraft programs. For instance, one story relates how the unacceptable field performance of the first F-18 fighter was traced to an error in the calculation of aerodynamic forces in the ground effect.

Another war story describes the Fowler flaps crunching in the first flight of the General Dynamics strike aircraft F-111A, when the pilot engaged the wing sweep system to sweep the wing aft after landing. The accident was clearly the designer's fault, in not expecting such an event. The solution was to employ an interlocking device to prevent a pilot from sweeping the wings with the flap down. One of the continuing functions of a design engineer is to compile development and operations "lessons learned" documents and ensure their integration into future systems development activities. Lessons learned files from previous projects are especially valuable in risk identification and characterization, and must be employed in feasibility studies.

The following three aircraft-related cases arose out of tragic accidents occurring at different times, and where the relatives of the victims brought a wrongful death case to court. In all three cases the court found the company (i.e., the designer) *negligent* and *liable*. Once a judgment has been made in favor of the plaintiff in a liability case, a monetary award is made. However, in more serious cases, punitive damages may also be awarded. In the area of astronautics, most satellite mishaps stem from engineering mistakes. To prevent the same errors from being repeated, some references have compiled lessons that the space community should heed.

- **Case 1**: United States versus "*Weber Aircraft Corp*." in 1984. When the engine of an Air Force aircraft failed in flight, the pilot was severely injured when he ejected from the plane. After Air Force collateral and safety investigations of the incident had been completed, the pilot filed a damages action against respondents as the entities responsible for the design and manufacture of the plane's ejection equipment.
- **Case 2**: Jack King and 69 European plaintiffs versus "*Cessna Aircraft Company*" in a tragic plane crash that occurred at Linate Airport in Milan, Italy, on October 8, 2001. On that foggy morning, a private Cessna jet operated by Air Evex, a German charter company, made a wrong turn and taxied toward an active runway, causing it to collide with Scandinavian Airlines Flight 686, which was just taking flight. One hundred and eighteen people died, including everyone on board both planes and four people on the ground, and others on the ground were injured.
- **Case 3**: Starting in 1991, a number of accidents and incidents involving the Boeing 737 were the result of the airplanes' unexpected rudder movement. One incident occurred on September 8, 1994 when a Boeing 737-300 of USAIR Flight 427 crashed near Pittsburgh, PA, killing 132 people. Another incident was when the Boeing 737 Flight 185 of SilkAiron plunged from 35 000 ft into a muddy river in Indonesia on December 19, 1997, killing all 104 people aboard. The Los Angeles Superior Court jury decided defects in the rudder control system caused the crash and Parker Hannifin Corp., the world's largest maker of hydraulic equipment, was told to pay US$43.6 million to the families of three people killed. On the contrary, the US National Transportation Safety Board (NTSB) concluded that there were no mechanical defects and the pilot intentionally caused the crash. The Federal Aviation Administration (FAA) ultimately ordered an upgrade of all Boeing 737 rudder control systems by November 12, 2002.
- **Case 4**: A Continental Airlines Boeing 737 went off the runway during takeoff from Denver International Airport in Colorado, plunging into a ravine and shearing off its landing gear and left engine. At least 58 people were injured in the crash that happened on December 20, 2008. The entire right side of the plane was burned, and melted plastic from overhead compartments dripped onto the seats. Note that the plane's left engine was ripped away along with all the landing gear. NTSB published that the probable cause of this accident was the captain's error (cessation of right rudder input).

Figure 1.11(a) shows a Tupolev Tu-154 which crashed while attempting to land in poor weather conditions on September 14, 1991 in Mexico City. Luckily all 112 occupants survived. Figure 1.11(b) illustrates the transport aircraft Ilyushin Il-76 freighter,

(a) (b)

Figure 1.11 Two aircraft in tragic accidents: (a) Tupolev Tu-154 crashed due to poor weather conditions; (b) An Ilyushin Il-76 freighter which caught fire on the ground. Reproduced from permission of (a) Augusto G. Gomez; (b) Serghei Podlesnii Part (a) reproduced from permission of Augusto G. Gomez

which caught fire on the ground while it was being loaded in preparation for a flight to Brazzaville, Congo on May 10, 2007.

The threat of liability law suits must spur on designers and manufacturers to be more sensitive to safety issues and to address them in more creative and innovative ways. The liability threat should not have a stifling effect on creative design and technological innovation. For this reason, the employment of safety factors is highly recommended. Federal Aviation Regulations have addressed this issue in many ways, but it does not suffice; aircraft designers and all involved engineers must be prudent and careful in the design process. A prudent design strategy is to employ the utmost care; to anticipate relevant wrongful events; and to incorporate some features into products to make them more robust.

There is a famous 10^9 rule in aircraft design which is acceptable within society. This rule states that one death in 1 000 000 000 aircraft travelers is accepted. Even one human death is a great disaster to a community, but stupidity and negligence can sometimes lead to a deadly crash. In terms of statistics, about 300 people are killed every year in aviation-related accidents in the USA while about 45 000 are killed in car accidents. Therefore, the aircraft is much safer than the car, and air travel is 150 times safer than road travel. About one-third of aviation accidents are because of CFIT (controlled flight into terrain). When a pilot makes a mistake and hits a mountain, a designer has almost no influence on this incident. Not every pilot mistake has a solution by the aircraft designer; some mistakes may be avoided by design, but not all. Reference [7] describes several stories about pilot mistakes as well as designer mistakes. All stories are beneficial to aircraft designers and have lessens to be learned.

References

[1] Robbins, S.P. and Coulter, M. (2008) *Management*, 10th edn, Pearson Prentice Hall.
[2] Dieter, G. and Schmidt, L. (2008) *Engineering Design*, 4th edn, McGraw-Hill.
[3] Hyman, B. (2003) *Fundamentals of Engineering Design*, 2nd edn, Prentice Hall.
[4] Eggert, R.J. (2005) *Engineering Design*, Pearson Prentice Hall.
[5] ABET Constitution, Accreditation Board for Engineering and Technology (2012), www.abet.org.
[6] Blanchard, B.S. and Fabrycky, W.J. (2006) *Systems Engineering and Analysis*, 4th edn, Prentice Hall.
[7] Roskam, J. (2006) *Roskam's Airplanes War Stories*, DAR Corporation.