1 Introduction

1.1 Overview

This book begins with a brief historical introduction in which our aeronautical legacy is surveyed. The historical background illustrates the human quest to conquer the sky and is manifested in a system shaping society as it stands today: in commerce, travel, and defense. Its academic outcome is to prepare the next generation for the advancement of this cause.

Some of the discussion in this chapter is based on personal experience and is shared by many of my colleagues in several countries; I do not contest any differences of opinion. Aerospace is not only multidisciplinary but also multidimensional – it may look different from varying points of view. Only this chapter is written in the first person to retain personal comments as well as for easy reading.

Current trends indicate maturing technology of the classical aeronautical sciences with diminishing returns on investment, making the industry cost-conscious. To sustain the industry, newer avenues are being searched through better manufacturing philosophies. Future trends indicate "globalization," with multinational efforts to advance technology to be better, faster, and less expensive beyond existing limits.

1.1.1 What Is to Be Learned?

This chapter covers the following topics:

Section 1.2: A brief historical background
Section 1.3: Current design trends for civil and military aircraft
Section 1.4: Future design trends for civil and military aircraft
Section 1.5: The classroom learning process
Section 1.6: Units and dimensions
Section 1.7: The importance of cost for aircraft designers

1.1.2 Coursework Content

There is no classroom work in this chapter, but I recommend reading it to motivate readers to learn about our inheritance. Classwork begins in Chapter 6 (except for the mock market survey in Chapter 2).

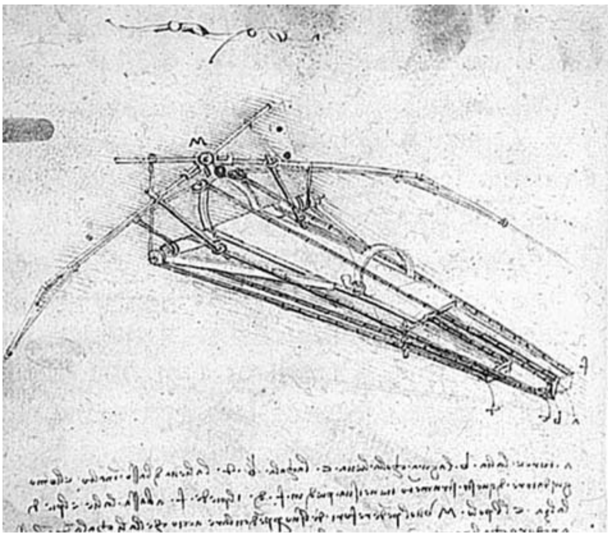


Figure 1.1. Da Vinci's flying machine

1.2 Brief Historical Background

This section provides a compressed tour of history, which I hope will motivate individuals to explore human aerial achievements in more detail. Many books cover the broad sweep of aeronautical history and many others depict particular cases such as famous people and their achievements in aeronautics ([1] is a good place to start). Innumerable Web sites on these topics exist; simply enter keywords such as *Airbus*, *Boeing*, or anything that piques your curiosity.

The desire to become airborne is ancient and it is reflected in our imagination and dreams. In the West, Daedalus and Icarus of Greek mythology were the first aviators; in the East, there are even more ancient myths – with no crashes. In Indian mythology, Pakshiraj is a white stallion with wings; the Greeks had a flying horse called Pegasus; and the Swedes also have flying horses. Garuda of Indonesia – half man and half bird – is another example from the Ramayana epic. Middle Eastern and South Asiatic "flying carpets" are seen in many Western cartoons and films. These contraptions are fully aerobatic with the ability to follow terrain; there are no seat belts and they can land inside rooms as well as on rooftops. Recreational possibilities and military applications abound!

Unfortunately, history is somewhat more "down to earth" than mythology, with early pioneers leaping from towers and cliffs, only to leave the Earth in a different but predictable manner because they underestimated the laws of nature. Our dreams and imagination became reality only about 100 years ago on December 17, 1903, with the first heavier-than-air flight by the Wright brothers. Yet, man first landed on the Moon about three decades ago, less than 70 years after the first powered flight.

The first scientific attempts to design a mechanism for aerial navigation were by Leonardo da Vinci (1452–1519) – he was the true grandfather of modern aviation, even if none of his machines ever defied gravity (Figure 1.1). He sketched many contraptions in his attempt to make a mechanical bird. However, birds possess such refined design features that the human path into the skies could not take that route; da Vinci's ideas contradicted the laws of nature.

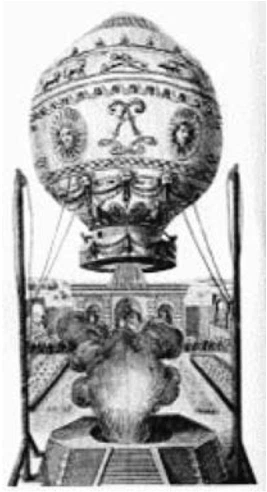


Figure 1.2. Montgolfier balloon

After da Vinci, and after an apparent lull for more than a century, the next prominent name is that of Sir Isaac Newton (1642–1727). Perhaps we lack the documentary evidence for I am convinced that human fascination with and endeavor for flight did not abate. Newton developed a theory of lift that although erroneous for low-speed flows, actually has some hypersonic application (although, of course, this was beyond his seventeenth-century understanding of fluid mechanics). Flight is essentially a practical matter, so real progress paralleled other industrial developments (e.g., isolating gas for buoyancy).

In 1783, de Rozier and d'Arlandes were the first to effectively defy gravity, using a Montgolfier (France) balloon (Figure 1.2). For the first time, it was possible to sustain and somewhat control altitude above the ground at will. However, these pioneers were subject to the prevailing wind direction and therefore were limited in their navigational options. To become airborne was an important landmark in human endeavor. The fact that the balloonists did not have wings does not diminish the importance of their achievement. The Montgolfier brothers (Joseph and Etienne) should be considered among the fathers of aviation. In 1784, Blanchard (France) added a hand-powered propeller to a balloon and was the first to make an aerial crossing of the English Channel on July 15, 1765. Jules Verne's fictional trip around the world in eighty days in a balloon became a reality when Steve Fossett circumnavigated the globe in fewer than fifteen days in 2002 – approximately three centuries after the first balloon circumnavigation.

In 1855, Joseph Pline was the first to use the word *aeroplane* in a paper he wrote proposing a gas-filled dirigible glider with a propeller.

Tethered kites flew in the Far East for a long time – in China, 600 B.C. However, in 1804, Englishman Sir George Cayley constructed and flew a kite-like glider (Figure 1.3) with movable control surfaces – the first record of a successful heavier-than-air controllable machine to stay freely airborne. In 1842, English engineer Samuel Henson secured a patent on an aircraft design that was driven by a steam engine.

With his brother Gustav, Otto Lilienthal was successfully flying gliders (Figure 1.4) in Berlin more than a decade (ca. 1890) before the Wright brothers' first

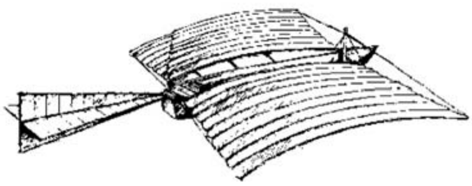


Figure 1.3. Cayley's kite glider

experiments. His flights were controlled but not sustained. The overestimation of the power requirement for sustained flight (based on work by Sir Isaac Newton, among others) may have discouraged the attempts of the best enginemakers of the time in Germany to build an aircraft engine – it would have been too heavy. Sadly, Lilienthal's aerial developments ended abruptly and his experience was lost when he died in a flying accident in 1896.

The question of who was the first to succeed naturally attracts a partisan spirit. The Wright Brothers (United States) are recognized as the first to achieve sustained, controlled flight of a heavier-than-air manned flying machine. Before discussing their achievement, however, some "also-rans" deserve mention (see various related Web sites). It is unfair not to credit John Stringfellow with the first powered flight of an unmanned heavier-than-air machine, made in 1848 in England. The Frenchman Ader also made a successful flight in his "Eole." Gustav Weisskopf (Whitehead), a Bavarian who immigrated to the United States, claimed to have made a sustained, powered flight [2] on August 14, 1901, in Bridgeport, Connecticut. Karl Jatho of Germany made a 200-ft hop (longer than the Wright Brothers first flight) with a powered (10-HP Buchet engine) flight on August 18, 1903. At what distance a "hop" becomes a "flight" could be debated. Perhaps most significant are the efforts of Samuel P. Langley, who made three attempts to get his designs airborne with a pilot at the controls (Figure 1.5). His designs were aerodynamically superior to the Wright flyer, but the strategy to ensure pilot safety resulted in structural failure while catapulting from a ramp toward water. (A replica of Langley's aircraft was successfully flown from a conventional takeoff.) His model aircraft were flying successfully since 1902. The breaking of the aircraft also broke Professor Langley – a short time afterward, he died of a heart attack. The Wright Brothers were mere bicycle mechanics without any external funding, whereas Professor Langley was a highly qualified scientist whose project had substantial government funding.

The discussion inevitably turns to the Wright Brothers. Their aircraft (Figure 1.6) was inherently unstable but – good bicycle manufacturers that they were – they understood that stability could be sacrificed if sufficient control authority was maintained. They employed a foreplane for pitch control, which also served as a stall-prevention device – as today's Rutan-designed aircraft have demonstrated.

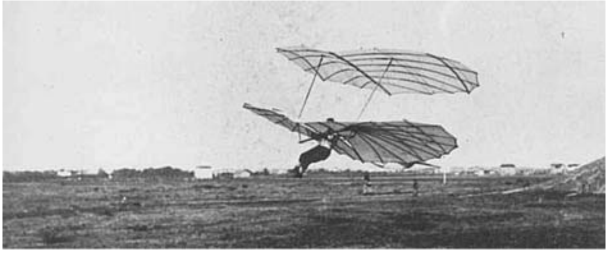
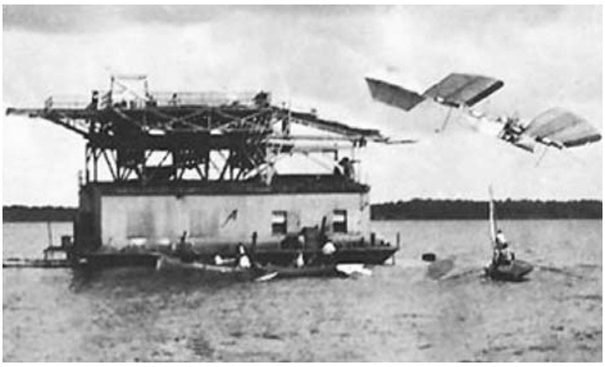


Figure 1.4. One of Lilienthal's gliders

Figure 1.5. Langley's catapult launch

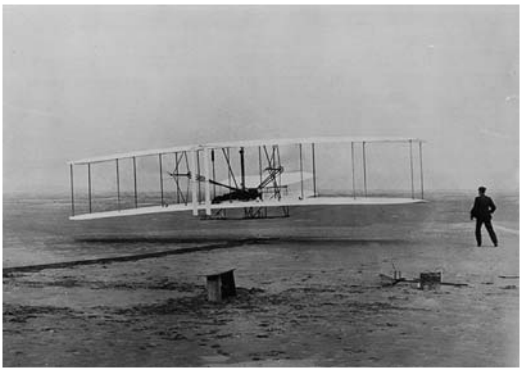


Exactly a century later, a flying replica model of the Wright flyer failed to lift off on its first flight. The success of the Wright Brothers was attributed to a freak gust of wind to assist the liftoff. A full-scale nonflying replica of the Wright flyer is on display at the Smithsonian Museum in Washington, DC, and the exhibit and others are well worth a trip.

Strangely, the Wright Brothers did not exploit their invention; however, having been shown that sustained and controlled flight was possible, a new generation of aerial entrepreneurs quickly arose. Newer inventions followed in succession by pioneering names such as Santos Dumas, Bleriot, and Curtis, and the list grew rapidly. Each inventor presented a new contraption, some of which demonstrated genuine design improvements. Fame, adventure, and "*Gefühl*" (feelings) were the drivers; the first few years barely demonstrated any financial gain except through "joy rides" and air shows – spectacles never seen before then and still just as appealing to the public now. It is interesting to observe the involvement of brothers from the eighteenth to the twentieth century – the Montgolfiers, du Temples, Lilienthas, and Wrights – perhaps they saw the future potential and wanted to keep progress confidential, and who can be better trusted than a brother?

It did not take long to demonstrate the advantages of aircraft, such as in mail delivery and military applications. At approximately 100 miles per hour (mph), on average, aircraft were traveling three times faster than any surface vehicle – and in straight lines. Mail was delivered in less than half the time. The potential for military applications was dramatic and well demonstrated during World War I. About a decade after the first flight in 1903, aircraft manufacturing had become a lucrative business. I am privileged to have started my own aeronautical engineering career

Figure 1.6. The Wright flyer



with Short Brothers and Harland (now part of the Bombardier Aerospace group), a company that started aircraft manufacturing by contracting to fabricate the Wright designs. The company is now the oldest surviving aircraft manufacturer still in operation. In 2008, it celebrated its centenary, the first aircraft company ever to do so.

The post–World War I aircraft industry geared up in defense applications and in civil aviation, with financial gain as the clear driver. The free-market economy of the West contributed much to aviation progress; its downside, possibly reflecting greed, was under-regulation. The proliferation showed signs of compromise with safety issues, and national regulatory agencies quickly stepped in, legislating for mandatory compliance with airworthiness requirements. Today, every nation has its own regulatory agency. The FAA in the United States and the Joint Aviation Authority (JAA) in Europe (recently renamed EASA) are the most recognized.

Early aircraft design was centered on available engines, and the size of the aircraft depended on the use of multiple engines. The predominant material used was wood. The combination of engines, materials, and aerodynamic technology enabled aircraft speeds of approximately 200 mph; altitude was limited by human physiology. Junker demonstrated the structural benefit of thick wing sections and metal construction. In the 1930s, Durener Metallwerke of Germany introduced *duralumin*, with higher strength-to-weight ratios of isotropic material properties, and dramatic increases in speed and altitude resulted. The introduction of metal brought a new dimension to manufacturing technology. Structure, aerodynamics, and engine development paved the way for substantial gains in speed, altitude, and maneuvering capabilities. These improvements were seen preeminently in World War II designs such as the Supermarine Spitfire, the North American P-51, the Focke Wolfe 190, and the Mitsubishi Jeero-Sen. Multiengine aircraft also grew to sizes never before seen.

The invention of the jet engine (independently by Whittle of the United Kingdom and von Ohain of Germany) realized the potential for unheard-of leaps in speed and altitude, resulting in parallel improvements in aerodynamics, materials, structures, and systems engineering. A better understanding of supersonic flow and a suitable rocket engine made it possible for Chuck Yeager to break the sound barrier in a Bell X1 in 1949. (The record-making aircraft is on exhibit at the Smithsonian Air and Space Museum in Washington, DC.)

Less glamorous multiengine heavy-lifters were slower in progress but with no less success. Tens of thousands of the Douglas C-47 Dakota and Boeing B17 Flying Fortress were produced. Postwar, the De Havilland Comet was the first commercial jet aircraft in service; however, plagued by several tragic crashes, it failed to become the financial success it promised. (The first Comet crash occurred at Dum Dum, near Calcutta, in 1952, in a monsoon storm. At that time, I lived about 12 miles from the crash site.)

The 1960s and 1970s saw rapid progress with many new commercial and military aircraft designs boasting ever-increasing speed, altitude, and payload capabilities. Scientists made considerable gains in understanding the relevant branches of nature: in aerodynamic [3] issues concerning high lift and transonic drag; in materials and metallurgy, improving the structural integrity; and in significant discoveries in solid-state physics. Engineers made good use of the new understanding. Some of the outstanding designs of those decades emerged from the Lockheed

Company, including the F104 Starfighter, the U2 high-altitude reconnaissance aircraft, and the SR71 Blackbird. These three aircraft, each holding a world record of some type, were designed in Lockheed's Skunk Works, located at the Los Angeles airport, under the supervision of Clarence (Kelly) Johnson, who graduated from the University of Michigan (my alma mater). I recommend that readers study the design of the nearly 40-year-old SR71, which still holds the speed–altitude record for aircraft powered by air-breathing engines.

During the late 1960s, the modular approach to gas turbine technology gave aircraft designers the opportunity to match aircraft requirements (i.e., mission specifications and economic considerations) with "rubberized" engines. This was an important departure from the 1920s and 1930s, when aircraft sizing was based around multiples of fixed-size engines. The core high-pressure gas turbine module could now be integrated with an appropriate low-pressure compressor, and turbine modules could offer designs with more than 50% thrust variation from the largest to the smallest in a family of derivatives. This advancement resulted in the development of families of aircraft design. Plugging the fuselage and, if necessary, allowing wing growth covered a wider market area at a lower development cost because considerable component commonality could be retained in a family: a cost-reduction design strategy – that is, "design one and get the other at half price."

Rocket-powered aircraft first appeared during World War II. The advent and success of the Rutan-designed Space Ship One in 2004 (see Figure 1.14) to the fringes of the atmosphere will certainly bring about the large market potential of rocket-powered airplanes. Rocketry first entered the Western European experience when Tippu Sultan used rockets against the British-led Indian army at the Battle of Srirangapatnum in 1792. The propellants were based on a Chinese formula nearly a thousand years old. Many people are unaware that the experience of Tippu's rockets led the British to develop missiles at the Royal Laboratory of Woolwich Arsenal, under the supervision of Sir William Congrave, in the late eighteenth century. Von Braun [4] mentions that he took the idea from Tippu's success for his V2 rocket, paving the way for today's achievement in space flight as an expanded envelope beyond winged flight vehicles.

There was a time when designers could make sketches to generate candidate configurations, sometimes stretching to exotic "star-wars" shapes; gradually, however, creating ideas with a pencil has diminished. Capitalistic objectives render designers quite conservative, forcing them to devote considerably more time to analysis. The next section discusses why commercial aircraft designs are similar, with the exception of a few one-off, special-purpose vehicles. Military designs emerge from more extensive analysis – for example, the strange-looking Northrop F117 is configured using stealth features to minimize radar signature. Now, more matured stealth designs look conventional; however, some aircraft are still exotic (e.g., the Lockheed F22).

1.3 Current Aircraft Design Status

This section discusses the current status of forces and drivers that control design activities. It is followed by a review of civil and military aircraft design status. Readers are advised to search various Web sites on this topic.

1.3.1 Forces and Drivers

The current aircraft design strategy is linked to industrial growth, which in turn depends on national infrastructure, governmental policies, workforce capabilities, and natural resources; these are generally related to global economic–political circumstances. More than any other industry, the aerospace sector is linked to global trends. A survey of any newspaper provides examples of how civil aviation is affected by recession, fuel price increases, spread of infectious diseases, and international terrorism. In addition to its importance for national security, the military aircraft sector is a key element in several of the world's largest economies. Indeed, aerospace activities must consider the national infrastructure as an entire system. A skilled labor force is an insufficient condition for success if there is no harmonization of activity with national policies; the elements of the system must progress in tandem. Because large companies affect regional health, they must share socioeconomic responsibility for the region in which they are located. In the next two subsections, civil and military aircraft design status are discussed separately.

The current status stems from the 1980s when returns on investment in classical aeronautical technologies such as aerodynamics, propulsion, and structures began to diminish. Around this time, however, advances in microprocessors enabled the miniaturization of control systems and the development of microprocessor-based automatic controls (e.g., FBW), which also had an additional weight-saving benefit. Dramatic but less ostensive radical changes in aircraft management began to be embedded in design. At the same time, global political issues raised new concerns as economic inflation drove man-hour rates to a point at which cost-cutting measures became paramount. In the last three decades of the twentieth century, man-hour rates in the West rose four to six times (depending on the country), resulting in aircraft price hikes (e.g., typically by about six times for the Boeing 737) – accompanied, of course, by improvements in design and operational capabilities. Lack of economic viability resulted in the collapse or merger/takeover of many well-known aircraft manufacturers. The number of aircraft companies in Europe and North America shrunk by nearly three quarters; currently, only two aircraft companies (i.e., Boeing and Airbus in the West) are producing large commercial transport aircraft. Bombardier Aerospace has risen rapidly to the third largest in the West and recently entered the large-aircraft market with an aircraft capacity of more than 100 passengers. Embraer of Brazil has also entered in the market.

Over time, aircraft operating-cost terminologies have evolved and currently, the following are used in this book (Section 16.5 gives details).

IOC – Indirect Operating Cost: Consists of costs not directly involved with the sortie (trip)
COC – Cash Operating Cost: Consists of the trip (sortie) cost elements
FOC – Fixed Operating Cost: Consists of cost elements even when not flying
DOC – Direct Operating Cost: = COC + FOC
TOC – Total Operating Cost: = IOC + DOC

Because there are variances in definitions, this book uses these standardized definitions.

With rising fuel prices, air travelers have become cost-sensitive. In commercial aircraft operations, the DOC depends more on the acquisition cost (i.e., unit price) than on the fuel cost (2000 prices) consumed for the mission profile. Today, for the majority of mission profiles, fuel consumption constitutes between 15% and 25% of the DOC, whereas the aircraft unit price contributes between three and four times as much, depending on the payload range [5]. For this reason, manufacturing considerations that can lower the cost of aircraft production should receive as much attention as the aerodynamic saving of drag counts. The situation would change if the cost of fuel exceeds the current airfare sustainability limit (see Section 1.7 and Chapter 16). The price of fuel in 2008 was approaching the limit when drag-reduction efforts were regaining ground.

A major concern that emerged in the commercial aircraft industry from the market trend and forecast analysis of the early 1990s was the effect of inflation on aircraft manufacturing costs. Airline operators conveyed to aircraft manufacturers that unless the acquisition cost was lowered by a substantial margin, growth in air-traffic volume would prove difficult. In addition to this stringent demand, there was fierce competition among aircraft manufacturers and their subcontractors. Since the mid-1990s, all major manufacturers have implemented cost-cutting measures, as have the subcontracting industries. It became clear that a customer-driven design strategy is the best approach for survival in a fiercely competitive marketplace. The paradigm of "better, farther, and cheaper to market" replaced, in a way, the old mantra of "higher, faster, and farther" [6]. Manufacturing considerations came to the forefront of design at the conceptual stage and new methodologies were developed, such as DFM/A and Six Sigma.

The importance of environmental issues emerged, forcing regulatory authorities to impose limits on noise and engine emission levels. Recent terrorist activities are forcing the industry and operators to consider preventive design features.

The conceptual phase of aircraft design is now conducted using a multidisciplinary approach (i.e., concurrent engineering), which must include manufacturing engineering and an appreciation for the cost implications of early decisions; the "buzzword" is integrated product and process development (IPPD). Chapter 2 describes typical project phases as they are practiced currently. A chief designer's role has changed from *telling* to *listening*; he or she synthesizes information and takes full command if and when differences of opinion arise. Margins of error have shrunk to the so-called zero tolerance so that tasks are done right the first time; the Six Sigma approach is one management tool used to achieve this end.

1.3.2 Current Civil Aircraft Design Trends

Current commercial transport aircraft in the 100- to 300-passenger classes all have a single slender fuselage, backward-swept low-mounted wings, two underslung wing-mounted engines, and a conventional *empennage* (i.e., a horizontal tail and a vertical tail); this conservative approach is revealed in the similarity of configuration. The similarity in larger aircraft is the two additional engines; there have been three-engine designs but they were rendered redundant by variant engine sizes that cover the in-between sizes and extended twin operations (ETOPS).

Figure 1.7. Boeing Sonic Cruiser

Boeing tried to break the pattern with a "Sonic Cruiser" (Figure 1.7) that proved, at best, to be a premature concept. Boeing returned with the Boeing 787 Dreamliner (Figure 1.8) as a replacement for its successful Boeing 767 and 777 series, aiming at competitive economic performance; however, the configuration remains conventional.

The last three decades witnessed a 5 to 6% average annual growth in air travel, exceeding 2×10^9 revenue passenger miles (rpms) per year. Publications by the International Civil Aviation Organization (ICAO), National Business Aviation Association (NBAA), and other journals provide overviews of civil aviation economics and management. The potential market for commercial aircraft sales is on the order of billions of dollars per year. However, the demand for air travel is cyclical and – given that it takes about 4 years from the introduction of a new aircraft design to market – operators must be cautious in their approach to new acquisitions: They do not want new aircraft to join their fleet during a downturn in the air-travel market. Needless to say, market analysis is important in planning new purchases. Chapter 2 briefly addresses market studies.

Deregulation of airfares has made airlines compete more fiercely in their quest for survival. The growth of budget airlines compared to the decline of established airlines is another challenge for operators. However, the reputation of an aircraft manufacturer significantly influences aircraft sales. When Boeing introduced its 737 twinjet aircraft (derived from the three-engine B727, the best seller at the time), the dominant-selling two-engine commercial transport aircraft were the Douglas DC-9 and BAe 111. I was employed at Boeing then and remember the efforts by engineers to improve the aircraft. The Boeing 737 series, spanning nearly four decades of production to this day, has become the best seller in the history of the commercial-aircraft market. Of course, in that time, considerable technological advancements

Figure 1.8. Boeing 787 Dreamliner