STEM KIT

Teachers' Notebook

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2019
Integrant part of Learn&Fly Project - *Learning materials and support tools to foster engagement of students in science subjects and aeronautics-related careers*

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INTRODUCTION

The Learn&Fly Project proposes to develop the interest and basic skills of young students in science, technology, engineering and mathematics (STEM) related subjects by engaging them in aeronautic themes.

Flight is a fascinating theme for most people. It especially passions youngsters, possibly because of the freedom and mystery it conveys, associated to the charm and social appraisal of many aeronautic-related professions. On the other hand, powered flight represents an amazing technological achievement, requiring huge technical and technological capability, and the crossing of knowledge in many STEM disciplines, including math, computer science, physics, materials science, electronics, automation, control, fluids mechanics, among many others. Learn&Fly proposes to intersect those features as a way to encourage and empower students to pursue the studying of STEM disciplines. By showing their importance and application in aeronautics, the Project aims both to demystify and to crack STEM subjects to the involved youngsters.

The followed approach is based on the final goal of building an aircraft with simple materials, to be tested in a flight competition, called Learn&Fly Challenge. This is a practical and engaging process, and the fact that it is student-centered and problem-based learning is expected to increase students motivation, while fostering critical thinking and team spirit. Learn&Fly comprises the Students Kit, the Teachers Kit, and the Careers Kit.

The Learn&Fly Project development was envisioned in the frame of Aeronautics Clubs, where students are required to study fundaments of materials science and processing, flight physics and mechanics, and aircraft design was a way to advance in the construction of their envisioned glider. Lectures on those subjects are divided in seven modulus, each based on a set of slides, which accompany the glider construction process and the needs it arises, both theoretical and practical. These slides, some materials to start glider construction, and the competition regulation constitute the Students Kit.

The Teachers Kit comprises this Notebook in addition to the slides, in order to assist the teacher in subjects that are not part of his/hers academic background. Apart from the introduction, the Notebook is organized in eight main chapters: the first seven correspond to the seven modulus composing the slides. In each of those chapters some detail is given on the corresponding subject, so that the teacher can quickly and easily prepare to class. The eighth chapter enlightens and assists the use of the e-learning platform Moodle in the frame of the Project. This includes making contents available to the students, accessing students projects, exchanging data between partners, establishing and participating in forum and chats, proposing and correcting verification tests for students knowledge evaluation and levelling. This document is thus a simple guide to assist teachers in the task of implementing Learn&Fly in class (Figure 1).

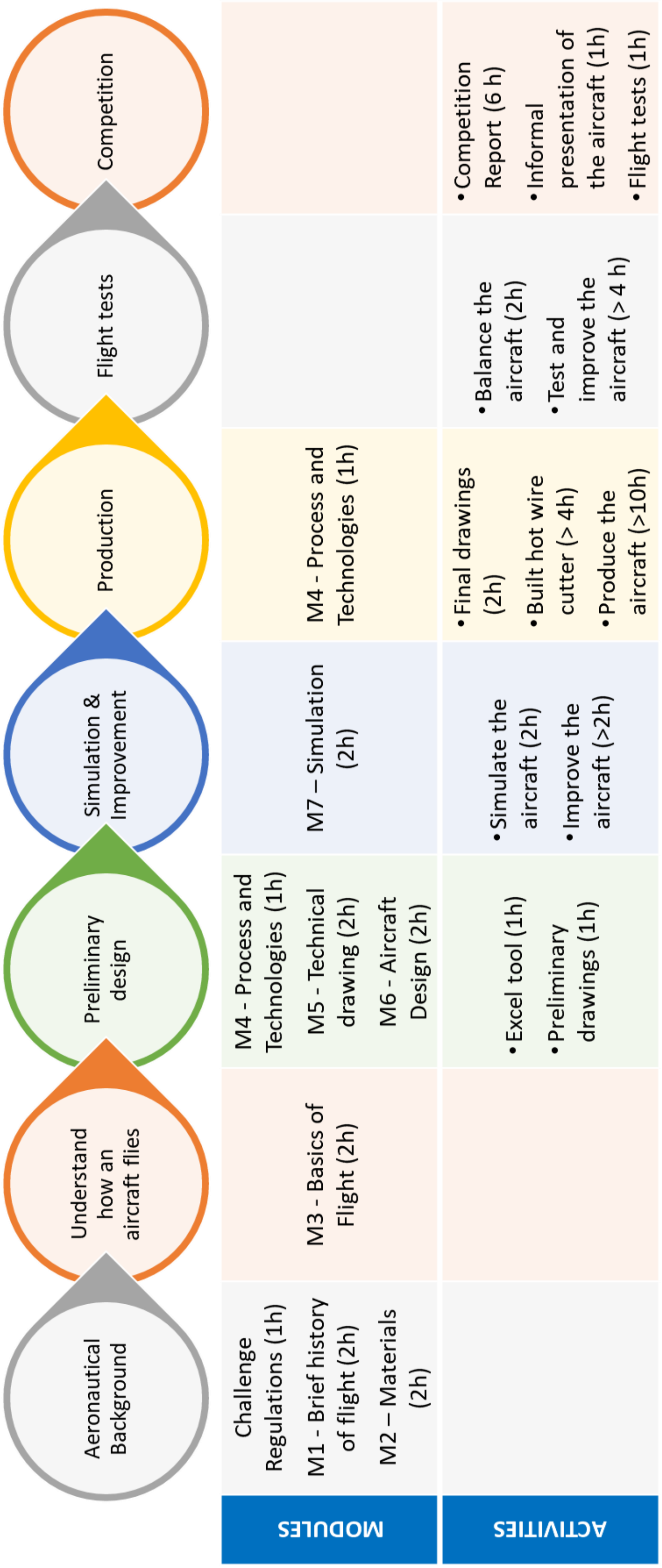
The Careers Kit is a dynamic database that comprehensively lists the numerous jobs and career opportunities in aeronautic industry (jobs in design, manufacturing, maintenance), air transport and flight operations (jobs in maintenance, ground handling services, flight operations, and navigation). It provides a list of career opportunities related to aeronautics (with task description and working conditions), employment statistics, and testimonials of professionals. This kit is expected to toil as a career-counselling support tool for both students and their dependable adults (parents, teachers, other education support staff).

The Learn&Fly challenge is oriented to involve students in the development and building of an aircraft, following procedures and tasks similar to actual aeronautical project, Figure 1. According to the Learn&Fly Challenge Regulations, this competition can be divided in two editions, national and international. Depending on the involvement of the school, different

approaches can be taken for the national and international editions. For example a school can transform the national edition in a challenge between different teams from the same school. The winners of different schools can compete, following the rules of the international challenge.
In national challenge, students must develop a model glider, following some requirements, with a limit budget of 50€. A list of simple materials is provided, easy to purchase in regular stores. These materials, together with the information provided in the slides, allows students to easily develop a glider that flies. This requires that the school provides a place for students to work with some basic tools, such as manual saws, pliers, tape measure, and drill. Even if the school does not have these tools available, most of the students probably have them at home. In addition to the development of the glider, students must write a report following a provided template, supplying some technical information about the aircraft developed. At the end, students must present the developed glider and launch it. The team that score higher, according to the rules in the Regulation, is the winner. If students correctly answer quizzes proposed in the Moodle platform, which are directly related with the slides provided in the Students Kit, they may win extra launches in the final competition.

The participants in the international challenge, are the winners of the national challenges. Those teams must improve their aircrafts and add a propeller powered by a rubber band, with a limit budget of an extra 50 €. A new report must be written, in English, to include these improvements.

Both challenges should to end with a an award ceremony involving. In this event students present their aircraft to the jury, carry out the aircraft launch competition, and receive the corresponding awards. It is also an opportunity for the presentation of the careers kit, thus involving students, parents, school teachers, universities, companies and government authorities.



	Aeronautical Background	Understand how an aircraft flies	Preliminary design	Simulation & Improvement	Production	Flight tests	Competition
MODULES	Challenge Regulations (1h) M1 - Brief history of flight (2h) M2 – Materials (2h)	M3 - Basics of Flight (2h)	M4 - Process and Technologies (1h) M5 - Technical drawing (2h) M6 - Aircraft Design (2h)	M7 – Simulation (2h)	M4 - Process and Technologies (1h)		
ACTIVITIES			• Excel tool (1h) • Preliminary drawings (1h)	• Simulate the aircraft (2h) • Improve the aircraft (>2h)	• Final drawings (2h) • Built hot wire cutter (> 4h) • Produce the aircraft (>10h)	• Balance the aircraft (2h) • Test and improve the aircraft (> 4 h)	• Competition Report (6 h) • Informal presentation of the aircraft (1h) • Flight tests (1h)

Figure 1 - Schematics of Learn&Fly development throughout the challenge.

1 A BRIEF HISTORY OF FLIGHT

The term "aviation" was coined in 1863 by pioneer Guillaume de La Landelle, from the Latin "avis" (bird).

The term "aeroplane" was first used in 1871-1872 by Francis Herbert Wenham to describe the stiff wings of a beetle, associating high aspect ratio wings to a better lift-to-drag ratio than short stubby wings with the same lifting area.

The term "aerospace" was first coined in 1959 by Thomas D. White, the US Air Force Chief of Staff, aiming to describe air and space as "an operational indivisible medium consisting of the total expanse beyond the earth's surface".

1.1 INTRODUCTION

Invented in the 20th century, the airplane embodies the idea of modernity and changed the world forever, carrying society into the future and affecting human life in many and different ways [1]. Flight brought people together and encouraged the homogenisation of diverse cultures. It allowed families spread across the world to maintain personal contact [1]. It opened the distant corners of the globe to commerce, transformed common people into globe-trotter air travellers, created new industries providing to the needs of business travellers and tourists, and opened vast areas of the planet for study, settlement and economical exploitation [1]. On the other hand, it also made possible for viruses to spread with frightening velocity, and redefined the way wars are fought [1]. Beyond its impact on society, culture, war and commerce, the aerospace industry drove the development of twentieth-century technology - from the development of new materials to the introduction of electronic computing, and new approaches to the management of complexity [1].

The history of aviation extends for more than two thousand years, from the earliest forms of aviation such as kites and attempts at tower jumping to supersonic and hypersonic flight by powered heavier-than-air jets. Nowadays, in an age when air travel to the other side of the world is commonplace and humans have established a permanent foothold in space, flight continues to inspire the same sense of awe, magic and power that it did when the airplane was new [1].

1.2 EARLY FLYING MACHINES

Human beings have always dreamed of flying, as testified by myths and legends of many cultures involving flying carpets, broomsticks, glued feathers and artificial flapping wings [2]. They did not, however dream of the Boeing 747. The flight to which humans traditionally aspired was that of birds, and the illusion that a person could fly like a bird costed many men their life or limbs. Historical records are scattered with "tower-jumpers" who launched themselves into the air supported only by blind conviction and poorly improvised wings, "instruments to fly" involving a mechanism that would flap wings, or kites [2].

Flight was an unaccomplished obsession also in the Renaissance period. *Leonardo da Vinci* (1452-1519) believed that mechanical flight was possible and achievable through careful observation and study of the basic physical principles underlying flight in nature [1]. His dream of flight found expression in several rational designs of artificial flight machines based on those principles [1,2]. His drawings of an ornithoper (Figure 2a), a parachute (Figure 2b), and a helicopter (Figure 2c) are among the most familiar images of Renaissance technology, although he did not attempt to build any of them. Da Vinci was a man ahead of its time, and in the history of fluid dynamics, he stands as a lone giant between the Greeks and the 17th century precursors of the scientific revolution [1]. However, he kept his notebooks jealously secret, and the ideas that could have qualified him has the founder of aerodynamics remained unveiled until the 19th century.

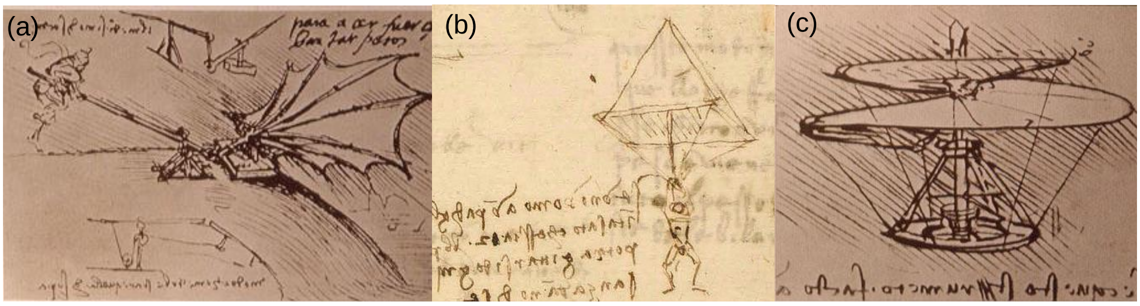


Figure 2 - Leonardo da Vinci's design of (a) an ornithopter, (b) a parachute; and (c) a helicopter (images in public domain).

1.3 MODERN ERA: LIGHTER-THAN-AIR FLIGHT

The foundations of the aerodynamic theory were thus developed by generations of brilliant thinkers unaware of *da Vinci'*s studies and not in the least interested in flight. Researchers including *Galileo Galilei* (1564-1642), *Edme Marriot* (1620-1684), *Christiaan Huygens* (1629-1695) and *Isaac Newton* (1642-1727) established the science of mechanics, the laws of motion and basic notions regarding fluid dynamics, and developed the major principles of aerodynamics [1]. Other significant figures include *Daniel Bernoulli* (1700-1782), *Jean d'Alembert* (1717-1783), *Leonhard Euler* (1707-1783), *Joseph-Louis Lagrange* (1736-1813) and *Pierre-Simon de Laplace* (1749-1827), who established fundamental physical and mathematical principles of fluid flow [1].

1.3.1 Balloons

17th and 18th century philosophers who studied the physics and chemistry of the atmosphere laid the foundation for the invention of the balloon. Early works established that the atmosphere could be pumped out of a closed vessel like any fluid, and stated the physical laws explaining the behaviour of "air", the only gas known that far [1]. This had profound technological consequences in several fields, and inspired aspirations on buoyant flight, including the attempts of Francesco Lana de Terzi (1670) and Bartolomeu Lourenço de Gusmão (1709) to build structures whose interior weighted less than the amount of air they displaced. However, it was the analysis of the elemental constituent gases of the atmosphere in the 18th century that directly led to the invention of the balloon [1]. In 1765 Joseph Black identified nitrogen, in 1774 Joseph Priestley identified oxygen, in 1775 Henry Cavendish identified hydrogen [1]. The discovery of a gas many times lighter than air (the density of air is 0.001225 g/cm^3 [3], versus 0.00008988 g/cm3 for hydrogen) inspired chemists to explore how much weight such gas could lift, and in 1780 Black proposed that if hydrogen gas filled a balloon, the inflated object could rise into the air.

Inspired by the new science of the atmosphere and by the work of English pneumatic chemists, several Frenchman begin conducting their own experiences. 1783 was a crucial year for ballooning, and between June and December six milestones were achieved in France:

- June 4: the *Montgolfier brothers* (Joseph and Étienne) demonstrated their unmanned hot air balloon at Annonay, France. The balloon consisted of a light wooden frame covered with a sandwich of paper and fine taffeta fabric, and filled with hot air [1].
- August 27: *Jacques Charles* and the *Robert brothers* (who had developed a process for coating fabric with natural rubber, making it airtight) launched the world's first unmanned hydrogen-filled balloon, from the Champ de Mars, in Paris. A huge crowd accompanied filling of the balloon (which started on August 23) and was present on launch; one of the spectators was *Benjamin Franklin* [4]. After 45 minutes the balloon landed 21 kilometres away in the village of Gonesse, where terrified local peasants attacked it with pitchforks and knives, destroying it [4].
- September 19: the *Montgolfier brothers* rose the first balloon with living creatures, a sheep, a duck and a rooster, in an attached basket.
- October 19: the Montgolfier brothers launched the first manned flight, a tethered balloon with humans on board, in Paris. The aviators were the scientist *Jean-François Pilâtre de Rozier*, *Jean-Baptiste Réveillon*, and *Giroud de Villette*.
- November 20: the *Montgolfiers* launched the first free flight with human passengers, *Pilâtre de Rozier* and *François Laurent*. They drifted 8 km in a balloon powered by a wood fire.
- December 1: *Jacques Charles* and *Nicolas-Louis Robert* launched their manned hydrogen balloon from the Jardin des Tuileries in Paris, witnessed by a crowd of 400,000. They ascended to a height of about 1,800 feet (550 m) and landed after a flight of 2 hours and 5 minutes, covering 36 km [4].

Ballooning became a major trend in Europe in the late 18th century, providing the first detailed understanding of the relationship between altitude and the atmosphere. Ballooning captured the public imagination, crowds flocked to demonstration flights and fliers became national heroes [2].

1.3.2 Airships

Prussian count *Ferdinand von Zeppelin* (1838-1917) (Figure 3 a) interest in airships was inspired by a visit to the United States during the Civil War, where he witnessed the use of tethered balloons as military observation posts [2]. From 1891, he devoted his personal fortune to the development of powered rigid airships, achieving the basic design in 1898 [1]. Differently from balloons, the shape of the hydrogen-filled envelope was maintained by a solid framework rather than by the pressure of the gas inside [2]. Despite numerous drawbacks, Zeppelin’s first airship, the LZ-1 (measuring 128 m long and operated by a crew of 5, Figure 3 b), made its maiden voyage on July 2, 1900, but the behemoth was so underpowered and impossible to control that it was immediately abandoned. Zeppelin and his designer *Ludwig Dürr* (1878-1956) then worked on the LZ-2 (which was destroyed on its second flight), the LZ-3 (which completed two flights of two hours each on October 9 and 10, 1906), and the LZ-4 (which could carry out flights with duration up to 8 h; it was destroyed on the ground by a storm) [1,2]. In 1910 zeppelin airships began passengers service. The airship design steadily improved under Dürr’s direction and from 1914 a new aluminium alloy (*Duraluminium*, § Module 2) was in use for the framework, and more powerful engines were introduced. This allowed the LZ-26 to carry a 12.7 ton load at more than 80km/h. By 1914 zeppelins had carried more than 37000 passengers [2].

Airships were also developed in other countries, but it was only in Germany that they attained the status of a national icon [2]. During World War I the German military made extensive use of zeppelins as scouts and bombers, killing over 500 people in bombing raids in Britain. The defeat of Germany in 1918 slowed down the airship business, because under the terms of the Treaty of Versailles Germany was prohibited from building large airships. In 1926, those restrictions were lifted and the production of the LZ-127 Graf Zeppelin (Figure 3 c) was started, reviving the company. During the 1930s the zeppelin airships operated regular transatlantic flights from Germany to Brazil and to North America (where the spire of the Empire State Building was originally designed to serve as a mooring mast for airships, although it was later found that high winds made this impossible) [5]. It was the Hindenburg disaster in 1937 (when the LZ-129 Hindenburg caught fire and was destroyed during its attempt to dock with its mooring mast at Naval Air Station Lakehurst, making 36 fatalities), along with political and economic issues, that hastened the termination of the zeppelins.

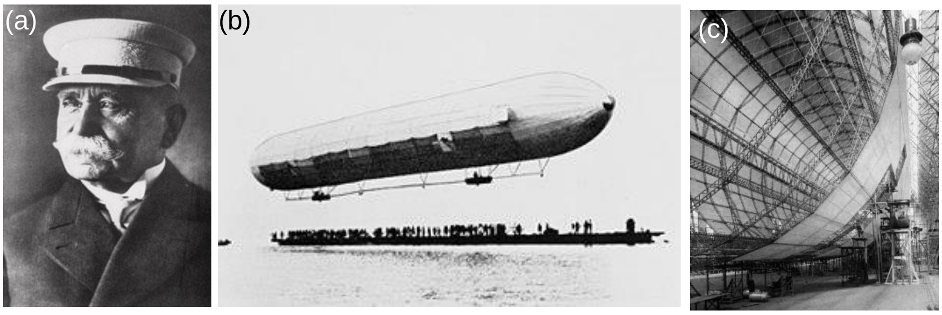


Figure 3 - (a) Ferdinand von Zeppelin; (b) LZ-1, the first zeppelin; (c) the Graf zeppelin under construction.

1.4 MODERN ERA: HEAVIER-THAN-AIR FLIGHT

By the end of the 19th century practical efforts to progress in heavier-than-air manned flight were mainly carried out via two main approaches [2]. One focused on power, aiming to develop an engine powerful enough to lift a man and a machine in the air. The other focused on unpowered flight aiming to understanding the secret of flight as exhibited by birds and insects.

1.4.1 Sir George Cayley

Sir George Cayley (1773-1857) is one of the most remarking figures in the history of aeronautics and considered the founding father of aerial mechanical navigation [1]. He contributed to fields ranging from architecture and railroading to the design of lifeboats and prosthetics. The great passion of his life was however the dream of "aerial navigation". He identified heavier-than-air flight as a problem amenable to solution through scientific and technological research; he established a significant number of basic principles in aerodynamics; and he performed has the first aeronautical engineer, building and flying the first fixed-wing gliders capable of giving humans a taste of flight [1]. In 1799, he engraved on a small silver disk (Figure 3a) his conception of a flying machine as a fixed-wing craft with separate systems for lift, propulsion and control on one side, and a remarkable diagram of the forces acting on a wing on the other.

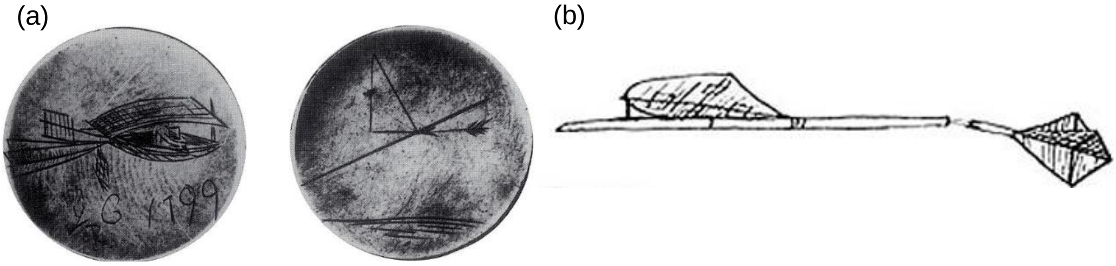


Figure 4 - George Caley's (a) silver disk with the first illustration of what evolved into the modern airplane design; the other side displays the first diagram of aerodynamic forces on a wing (British Science Museum, public domain); (b) first craft (1804).

In 1804, Cayley designed and built his aircraft (Figure 3b), the predecessor of all fixed-wing flying machines [1]. It consisted of a 120 cm long horizontal pole with attachments: a kite, set at a six-degree angle to the horizontal, served as the wing; a weight could be positioned to alter the centre of gravity and maintain balance; a cruciform tail mounted on a universal joint served both as elevator and rudder. He continuously refined his design through the years, culminating in a final and more fully developed version (1849 and 1852) of his basic design for a piloted glider.
The most important contributions of Cayley's aeronautic work provided a solid foundation for future aeronautic research, and include [1]:

- Confirmation of earlier suggestions that a curved (*cambered*) wing produces greater lift than a flat plate set at low angle of attack.
- Identification of an area of low pressure on the upper surface of a cambered wing in flight and of an area of high pressure on the underside.
- Suggestion that angling the tips of the wings above the centreline of the aircraft, creating a dihedral angle, results in lateral stability.
- Providing the earliest studies on the movement of the centre of pressure on airplane wings during flight.
- Explaining how to calculate the performance of an aircraft.

Cayley's calculation of *lift* and *drag*, and his comments on how an aircraft could be stabilised and controlled constituted a solid base for potential progress towards heavier-than-air flight [2]. Modern aviation did in fact began with Sir George Cayley [1].

1.4.2 Steam as propeller

Between 1850 and 1890 European and American publications were filled with reports of flying machines, and some of them provided insights of information that contributed to flight evolution [1]. The awakening of a sustained interest in heavier-than-air flight happened some 30 years after Cayley's published research, and was triggered by the success of the steam engine applied to transport systems: steam trains and steam ships notably decreased journey times by land and by sea [2]. Experiments with steam power were the first attempts in powered flight [2].
The first serious experimenter was the French *Félix de la Croix* (1823-1890). In the 1850s he and his brother *Louis* designed and flew a model aeroplane powered first by clockwork and then by a miniature steam engine [2]. He then patented a design for a full-size monoplane with a lightweight steam engine and the surprising refinement of a retractable undercarriage, which he built and tested in 1874. The aircraft ran down a sloping ramp, briefly lifted into the air and immediately came down to the ground [2]. This was also the faith of all other power-approached flight experiments. Their inventors gave little or no thought to how they would fly their machines should they take to the air.

1.4.3 Gliders

Contrasting with the enthusiasts of motorised flight, the experimenters in unpowered flight hoped to make progress through mimicking bird flight. The acknowledged leader of the "flying man" approach was the German *Otto Lilienthal* (1848-1896) [2]. Lilienthal´s flights - pacing down a hill into the wind, encumbered by his wide bird-like wings, and lifting into a glide that carried him above the ground - were an impressive spectacle, and far more scientific and practical in the exploration of flight than it seemed. From a scrupulous study of bird flight and bird anatomy, Lilienthal concluded that a curved (i.e., cambered) wing was essential to produce lift; he systematically studied aerodynamics by carrying out experiments with specially built test equipment to see what precise wing shape (i.e., aerofoil) would give maximum lift; and he committed to practical experiment through flying himself [2]. We soon realised that wing-flapping experiments were futile, and began a more fruitful exploitation of the potential of fixed-wing gliders. Between 1891 and 1896 Lilienthal built 16 different gliders, mostly monoplanes but also biplanes. They were light and flimsy structures, made by stretching a cotton fabric over willow and bamboo ribs. They flew, but since there was no control system he had to throw his body around to maintain balance and stability amid the shifting air currents, hurting himself. On August 9, 1896, Lilienthal´s glider was caught in a gust of wind, stalled and crashed; he died from the injuries the next day. Lilienthal carried out more than 2000 flights, the longest covering a distance of 350 m [2].

Experiments with gliders provided groundwork for heavier-than-air crafts, and showed that if flight was ever to have practical use, it would have to involve powered machines [2]. As the 19th century drew to an end, the attaching of an engine to some form of glider suddenly become more feasible through the development of the internal combustion engine, which had the potential to generate more power per weight than any steam engine [2]. *Samuel Langley* (1834-1906), an American leading scientist at the Smithsonian Institute in in Washington D. C., was a detractor of Lilienthal and his followers. He believed that the application of sufficient power to an aerodynamically stable machine would solve the problem of flight, and investigated its practicalities [2]. In 1986, he built the steam-powered *Aerodrome* model, that flew 1200 m. He then settled on a gasoline engine to power is aeroplane, but it took years to develop the required power-to-weight. The project ended in December 1903, way over budget and four years behind schedule. The resulting huge flying machine was aerodynamically and structurally unsound and had no adequate control system. It simply didn't work, plunging straight from launch into the Potomac River in its maiden flight [2]. Ironically, only 9 days later success was to be achieved by the *Wright brothers* [2].

1.4.4 The Wright brothers

Success was attained when the traditions of powdered and unpowered flight came together with the *Wright brothers* [2]. It is generally (although not universally) accepted that the Wright brothers were the inventors of the first heavier-than-air machine capable of sustained, controlled, powered flight [2]. *Wilbur* (1867-1912) and *Orville* (1871-1948) Wright grew up in Dayton, Ohio, however very much in touch with contemporary currents of thought and innovation. They took strong interest in the widely publicised fight experiments of the 1890s, and from 1899 onwards they started financing their aeronautic experiments with the profits from their bicycle business (they estimated that it cost them 1000 $ to crack the problem of powered flight) [2]. Although initially they had a shop to rent bicycles, they soon expanded into building their own. Their experience building something as inherently unstable as bicycles and the insights it gave them into combining lightness with strength to achieve balance and control gave them a novel approach to the problem of creating a controllable heavier-than-air flying machine [2]. The availability of raw materials and machinery in their well-equipped workshop helped them with their investigations into the flying problem. The Wrights approach the problem systematically: they first wanted to absorb existing knowledge and wrote a letter to the Smithsonian Institution asking for any scientific papers it might have on flight and a reading list of books on the subject. That letter received a prompt and helpful response, allowing the brothers to get acquainted with the works of *Cayley*, *Lilienthal*, *Chanute* (a pioneer of glider design) and *Langley*, among others. Since they felt that a flying machine was somewhat like a bicycle in the sense that it would need to be flown with constant adjustment of *balance*, they immediately identified an area that seemed to have been neglected: *control* [2]. From the start the Wrights pose the problem not simply on *how to build* a flying machine, but also on *how to fly* it. They got a lot of inspiration from studying the flight of birds and insects and their first breakthrough came from watching soaring buzzards [6]: Wilbur was struck by the movement of the feathers on their wing tips, which kept the birds lateral balance, and devised that a similar effect could be achieved on an aircraft wing, much like twisting the ends of a cardboard in opposite directions: *wing-warping* had been devised. In 1900, they had built their first glider in the bicycle workshop and began experiments in Kitty Hawk, North Carolina. This small beach settlement was chosen because of its frequent winds and soft sandy surfaces, suitable for their glider experiments, which they conducted over a three-year period prior to making the powered flights [6]. During that time they carried out a remarkable set of experiments featuring wing design: in their home-made wind tunnel they calculated the lift created by various combinations (around 200) of wing size, shape, curvature and profile moving at different speeds and angles [2] (Figure 5). This resulted in a highly accurate database that they applied to wing design. By the end of the summer of 1902 they were making controlled glides of up to 200 m, staying airborne for up to 26 sec. By then the Wrights felt ready to approach powered flight, for which they needed an engine and a propeller. Since automotive companies proved incapable of supplying an adequate engine, they had one done by their assistant *Charlie Taylor*, who delivered a remarkable aluminium gasoline engine weighting 82 kg and delivering 12 hp. The propeller design was a more complex problem, forcing the brothers to tackle intricate questions of physics and mathematics. In late September 1903, they returned to Kitty Hawks to test the flying machine, but several drawbacks with the engine and the propeller shafts delayed their success. On December 17, 1903, the goal of so many was finally attained when the *Wright Flyer I* flew for 59 seconds, travelling 260 m with Orville at the controls. This first powered flying machine (Table 1) was constructed from spruce and ash woods, muslin and piano wire, and was launched from a wooden monorail. The pilot lay face down in a gap in the lower wing, a position that minimised drag. The engine, flight-data instruments and an anemometer were positioned to his right. The aircraft was controlled in horizontal *pitch* with a movable elevator in front of the pilot, in *yawn* by twin vertical rudders, and in *roll* by the twisting of the wings (*wing-warping*) [2].

The Wright brothers pursued efforts to build and test improved models of their flying machine. Between June and October 1905, in the much-improved Flyer III they made flights up to 38 minutes' duration covering more than 30 km at a time. Then, the brothers took the decision to cease all further flying experiments, devoting their effort to search for lucrative business contracts. Most aspects of their work were known to aviation enthusiasts, and soon many challenged their achievements.

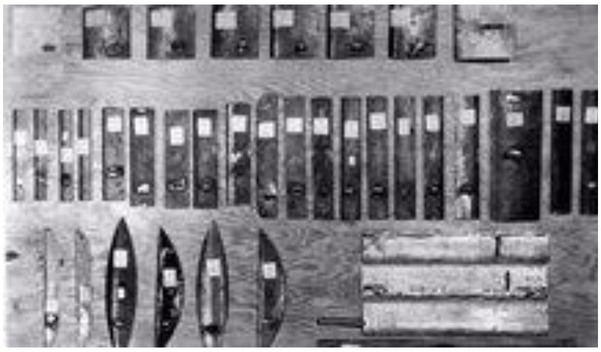


Figure 5. Some of the different model airfoils tested by the Wright brothers [2].

Table 1. Technical specifications of the Wright Flyer I [7].

Engine	12 hp water-cooled four-cylinder gasoline engine
Wingspan	12.3 m
Length	6.4 m
Height	4.1 m
Weight	274 kg
Maximum speed	48.3 km/h

1.4.5 Flight as an established technology

During 1907 *Louis Blériot* and *Robert Esnault-Pelterie* achieved small flights in tractor (i.e., powered from the front) monoplanes, a configuration that would play a crucial role in the evolution of flight [2]. French aviators had at their disposal the first aeroplanes factory, established in 1906 by brothers *Gabriel and Charles Voisin* (by 1918 it had produced over 10000 aircraft). Also in 1907 *Léon Delagrange* and *Henri Farman* approached them with an individual modified version of Voisin biplanes. These basically resembled the Wright flying machine, but they had a box-kite tail structure and lacked any form of lateral control [2]. Both men quickly taught themselves to fly, making a series of increasingly impressive flights. In January 1908 Farman flew a 1 km circuit; on June Delagrange stayed aloft for more than 18 min; on July *Glenn Curtiss* (USA) made the first flight over a mile (1.6 km); on October Farman (after further modifications including the addition of four large ailerons to the wings) made the first cross-country flight, covering 27 km in 20 min [2]. Early powered flying machines were finally developing into true fliers, and in July 1909 Louis Blériot made the first flight across the English Channel. This started a new phase in air conquest, turning aviation from an object of curiosity into a modern craze that gripped popular imagination.

Early airplanes were fragile machines, mere contraptions of wire, wood and fabric. Landing was a tricky manoeuvre, much harder to master than taking off. All flying machines suffered from unreliable engines, and engine failure was common, although it didn't necessarily lead to a crash, because they could glide well [2]. Structural failure was however a serious matter: if wings or control surfaces collapsed under the pressure of sudden manoeuvres or through the cumulative strain of use, a pilot was doomed.

From 1909 onwards, there was a swift expansion in the range of aircraft designs, with successful aeroplanes evolving from the accumulation of knowledge based on the experience of flying and of building flying machines. Small-scale manufacturing companies employed engineers and artisans who might have previously worked on anything from shipbuilding to furniture making. The production process was slow and laborious. More mechanised, large-scale production only began to develop after 1911, when the first military contracts were made [2]. By then France, Germany and Great-Britain were the only European countries making significant steps towards building up an aviation industry. Some progress was achieved, including the introduction of metal airframes in the factory of *Louis Bréguet*. The greatest technical breakthrough immediately before World War I (WW I) concerned size: to be of practical use, both in peace and war, aeroplanes had to be bigger. This required the use of more than one engine. The Russian designer *Igor Sikorsky* (1889-1972) built and repeatedly flew large four-engines aeroplanes in 1913-1914, including a 2600 km round trip from St Petersburg to Kiev. This opened the path to the design of viable passenger-transport aircraft and heavy bombers. Aeronautics was rapidly becoming an industry and, a little more slowly, a science [2].

1.4.6 Military uses: World War I (1914-1918)

Aircraft found their first practical use as an instrument of war [2]. During WW I the great strides made in former years in the new science of aerodynamics finally began to seriously influence aircraft design [2]. The aeroplane rapidly developed as a weapon of war, and matured under the stress of combat during World War I, when the techniques of air power were initially developed. For the first time, aircraft were operated daily, with all that implies of regular servicing and focus on reliability. More powerful engines and robust airframes contributed to great improvement in overall performance. There was also a change of scale: aircraft has been manufactured in hundreds before the war, they were now produced in thousands. Militarily, the different roles aircraft could perform and the design of specialist aircraft to fulfil them were identified. Although up to then wars were fought by navies and armies, aeroplanes proved more useful and reliable, and much cheaper to produce.

1.4.7 Other technological landmarks

In the aftermath of WW I aircraft manufacturers struggle to survive as air forces were run down and the market was awash with surplus military aircraft [2]. Despite the rundown of the aviation industry, the public's fascination with flight remained intense and record-breaking long-distance flights were carried out to ever more distant destinations. After the rapid improvements in aircraft performance brought by the war, the advent of all-metal aircraft led to radical advances in speed and range, while improved flight instruments and navigation devices made them increasingly safe to fly [2].

In the 1930s the revolution in aircraft design was on fruition: monoplanes overcome high-drag biplanes; all-metal stressed-skin construction became the rule, benefiting from improved metallurgy, especially lightweight aluminium alloys (aircraft manufacture was the first major use found for aluminium); engines continued to improve in power-to-weight and reliability (by the late 1930 aircraft engines were capable of delivering over 1000 hp; and retractable undercarriages became standard. Other improvements included constant-speed propellers, the use of *flaps* was introduced to temporarily change the shape of the wing, and safety was improved by fitting de-icers to leading wing edges [2].

By the end of WW I airplanes had a top speed of less than 200 km/h (approx. 125 mph), at which air behaves like an uncompressible fluid. In 1930, high-speed aircraft passed the 650 km/h mark, and limitations of the traditional aeronautical propulsion became evident: the air moving over the top of the small blade sections of the propeller was approaching supersonic speed[1] and detaching from the airfoil, with increase in drag and loss of lift [1]. This is because when approaching the speed of sound (1234.8 km/h) the atmosphere begins to compress in the front of the aircraft, creating a shockwave sweeping back from the nose in a great cone shape. When the wave crosses the wing, the pressure on the wing rises to the point where the pilot cannot operate the controls. In 1935 *Adolf Busemann* suggested that a wing with delta-shape would remain inside the shock cone, enabling the airplane to escape the compressibility effects. On its

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[1] The ratio of the aircraft speed to the speed of sound is the aircraft *Mach number*. At 11,000-20,000 m, the cruising altitude of commercial jets, the speed of sound in air is 295 m/s (1062 km/h) *vs* 340 m/s at sea level. At speeds above Mach 1 aircrafts are described as traveling at supersonic speed.

turn the development of larger and more powerful combustion engines did not suffice, and the propulsion industry responded by introducing a radically different type of power generation, the gas turbojet reaction engine.

1.4.8 Military uses: World War II (1939-1945)

Used widely during WW I, where the techniques of air power were initially developed, military aircraft became an integral part of warfare during the World War II (WW II) [2]. Aircraft played a vital role in army operations, providing ground troops with mobility, supplies and supporting fire; transporting parachutists; and carrying out strategic bombing to destroy the enemy's productive capacity and spirits. For example, the US industry produced five times more airplanes from 1939 to 1945 (324750) than the total number (50031) manufactured during the 1911-1938 period [1].

Main technical developments took place during this time and a series of impressive new technologies were produced, including nuclear weapons, jet aircraft, guided missiles, long-range rockets and an array of electronic systems. In particular, turbojet propulsion marked a turning point in the history of aviation, and represented a fundamental shift in aeronautical technology [1].

1.4.9 Technological landmarks in the post war

After WW II the new and immensely powerful jet engine revolutionised both air travel and military aviation, beginning a new age of high-speed aeronautics [1]. On 1950 air travel was common, and by the end of the decade it had replaced train and steamship as the preferred means of transport [2]. The primary driving force behind technological developments in aviation in the 40 years after the end of WW II was the Cold War confrontation between Western allies and the communist bloc [2], and resulted in remarkable progress in aircraft design, jet engines, avionics and weaponry, developed with the aim to assure air supremacy in any future conflict.

In 1947, *Chuck Yeager* became the first human to officially break the sound barrier (October 14, 1947), flying the experimental *Bell X-1* at Mach 1 at an altitude of 45000 ft (13700 m). *Albert Scott Crossfield* achieved Mach 2 flying the *Douglas D-558-II Skyrocket* (November 20, 1953), and in September 1956 the *Bell X-2* flew three times the speed of sound [1]. At this speed, the biggest problem was aerodynamic heating, since skin friction raised temperature to values were standard light alloys began to lose strength and resistance to deformation (§ Module 2). To overcome this problem, the *Bell X-2* was constructed of a nickel superalloy (*K-Monel*) and stainless steel. In 1959 took place the first flight of the X-15 (constructed of a nickel-steel superalloy called *Inconel-X*), designed to explore flight at hypersonic speed (*i.e.*, above Mach 5) and to reach suborbital altitude. Over the following 9 years these aircraft reached speed up to Mach 6.72 and altitude up to 354,200 ft (108 km); eight pilots earn their astronaut wings flying the *X-15*.

The 1954-1964 decade did in fact witnessed the most dramatic change in the history of the industry, with the shift from aviation to airspace and marking the peak spending years for both the *Apollo* lunar program and the development of new families of nuclear-tipped, land-based and submarine launched guided missiles [1]. Airplanes were by then embedded in larger technological systems. New tools and techniques were developed to manage complex aerospace projects, steering the course of scientific research, the advance of a broad range of critically important technologies and laying the foundation for new industries that would shape the future of the world [1].

1.4.10 Technological landmarks in the 1980s and the 1990s

By the last quarter of the 20th century, with large, jet-powered aircraft, air travel was commonplace and affordable [2]. Flying become second nature to hundreds of millions of people, so deeply intertwined into the fabric of society that it’s impossible to imagine a world without it [2].
In the latter part of the 20th century the advent of digital electronics produced great advances in flight instrumentation and "fly-by-wire" systems [2].

1.5 THE 21ST CENTURY7

The 21st century saw the large-scale use of pilotless drones for military, civilian and leisure use. With digital controls, inherently unstable aircraft such as flying wings became possible [2].
Ultimately the greatest limitation to the future expansion of global air travel probably lies in the rising sensitivity to the environmental damage caused by aircraft [2]. By the end of the 20st century, the ability to fly cleaner, quieter and more fuel efficiently started to balance the need to fly higher and faster [1].
The most accomplished example of such trend is probably the *Helios Prototype* built by NASA in 1999 (Figure 6, Table 1.2). It was developed as part of an evolutionary series of solar- and fuel-cell-system-powered unmanned aerial vehicles. They were built aiming to develop the technologies that would allow long-term, high-altitude aircraft to serve as atmospheric satellites, to carry out atmospheric research tasks, as well as to serve as communications platforms at the limits of the Earth’s atmosphere. On August 13, 2001, the remotely piloted Helios reached an altitude of 96,863 feet (29,524 m), a world record for sustained horizontal flight by a winged aircraft and spent more than 40 minutes above 96,000 feet (29,000 m) [8].

Figure 6. The solar-electric Helios Prototype first test flight on solar power [8].

Table 2. Technical specifications of the *Helios Prototype* [8].

Propulsion	14 brushless direct-current electric motors, each rated at 1.5 kW, driving two-blade laminar-flow propellers
Wingspan	75 m
Length	3.7 m
Weight	600 kg
Maximum speed	up to 44 km/h at low altitude, up to 179 km/h at high altitude
Altitude	typical cruise 30 km maximum 60 km
Materials	Carbon fibre composite structure, Kevlar®, Styrofoam® leading edge, transparent plastic film wing covering

In the same line, the Suisse Solar Impulse 2 is a propeller-driven aircraft with more than 17,000 solar cells on its upper surface, powering four electric motors. It is built of carbon fibre composite and weights 2,300 kg, little more than a large car; yet its wingspan (71.9 m) is almost the same has the A380 [2]. From March 2015 to July 2016 it completed the first solar-powered circumnavigation of the globe, proving the effectiveness of clean technologies as a basis for environmentally friendly aviation [2].
Another current development strand has been remotely operated unmanned flight. An accomplished example is the Global Hawk aircraft. It was designed as a surveillance aircraft (it can survey as much as 100,000 km2 of terrain a day, approx. the area of Iceland), providing

broad overview and systematic surveillance by using high-resolution aperture radar and long-range electro-optical/infrared sensors with long loiter times over target areas [2]. It has been used since 1998 by the United States Air Force and by NATO, yet in 2007 two units were acquired by NASA for airborne Earth Science research. In this context, its ability to autonomously fly long distances, to remain aloft for extended periods of time and to carry large payloads, brought a new capability to the scientific community to measure, monitor and observe remote locations of Earth not feasible or practical with piloted aircraft, most other robotic or remotely operated aircraft, or space satellites [9].

At the beginnings of the 20th century the pioneers found it impossible to predict the future of the technology they created: “no airship will ever fly from New York to Paris”, “no engine can run for four days without stopping”, “the airship will always be a special messenger, never a load-carrier” were predictions of Wilbur Wright in 1909 [1]. His brother Orville did “not believe that airplane will ever take the place of trains and steamships for the carrying of passengers”. Flight technology was then new and immature, making impossible to foresee the future. Since then simple improvements have resulted in great leaps in performance, and change has been extraordinary and extremely fast. In as much the future is equally difficult to predict. However, there seems to be little doubt that investment will continue to fuel new technologies that will transform the way flight is carried out. Whatever the future holds, it is unlikely that humankind will lose the sense of wonder at its ability to fly.

2 MATERIALS

2.1 INTRODUCTION

Materials are the structural and/or functional support of all objects,
structures and systems used in every activity of human life.

Materials have accompanied humankind from the very beginning of its existence, and the history of materials somehow reflects the history of humankind [10]. Among the first materials used by humans were stone, wood, bone, fibbers, animal skin and fur, feathers, shells and clay. Materials were predominantly used for tools, weapons, utensils, clothing, shelter and self-expression. This is still true in the present days, although materials are now more numerous, complex and sophisticated. The increased usage and development of ever more sophisticated materials were paralleled by civilizational development, i.e., advanced civilizations invented and used more elaborated materials, that confer them power among surrounding communities.

Materials are so important that historians have named ancient periods after the material which was predominantly used at the time: the Stone Age, the Chalcolithic, the Bronze Age, the Iron Age [10]. Also, the names of some metals have entered linguistic usage, where they introduce a metaphoric distinction: medals for outstanding performance are conferred in gold, silver and bronze, and wedding anniversaries are classified using gold and silver, for example. From the end of World War II to the 1990's the time era was called the Silicon Age [10], because silicon is the material that drives all electric, electronic and microelectronic devices that permeate daily life in a very large extent. However, since then another category of materials has gained the largest impact on the lives of humans: nanomaterials. Nanomaterials are materials with at least one dimension in the 1 to 100 nm range (1 nm equals 10-9 m, which is the same proportion as between the size of an ant and that of a football stadium). Materials at the nanoscale display unique optical, electronic and mechanical properties, and are leveraging advances in materials synthesis and microfabrication research.

Materials can be classified in several manners. One of them considers materials origin, either natural or synthetic:

Natural materials. Natural materials come directly from nature, and exist without human action. They are obtained from nature with little or no chemical changes, and can be processed to shape, in order to produce finished parts able to be used. They can be either from vegetal (for example wood, bamboo, bark, and natural fibres such as cotton and linen), animal (silk and wool, for example) or mineral origin (clay, stones, pigments, petroleum, coal). Native metals are also included in this classification, mostly gold and platinum (but also lead, mercury, silver, iridium, osmium, palladium, rhodium and ruthenium).

Synthetic materials. Structural materials are made by humans through chemical synthesis, or by thermal, physicochemical or mechanochemical processing. They are the result of extensive research by scientists and engineers to improve raw-materials and make them better and more reliable.

Another possible classification is based on the main or more representative properties of the material considering the aimed application, either structural or functional:

Structural materials. Structural materials are used primarily for their mechanical properties, and are aimed to bear loads and to provide support for a given system.

Functional materials. Functional materials are selected based on properties other than mechanical. They play an increasingly important role in contemporary society, forming the basis for a wide range of technologies that require electric, electronic, magnetic, chemical, thermal or optical performance. Examples are computation, communication, storage and displaying of information (i.e., the entire IT sector), generation and storage of energy, and mobility.

Whatever their function or origin, all materials can be assigned to 4 main families: metals, ceramics and glasses, plastics, and composites (Figure 7).

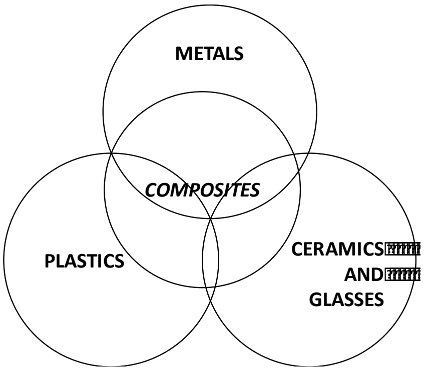


Figure 7. The four families of materials.

Metals. Most metals are found in nature as metal oxides (ores). Metal oxides are refined into pure metals in a process called smelting, in which the metal is extracted from its oxide through the use of a reducing agent [11]. Once the pure metal is produced, it can be alloyed and/or processed into the desired shape by forming operations (Figure 8).

Figure 8. From copper ore to copper wire: (a) chalcopyrite (CuFeS2, with 34.5 % copper) is one of the several copper ores; (b) it can be refined into copper metal by smelting; (c) and then the metal is formed to the final desired product shape.

Metals are materials mainly constituted by metal elements of the Periodic Table (Figure 9), which are held together by metallic bond (strong). Metallic bond characterises by valence electrons that are only loosely connected to their nuclei, and move freely between the atom cores (conduction electrons). This determines most properties of metallic materials. When in the solid state they are typically hard, opaque, shiny, and have good electrical and thermal conductivity. Metals are generally malleable (i.e., they can be permanently deformed out of shape without breaking or cracking), fusible and ductile (able to be drawn out into a thin wire without breaking). However, their density value is usually very high, although it varies broadly depending on the metal, from 0.53 g/cm^3 for lithium to 22.58 g/cm^3 for osmium (Table 4). Another limitation of several metals is their inclination to corrode in a number of chemical environments.

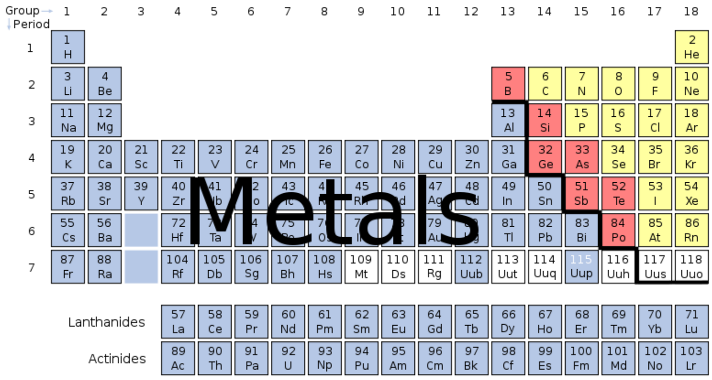


Figure 9. Periodic Table of the elements: 91 of the 118 elements are metals (coloured in blue).

METALLIC ALLOY = PURE METAL + ALLOYING ELEMENTS

Table 3. Density value of some pure metals and their relative density value compared to aluminium (highlighted in grey are the most important metals for aircraft construction).

Element	**Chemical symbol**	**Density** (g/cm^3)	**Density relative to Al**
Lithium	**Li**	0.53	0.20
Magnesium	**Mg**	1.74	0.64
Aluminium	**Al**	**2.70**	**1.00**
Titanium	**Ti**	**4.51**	**1.67**
Zinc	**Zn**	7.13	2.64
Tin	**Sn**	7.28	2.70
Iron	**Fe**	**7.87**	**2.92**
Nickel	**Ni**	**8.91**	**3.30**
Copper	**Cu**	8.93	3.31
Silver	**Ag**	10.50	3.89
Lead	**Pb**	11.34	4.20
Gold	**Au**	19.28	7.15
Osmium	**Os**	22.58	8.37

Table 4. Some examples of metal alloys used in common structural and functional applications.

Metal	**Common purpose**
steels	structural
cast irons	
wrought irons	
copper	functional (electrical conductivity)
bronzes (copper-tin alloys) brasses (copper-zinc alloys)	functional (low-friction, resonant qualities, resistance to corrosion)
nickel alloys	functional (high creep resistance)
gold alloys	functional (jewellery)
tinplate (tin-lead alloys)	functional (food cans)

A homogeneous mixture of metals or a homogeneous mixture of a metal with non-metals in small amount is called an alloy. Like pure metals, alloys are also defined by metallic bonding. These mixtures have the purpose of imparting or increasing specific characteristics to the material: in some cases, a combination of a metal with other elements may reduce the overall cost of the material while preserving important properties; in other cases, a tailored compositional combination allows to develop metals with a wider range of properties than could be achieved from pure metals alone, such as corrosion resistance or mechanical strength [11]. Examples of alloys are steel (iron+carbon), brass (copper+zinc), duralumin (aluminium+copper), bronze (copper+tin) and amalgams (such as mercury+silver). Metal and metal alloys are used both to structural and functional purposes (Table 4).

Ceramics and glasses. Chemically, ceramics and glass are compounds containing at least two types of elements of the Periodic Table elements, a metal and a non-metal (yellow, Figure 9) joined together by ionic and/or covalent bonding. These bonds are strong, but unlike the metallic bond there are no conduction electrons, determining properties such as the low thermal and electrical conductivity and the high chemical inertia of ceramics. Oxygen, carbon and nitrogen are the non-metals present in the most relevant engineering ceramics, respectively oxides (e.g. aluminium oxide, Al_2O_3), carbides (e.g. silicon carbide, SiC) and nitrides (eg titanium nitride, TiN).

The use of ceramic materials is probably as old as human civilization itself, first with the use of stone, clay and mineral ores, and later with fired clay. This explains why historians didn't specifically designate a Ceramics Age: while stone, copper, bronze and iron can be associated with reasonably well-defined time periods during which these materials were predominantly used, ceramic materials have been actively and continuously been in use from many millenniums ago to the present [10]. However, two revolutions in human civilization are associated to ceramics [12]. The first corresponds to the discovery that fire would irreversibly transform clay into ceramic pottery, around 20000 years ago. This eventually led to agrarian sedentary societies and to enormous improvement in the quality and length of human life. Another revolution has occurred in the 1950's with the innovative use of specially designed ceramics for the repair and reconstruction of diseased or damaged parts of the body; ceramics used for this purpose are termed bioceramics.

The properties of ceramics vary, but most tend to be strong and hard, yet very brittle [11]. As a result, the dominant ceramic materials continue to be pottery, glasses, abrasives, bricks and cements (Figure 10 a). However, there are many exceptions, and modern high-performance ceramics (Figure 10 b) are used for example in body armour, space shuttle tiles, and superconductors [11].

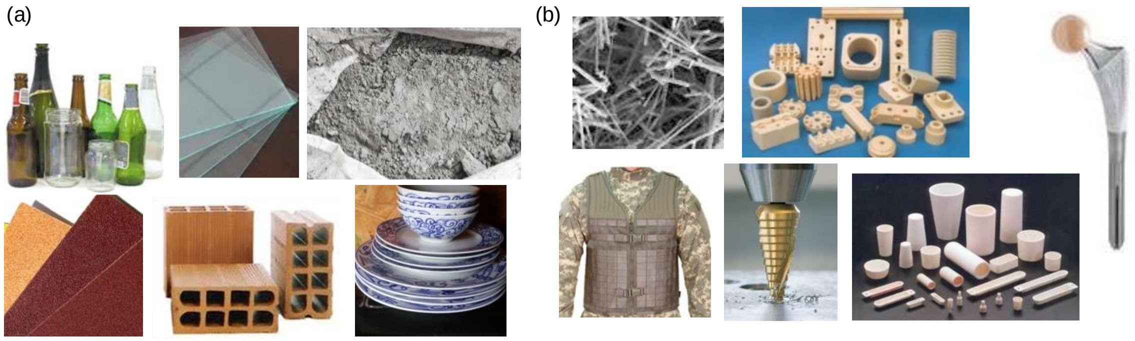


Figure 10. Some examples of application of ceramic materials. (a) Traditional ceramics (clock-wise): glass bottles, plain glass, cement, porcelain, brick, abrasives. (b) Technical ceramics (clock-wise): reinforcement fibres, electric insulators, bioceramic coating on hip prosthesis, lab material, hard coating on cutting tool, tiles in ceramic armour.

Polymers. Polymers are very large molecules (macromolecules), obtained via polymerization reaction of a large number of small molecules. The resulting chains have large molecular mass and covalent bond between carbon atoms, leading to unique physical properties that include toughness, viscoelasticity, and tendency to form amorphous and semicrystalline structures rather than crystals. Carbon is the main atom in the vast majority of polymeric chains, frequently with hydrogen, oxygen, nitrogen, chloride and/or fluoride attached to the sides [11]. Interaction between neighbouring chains occurs through van der Waals forces (weak), thus polymers typically have low mechanical strength and low melting temperature [11].

Both synthetic and natural polymers play essential and ubiquitous roles in everyday life. Polymers range from familiar synthetic plastics such as PVC, to natural biopolymers such as DNA and proteins that are fundamental to biological structure and function. Many polymers are flexible and lightweight, making them ideal for applications where high strength is not required. However, because so many types of polymers exist their properties vary widely [11], ranging from the weak and ductile polyethylene (which is the simplest synthetic polymer, used for example in inexpensive plastic bags, Figure 11 a), to Kevlar® (used as ballistic fibres in bullet resistance vests, Figure 11 b).

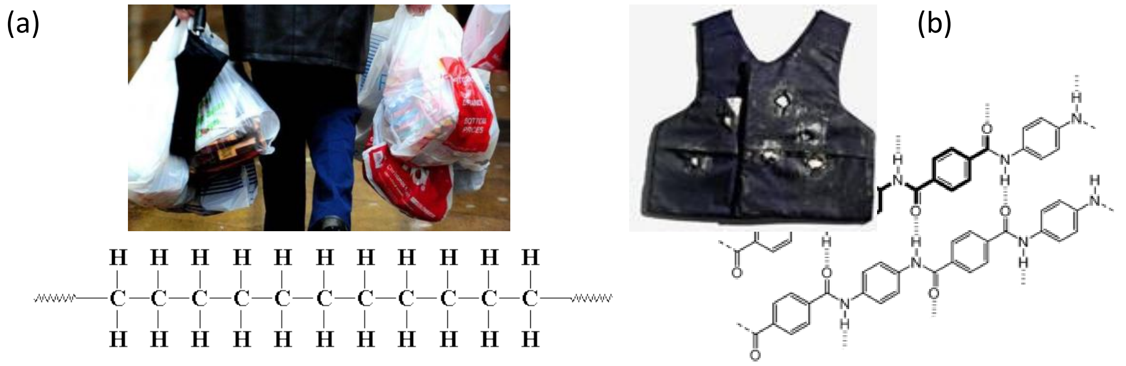


Figure 11. Polymer diversity, from (a) polyethylene application in grocery bags, to (b) Kevlar® vest after shot. The corresponding molecular chains are shown at the bottom of each image.

Composites. Composites are materials made from the mixture of two or more constituents with significantly different physical or chemical properties, that when combined produce a material with characteristics different from the individual parts. The individual components remain separate and distinct within the finished structure, thus differentiating composites from mixtures and solutions. Composites can be of natural (wood, for example) or synthetic origin. Composites of natural origin are seldom used in engineering applications, because of the associated lack of properties reproducibility and uncertain availability.

Composite materials are composed of two phases, matrix and reinforcement. The matrix is the material in the composite that protects, orients and transfers load to the reinforcement material. Depending on the reinforcement geometry, synthetic composites are classified in three main categories (Figure 12): particle-reinforced, fibre-reinforced and laminar composites. Particle-reinforced composites (Figure 12 a) contain a large number of particles (like the blend of cement and gravel used in concrete), that tend to enhance properties such as toughness or wear resistance rather than strength) [11]. In fibre-reinforced composites (Figure 12 b and Figure 12 c) strong and stiff but brittle reinforcement fibres are set in a tough but ductile matrix, resulting in materials with high strength, stiffness, and fatigue resistance. Common fibres used for reinforcement include carbon, glass and Kevlar®. Structural composites consist of alternating layers of different materials bonded together to form laminates (Figure 12d) or more complex stacking geometries.

COMPOSITE = MATRIX PHASE + REINFORCEMENT PHASE

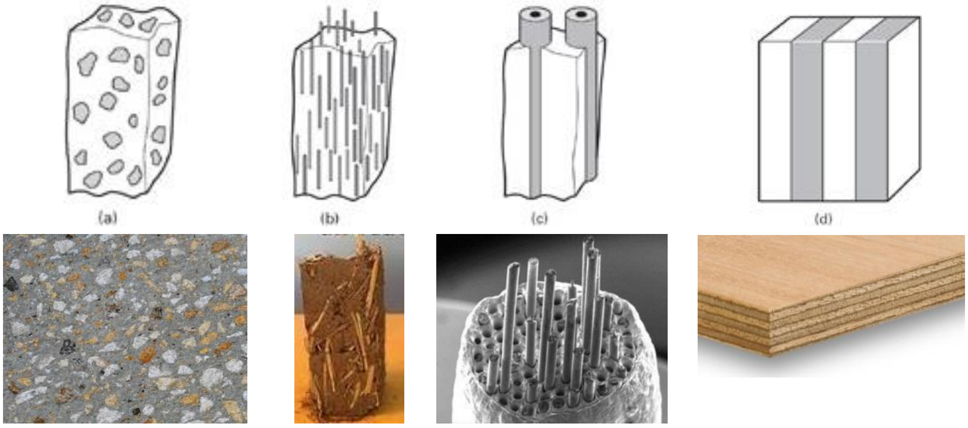


Figure 12. Classification of synthetic composites, showing a schematic representation [13] and an example of application: (a) particle-reinforced (e.g., concrete); (b) short fibre-reinforced composite (e.g., adobe bricks); (c) continuous fibre-reinforced composite (e.g., silicon carbide fibre-reinforced copper matrix used in aircraft turbine blades to increase engine efficiency); (d) laminar composite(e.g., plywood).

2.2 MATERIALS REQUIREMENTS FOR AIRCRAFT

Materials science and engineering is very important to aerospace engineering. Its practice is defined by international standards that maintain specifications for the materials and processes involved in aircraft construction. Aircraft design requires materials that allow to produce cost-effective, light-weight, durable structures, which are tolerant to damage at temperatures ranging from sub-zero to elevated [14]. Establishing performance goals is fundamental to the safe handling of an aircraft, but is also (indirectly) related to economic aspects of commercial aviation.

Regarding mechanical performance, the most relevant features in materials selection for aircraft are:

- **High strength.** Strength is the ability to withstand an applied load without failure or irreversible deformation (called plastic deformation). Applied loads may be axial (tensile or compressive) or rotational (shear), and will induce stresses that cause deformation of the material in various manners, including complete breakage of the part.
- **High rigidity.** Rigidity is the extent to which a solid is able to resist buckling in response to an applied force. The complementary concept is flexibility: the more flexible an object is, the less stiff it is. Buckling depends not only on the physical properties of the structural material but also on thickness and shape.
- **High toughness.** Toughness is the ability of a material to absorb energy and plastically deform without fracturing.
- **High resistance to fatigue.** Fatigue is the weakening of a material caused by repeatedly applied loads. This results in progressive and localized structural damage that occurs when a material is subjected to repeated loading and unloading. Microscopic cracks begin to form, and will propagate until the structure fractures. The shape of the structure significantly affects fatigue life: square holes or sharp corners lead to elevated local stresses where fatigue cracks can initiate; round holes and smooth transitions increase fatigue strength of the structure. (Breaking a paper clip is a fatigue example

most people can relate to: while a clip cannot be broken by pulling, this can be easily achieved by a cyclic load applied back and forth).

Some properties other than mechanical are also extremely important in aircraft construction:

- Low density. Density is the materials property that correlates with the weight of the aircraft structure (Figure 13). The density (ρ) of a substance is its mass (m) per unit volume (V) (1). Different materials usually have different densities. Density does not depend on size or shape of the part, but varies with temperature, pressure and composition.

$$\boldsymbol{\rho} = \frac{\boldsymbol{m}}{\boldsymbol{V}} \text{ (kg/m}^3 \text{ in SI units)} \qquad (1)$$

Density is particularly important in aircraft construction because weight minimization indirectly generates lift-induced drag (§ Module 3), leading to better aircraft efficiency. For a given payload, a lighter airframe generates a lower drag. Minimizing weight can be achieved through the airframe's configuration, materials selection and construction methods. To obtain a longer range, a larger fuel fraction of the maximum take-off weight is needed, adversely affecting efficiency. Jet fuel cost and emissions reduction are thus reduced in lighter aircraft.

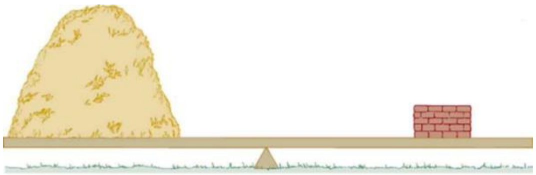


Figure 13. Illustration of the relation between mass and volume of objects.

- **High resistance to corrosion.** Corrosion is a natural process which converts a metal to a more chemically-stable form, such as its oxide, hydroxide, or sulphide. It leads to the gradual destruction of the materials by chemical and/or electrochemical reaction with the environment. Rusting, the formation of iron oxides, is a well-known example of electrochemical corrosion. Many alloys corrode merely from exposure to moisture in air, but the process can be strongly affected by exposure to specific substances (such as acid rain or combustion gases). Corrosion can extend across a wide area, corroding the all surface more or less uniformly, but some corrosion mechanisms are less visible and less predictable and corrosion can concentrate locally to form pits or cracks.
- **High resistance to sub-zero to elevated temperatures.** The standard temperature lapse rate is 2°C for every 1,000 feet of altitude. In as much, at a typical cruising flight altitude of 35,000 feet (11000 m), the outside temperature is below -51° C. On the other hand, several locations on Earth can reach air temperatures well above 50 ºC (for example in the Death Valley in the USA, Libya, Ethiopia, Sudan, Iran, Israel, Mali, and Tunisia), affecting taxi and take-off or landing. The used aircraft materials must not only resist such temperature range, but also to be dimensionally compatible within it. This is to say, materials within an aircraft structure must present similar dimensional expansion with temperature increase (and similar contraction with temperature decrease), and thermal expansion must be taken into consideration when designing airframes: if a part

is placed where it cannot expand freely, a huge force is exerted upon neighbouring regions due to thermal expansion, eventually leading to cracking.

2.3 MATERIALS FOR AIRCRAFT

2.3.1 Wood

The airplane was the first major technology where weight was an overriding concern, being crucial to the basic functioning of the associated technologies [15]. Because of the unique nature of an aircraft (namely that it must entirely operate against the force of gravity), power-to-weight and strength-to-weight ratios are chief design parameters. The basic structural design of the first generation of powered, heavier-than-air flying machines standard by the outbreak of World War I consisted of spar-and-rib wing (Figure 14), wire-braced, box-girder fuselage, wire-trussed, strut-supported biplane wing cell, sealed fabric skin over the airframe, and two-wheel fixed landing gear [15]. At the beginning of aviation history, wood was the only available viable material from which to build a flying machine with supporting surfaces light enough to fly while strong enough to withstand flight loads [15]. Other factors that made wood the material of choice were the ease with which it could be fashioned and repaired, and its low cost. Figure 15 summarises the highlights of wooden aircraft production: there was a steady rise of aircraft from 1903; from 1914 the demand on aircraft step increased because of the beginning of WWI; a second big increase was caused by the increasing use of aircraft for the means of transport [16]. Wood's success as aircraft material benefited from the slow development of lightweight high strength alloys and from the slow development of structural alloys with high corrosion resistance [15]. When aluminium alloys became more readily available at reasonable prices, the production of metal airplanes grew, and around 1935 the production of wooden airplanes was significantly reduced (Figure 15) [16]. In the mid-to-late 1930s wood aircraft were supplanted by sturdy all-metal monoplanes, because of improved power plants and because manufacturers were able to take advantage of lightweight metals as the primary building material [15]. A last increase of wooden airplanes was caused by WWII: metal was needed for weapons, so the demand for wooden airplane rose [16]. After the Second World War only small airplanes and gliders were built out of wood and with a steady decrease until 1970 also these sectors were substituted [16]. Since then wood is only used for niche products as for interior fitting at business jets but not for structural parts [16]. Only a limited number of wood aircraft are produced nowadays, mostly by their owners and for education or recreation purposes. However many aircraft in which wood is the primary structural material still exist and operate, including some from the1930s.

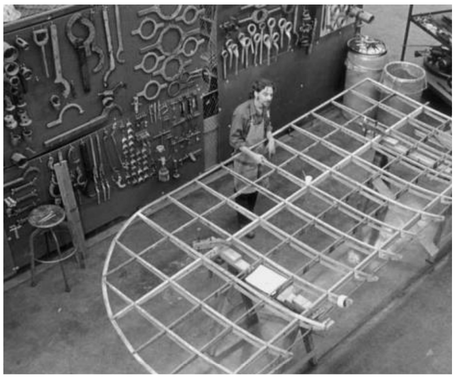


Figure 14. Standard spar-and-rib wing structure of the first generation of wooden airplanes.

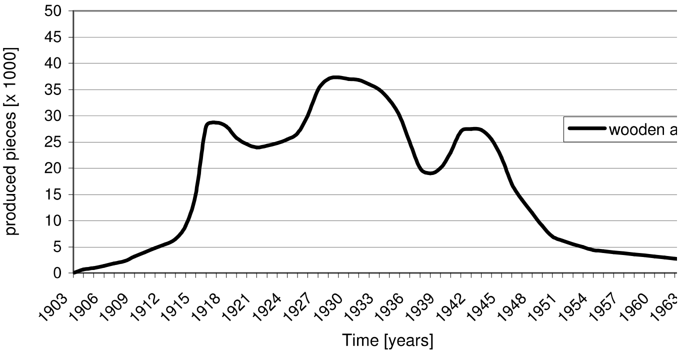


Figure 15. Development of wooden aircraft up to 1970 [16].

2.3.2 Aluminium

Aluminium is the most common metallic element in planet Earth. Aluminium is commonly alloyed with small quantities of magnesium, copper, lithium, silicon, tin, magnesium and/or zinc (

Table 5), and can be formed by plastic deformation (wrought alloys) or by melting and mould cast (casting alloys). Aeronautic construction almost exclusively uses wrought aluminium alloys.

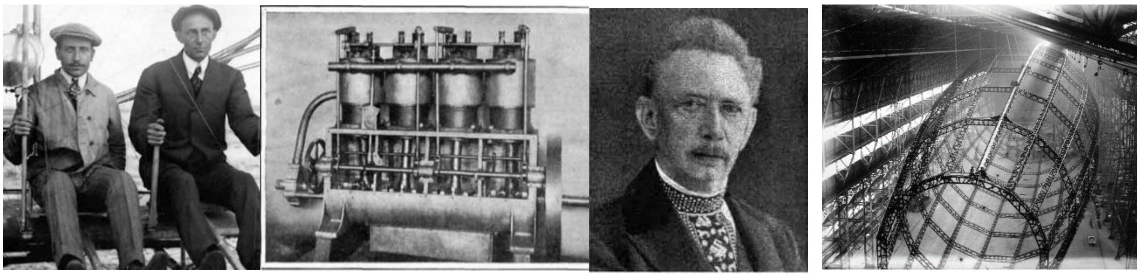
Aluminium alloys have density value around 2.70 g/cm^3, which is approximately one-third of that of steels. This results in exceptional tensile strength-to-weight ratio and makes them extensively used in airspace applications [11]. By using aluminium alloys, the aircraft skin can be made thicker (to help reduce buckling and fatigue) without adding as much weight as if it was made of steel. Also, aluminium alloys don't corrode as readily as steel. However, aluminium melting temperature is 660 ºC, thus the maximum allowed service temperature is quite low. Because aluminium and aluminium alloys lose their strength at high temperatures, they cannot be used in the skin surface of airplanes that fly faster than twice the speed of sound (these surfaces become very hot because of heat dissipation on friction). The Wright brothers' engine for the Wright Flyer I (respectively Figure 16 a and Figure 16 b) consisted of four horizontal inline cylinders fit into a cast aluminium crankcase that extended outward to form a water jacket around the cylinder barrels. This marked the first time this breakthrough material was used in aircraft construction. Lightweight aluminium became essential in aircraft design development and remains a major construction material for all types of aircraft.

Strong aluminium alloys date from the accidental discovery of the phenomenon of age-hardening by Alfred Wilm (Figure 16 c) in Berlin in 1906 [14]. His work led to the development of the wrought alloy known as Duraluminium (Al.3.5Cu-0.5Mg-0.5Mn), which was quickly adopted in Germany for structural sections of Zeppelin airships (Figure 16 d), and for the Junkers F13 aircraft that first flew in 1919 [14]. Since then, wrought aluminium alloys have been the major material for aircraft construction. Aircraft evolution has in turn provided much stimulus for the development of new improved alloys [14].

Table 5. Nomenclature of aluminium alloys, adapted from [11].

Designation*		Main alloying element	Purpose of alloying element
casting alloys	wrought alloys		
1xx.x	1xxx	aluminium > 99 %	
2xx.x	2xxx	copper	strength and machinability
3xx.x	3xxx	manganese	corrosion resistance and machinability
4xx.x	4xxx	silicon or silicon+magnesium	lowering of melting temperature
5xx.x	5xxx	magnesium	hardness and corrosion resistance
6xx.x	6xxx	magnesium+silicon	heat treatability and formability
7xx.x	7xxx	magnesium+zinc	stress corrosion resistance
8xx.x	8xxx	lithium, tin, boron or zircon	

*Wrought alloys are represented by a four-digit number, where the first digit represents the main alloying element, the second shows modifications, and the third and fourth stand for the decimal percentage of aluminium concentration. Casting alloys distinguish by the presence of a decimal point between the third and fourth digit.



(a) (b) (c) (d)

Figure 16. The Wright brothers (a) soon understood the importance of minimizing aircraft weight, using an aluminium alloy to manufacture the engine of the Wright Flyer I (b). Strong aluminium alloys were first developed by the German metallurgist Alfred Wilm (c), and readily adopted for structural sections of Zeppelin airships (d).

Several other alloys are used in aircraft construction besides aluminium:

Steels. Steels are the most ubiquitous and versatile metals in contemporary society [11]. Although they can be up to four times stronger and three times stiffer than aluminium, they are also three times denser (Table 3). This makes their use in aeronautics limited to critical components, such as the landing gear, where strength and hardness are especially important. It has also been used for the skin of some high-speed airplanes, because it holds its strength at higher temperatures better than aluminium.

Titanium alloys, on their turn, present a uniquely high strength-to-weight ratio over a wide temperature range [14] (Figure 17), and resist corrosion better than steel or aluminium. Although titanium is expensive, those characteristics have led to its greater use in modern aircraft (mainly the Ti6Al4V alloy). Titanium alloys were introduced in compressor blades and disks in aircraft gas turbines as early as 1952 [14]. Nowadays their major application is still aircraft gas turbines (especially in fan-jets), making up to 25-30% of the weight of most modern engines, and including blades, disks and sheet for casings and ducting [14]. In commercial aircraft the use of titanium alloys in other structural members has been developing slowly, because of their high cost compared to aluminium alloys. It now reaches approximately 9 % [14], concerning many specific purposes that include hydraulic tubing, and kitchen and toilet floor, where high corrosion resistance is required. Much greater use is made of titanium alloys in military aircraft (35-50 % in modern fighters), which may operate temperatures that exceed the capability of aluminium alloys.

Nickel superalloys. The term "superalloy" is applied to alloys with outstanding high temperature strength and oxidation resistance. Nickel superalloys are essential to the aircraft industry, where they are used to build the hottest parts of gas turbines for aircraft engines, although having a density value almost 3.5 times higher than aluminium and being extremely expensive [17]. Nickel-based superalloys may contain alloying additions of chromium, cobalt, aluminium, titanium, rhenium, ruthenium and other elements. Components are produced by carefully controlled solidification in order to get an optimum directionally solidified structure or a single crystal structure. As a result, components fabricated from nickel superalloys can reach strength values at 1000°C which exceed that of ordinary steels at room temperature (Figure 17) [17].

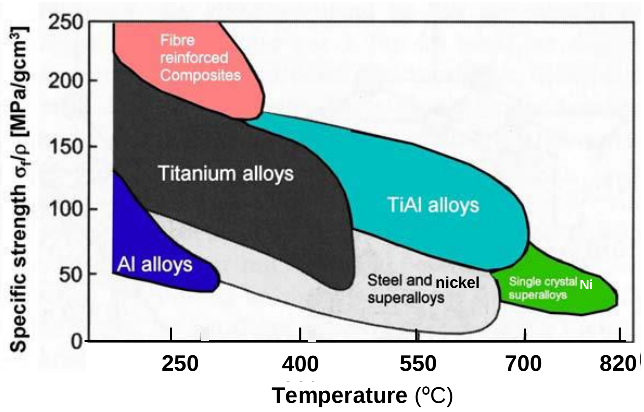


Figure 17. Specific strength (ratio of material strength to relative density) variation with temperature for aircraft structural materials (σf: yield strength for metals and tensile strength for composites; ρ: material density), adapted from [18].

2.3.3 Synthetic plastics

Plastics are polymeric materials that contain additional substances (additives) aimed to improve performance and/or reduce costs. Typical additives include:

- **Stabilizers**: prolong polymer lifetime by suppressing degradation resulting from UV-light and oxidation.
- **Fillers**: improve performance or reduce costs. Most fillers are inert and inexpensive materials, making products cheaper by weight, for example chalk, starch, cellulose, wood flour, and zinc oxide.
- **Plasticizers**: they are often the most abundant additives, blended into plastics to increase plasticity or decrease viscosity of the material.
- **Colorants**: chemical compounds in the form of dyes and pigments used to colour plastic.
- **Flame retardants**.

PLASTIC = POLYMER + ADDITIVES

The naming of polymers is complex and sometimes confusing [11], yet plastics can be classified based on commercial ranges (Table 6).

Table 6. Commercial classification of plastics.

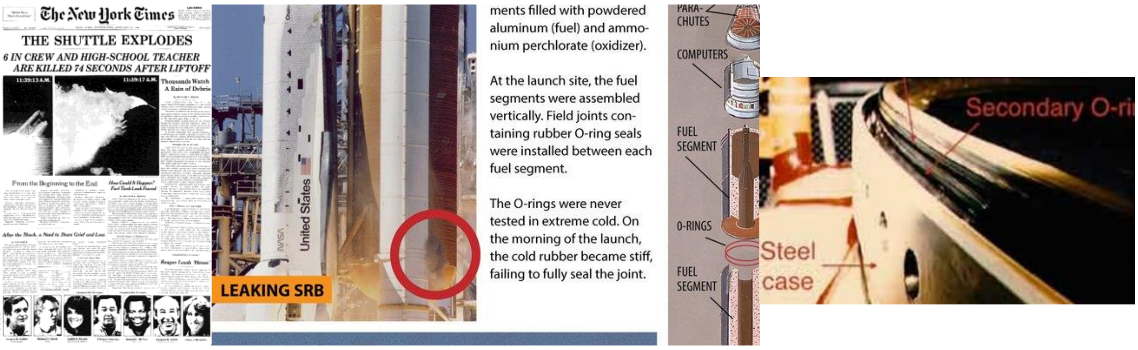
Commercial classification	Description	example
Commodity polymers	general use polymers simple composition mass production low added value	acrylics, polyamides, polyesters, polyolefins, rayon, PVC
Quasi-commodity polymers	specific use polymers medium scale production medium added value differentiated performance	Elastomers, polyurethanes, PET, PA, PU, PC
Speciality polymers	high-performance polymers dedicated composition custom applications high added value	POM, PTFE, PBT, PPS, liquid crystals

Because polymers have intrinsically low mechanical performance (low mechanical strength, low rigidity, low hardness), their role as monolithic materials in aircraft construction is limited to non-critical applications. The main areas of application include adhesives, coatings, foams, seals, elastomers and plastics components [19]. In each case, service conditions have to be taken in consideration as aircraft components may be subjected to all extremes from the arctic to the tropics, from sea level to eight or nine miles high, and often withstand unusual conditions such as rain erosion or lightning strike [19]. Different applications require different properties. Polymers exhibit a broad variety of mechanical properties, but are characterized by a physical property that is unique to polymers and glasses, the glass transition temperature [11]. Glass transition temperature (Tg) (Table 7) in fact determines the useful service temperature range of polymers and hence its application. This is because below Tg the polymer is glasslike and brittle, and above Tg the polymer becomes rubbery and flexible [11].

Table 7. Melting and glass transition temperature of some common polymeric materials, adapted from [11].

Polymer	Glass transition temperature (ºC)	Melting temperature (ºC)
Polyethylene (low density)	-110	115
Polytetrafluorethylene (ex: Teflon®)	-97	327
Polyethylene (low density)	-90	137
Polypropylene	-18	175
Nylon 6,6	57	265
Polyester (PET)	69	265
Polyvinyl chloride	87	212
Polystyrene	100	240
Polyisoprene rubber	-72	n/a

The explosion that destroyed the space shuttle Challenger in 1986 sadly illustrates this concept (Figure 18), since it resulted from a rubber o-ring that became glassy when the air temperature dropped below the glass transition temperature of the polymer. Instead of forming a tight seal, the now glassy air-ring form a breach in the solid rocket booster joint, allowing pressurized burning gas from the motor to reach the outside and impinge upon the external fuel tank, causing the shuttle to explode [11].



The New York Times

THE SHUTTLE EXPLODES

6 IN CREW AND HIGH-SCHOOL TEACHER ARE KILLED 74 SECONDS AFTER LIFTOFF

Thousands Watch A Rain of Debris

From the Beginning to the End

How Could It Happen? Fuel Tank Leak Feared

After the Shock, a Need to Share Grief and Loss

ments filled with powdered aluminum (fuel) and ammonium perchlorate (oxidizer).

At the launch site, the fuel segments were assembled vertically. Field joints containing rubber O-ring seals were installed between each fuel segment.

The O-rings were never tested in extreme cold. On the morning of the launch, the cold rubber became stiff, failing to fully seal the joint.

Figure 18. The Challenger disaster, in 1986.

Overall, the use of lightweight materials in aerospace power and propulsion components can lead to significant reductions in vehicle weight and improvements in performance and efficiency. Polymeric materials are well suited for many of these applications, but improvements in durability and performance are required for their successful use in critical components.

Polymers are however a very important constituents in high-performance composites, toiling as matrix material and/or as fibre reinforcement material.

2.3.4 Composites

In aerospace applications, where strength is required but weight is a significant factor, laminate composites and sandwich composites are mostly used [11]. Laminates consist of layers of sheets with polymeric matrix reinforced with strong ceramic or polymeric embedded fibres. Carbon fibres (Figure 19 a) to c)) in an epoxy resin matrix is the most widely used composite material in aircraft structures and components (although some others are gaining way), and graphite-epoxy composites (Figure 19 d)) are about as strong as aluminium and weighs about half as much.
Carbon fibres are weaved and imbedded in resin, forming a pre-impregnated (or prepreg, Figure 19 e)) intermediate product. These pre-impregnated thin sheets are supplied to the aircraft construction industry, where they are stacked, moulded to the desired shape (Figure 19 f)) and consolidated (Figure 19 g)). Stacking can be carried out in different ways to meet specific strength or stiffness needs of a critical part, although usually layering is carried out with fibres aligned in alternate directions (Figure 19 h)).

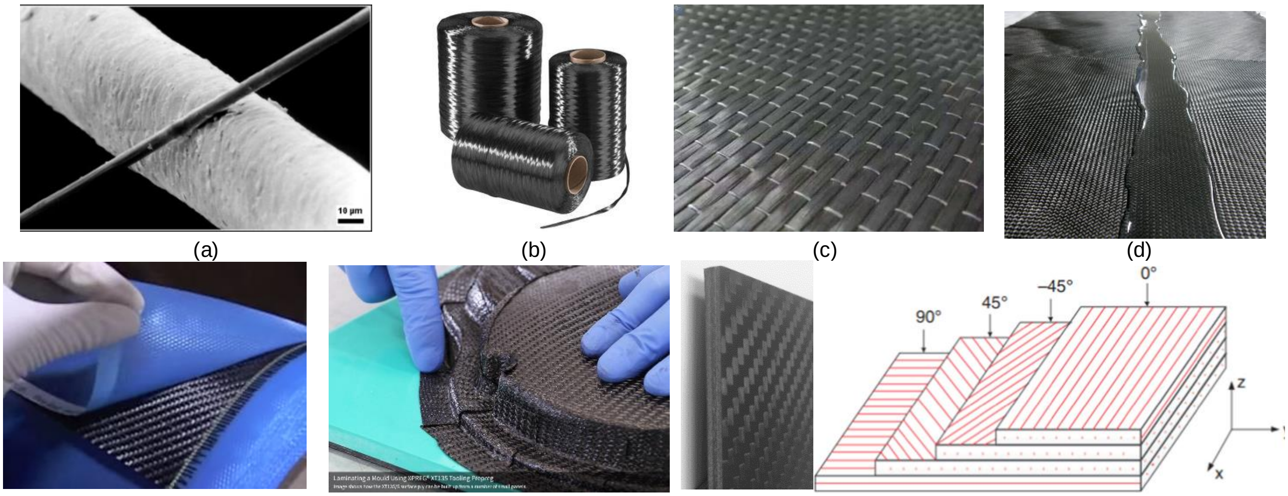


Figure 19. Laminate fibre-reinforced polymer-matrix composites: (a) carbon filament with 6 µm diameter (on top) compared to human hair; (b) filaments are roved into carbon fibre rolls that are then used to weave (c) carbon fibre cloths. For aircraft construction cloths are (d) previously impregnated with epoxy resin, forming (e) prepreg sheets that are later (f) stacked, moulded and (g) consolidated. (h) Stacking is usually carried out so that fibres are aligned in alternate directions in adjacent layers [20].

Sandwich composites are more complex stacking patterns, composed of strong face sheets on the outer ends of the composite, with a low-density material sandwiched inside (Figure 20a). Face sheets are responsible for handling most of the applied loads and stresses, and can be made from titanium alloys, aluminium alloys or fibre-reinforced composite laminates produced as described above (Figure 19). In-between the face sheets a low-density material is sandwiched, aiming to add stiffness and resistance to perpendicular stresses. These inner materials are often shaped in honeycomb structure, and in airspace applications they usually consist of aluminium alloy (Figure 20b) or high-performance polymer (Nomex® (Figure 20c), for example). The main concept of the sandwich panel (Figure 20d) is that exterior surfaces transfer loads caused by bending (flexural load and compression), while the core transfers load caused by shearing.

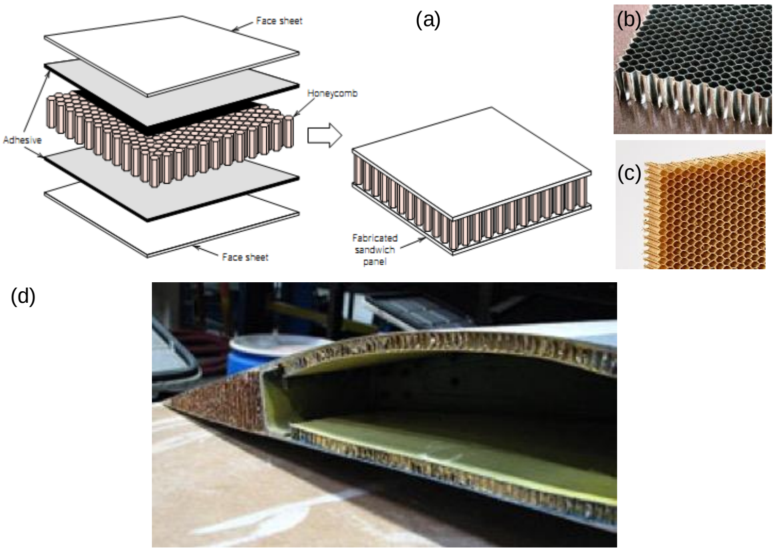


Figure 20. Sandwich composites: face-sheet and honeycomb stacking [11] (a), rendering a sandwich panel (b). Honeycomb core: (c) aluminium honeycomb; (d) Nomex® polymer honeycomb. (e) Example of sandwich panel application in the Boeing 747 fore flap.

Laminates and sandwich composites are called **structural composites**, because they present sufficiently high values of mechanical properties such as mechanical strength, stiffness and resistance to fatigue to be used in critical applications. Additionally, composites have very low density (1/3 to 1/2 that of aluminium) and high corrosion resistance, making them especially appropriate for aircraft application (Table 8).

Table 8. Typical aircraft fibre-reinforced structural composites [21].

Composite	structure	typical application
Laminate	sheets shells beams complex shapes	wing skin, tail skin fuselage sections spars/ribs aerofoils
Sandwich	panels	control surfaces, floor sections

Composite materials have been used in aircraft since World War II. Fiberglass was first used in aviation by Boeing in its passenger jet in the 1950s. Over the years, they have become ever more popular, and today can be found in many kinds of airplanes, as well as gliders. Composite materials and have allowed aeronautical engineers to overcome obstacles met when using the materials individually and to design structures with unique properties. Each generation of new aircraft built by the main constructers has an increased percentage of composite material usage, aiming for the design of high-performance, economical aircraft, with reduced fuel consumption, improved efficiency and reduced direct operating costs.

3 BASICS OF FLIGHT

3.1 AIRCRAFT COMPONENTS

Although airplanes are designed for a variety of purposes, most of them have the same major components (Figure 21). The overall characteristics are largely determined by the original design objectives. Most airplane structures include a fuselage, wings, empennage (vertical and horizontal stabilizers), landing gear and powerplant [22].

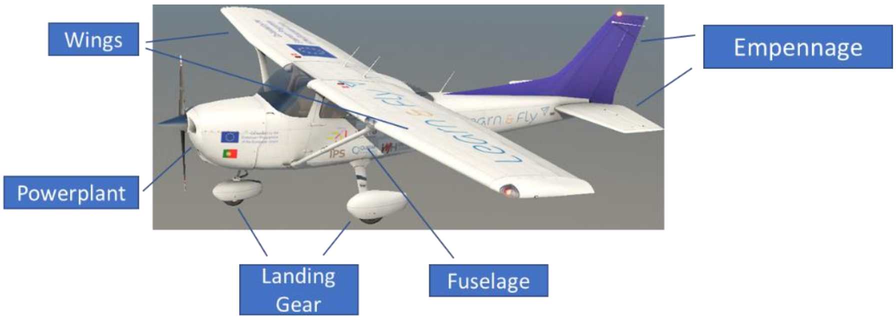


Figure 21. Major components of an aircraft

Fuselage. The fuselage (Figure 22) is the central body of an airplane and is designed to accommodate the crew, passengers, and cargo. It also provides the structural connection for the wings, tail assembly and powerplant for single engine.

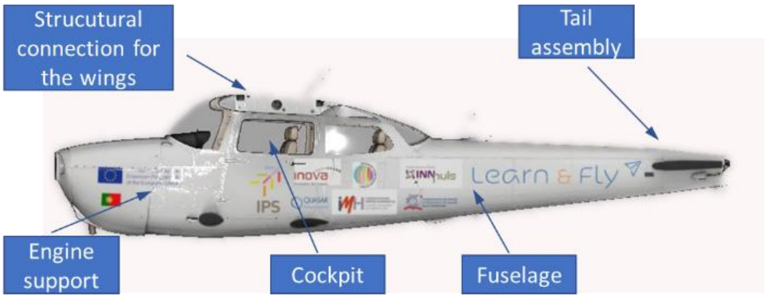


Figure 22. Fuselage

Wings. The wings are airfoils attached to each side of the fuselage and are the main lifting surfaces that support the airplane in flight. There are numerous wing shapes, sizes and profiles depending on the intended purpose of an airplane. However, each must meet the requirements needs regarding the expected performance for the airplane's flight purpose.

Wings may be attached at the top, middle or lower portion of the fuselage. These designs are referred to as high-, mid- and low-wing, respectively (Figure 23).

Figure 23. High-wing (left), mid-wing (center) and low-wing (right)

The number of wings can also vary. Airplanes with a single set of wings are referred to as monoplanes, while those with two sets are called biplanes (Figure 24).

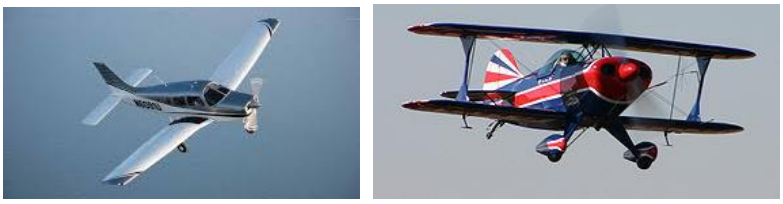


Figure 24. Monoplane (left) and Biplane (right)

Many high-wing airplanes have external braces or wing struts, which transmit the flight and landing loads through the struts to the main fuselage structure. Since the wing struts are usually attached approximately halfway out on the wing, this type of wing structure is called semi-cantilever. A few high-wing and most low-wing airplanes have a full cantilever wing designed to carry the loads without external struts (Figure 25).

Figure 25. Semi-cantilever wing (left) and full cantilever wing (right)

The principal structural parts of the wing are spars (normally front and rear) and ribs (Figure 26). These are reinforced by trusses, tubing or other devices, including the skin. The wing ribs determine the shape and thickness of the wing (airfoil). In most modern airplanes, the fuel tanks either are an integral part of the wing's structure, or consist of flexible containers mounted inside of the wing.

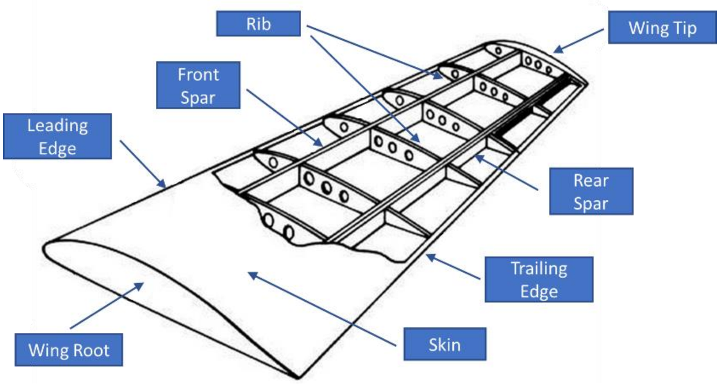


Figure 26. Wing components

Empennage. The correct name for the tail section of an airplane is empennage (Figure 27). The empennage includes the entire tail group, consisting of fixed surfaces such as the vertical stabilizer and the horizontal stabilizer and the movable surfaces (include the rudder, the elevator, and one or more trim tabs).

Figure 27. Empennage Components

Landing Gear. The landing gear is the principal support of the airplane when parked, taxiing, taking off, or landing. The landing gear consists of three wheels: two main wheels and a third wheel positioned either at the front or rear of the airplane (Figure 28). Landing gear with a rear mounted wheel is called conventional landing gear. Airplanes with conventional landing gear are sometimes referred to as tailwheel airplanes. When the third wheel is located on the nose, it is called a nosewheel, and the design is referred to as a tricycle gear.

Figure 28. Conventional landing gear (left) and tricycle gear (right)

A steerable nosewheel or tailwheel permits the airplane to be controlled throughout all operations while on the ground. Most aircraft are steered by moving the rudder pedals, whether nosewheel or tailwheel. Additionally, some aircraft are steered by differential braking.

The Powerplant. The powerplant usually includes both the engine and the propeller (Figure 29). The primary function of the engine is to provide the power to turn the propeller. The engine is covered by a cowling, or in the case of some airplanes, surrounded by a nacelle. The purpose of the cowling or nacelle is to streamline the flow of air around the engine and to help cool the engine by ducting air around the cylinders. The propeller, mounted on the front of the engine, translates the rotating force of the engine into a forward acting force called thrust that helps move the airplane through the air.

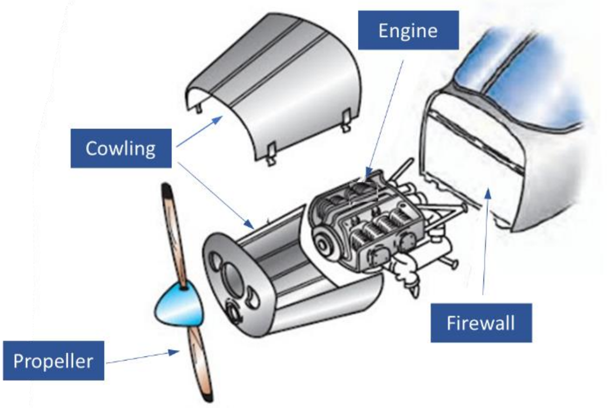


Figure 29. Powerplant (engine and propeller)

3.2 AERODYNAMICS OF FLIGHT

Thrust, drag, lift, and weight are forces that act upon all aircraft in flight. Understanding how these forces work and knowing how to control them with the use of power and flight controls are essential to flight. This section discusses the aerodynamics of flight—how design, weight, load factors, and gravity affect an aircraft during flight maneuvers [23,24]. The four forces acting on an aircraft in straight-and-level flight (cruise speed) are thrust, drag, lift, and weight (Figure 30).

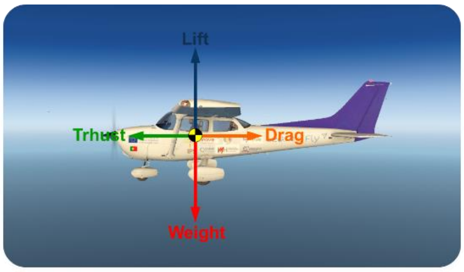


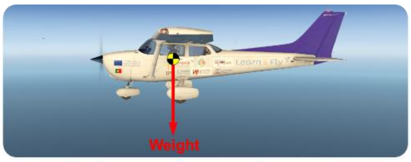
Figure 30. Relationship of forces acting on an airplane

These forces are defined as follows:

- Thrust — is the force which moves an aircraft through the air. It opposes or overcomes the force of drag. Thrust is generated by the engines of the aircraft through some kind of propulsion system. As a general rule, it acts parallel to the longitudinal axis.

- Drag — a rearward, retarding force caused by disruption of airflow by the wing, fuselage and other protruding objects. Drag opposes thrust, and acts rearward parallel to the relative wind.

- Weight — the combined load of the aircraft itself, the crew, the fuel, and the cargo or baggage. Weight pulls the aircraft downward because of the force of gravity. It opposes lift, and acts vertically downward through the aircraft's center of gravity (CG).



- Lift — opposes the downward force of weight, is produced by the dynamic effect of the air acting on the airfoil, and acts perpendicular to the flightpath through the center of lift.

Airfoil. The airfoil is the surface designed to obtain lift from the air through which it moves [25]. The chord, the thickness and the shape (upper surface and lower surface) of the airfoil is fundamental for generate lift. Usually the upper surface has a more pronounced curvature (camber) than the lower surface, Figure 31. It is this difference in the curvature surfaces that generates lift when a fluid (air) turned the airfoil.

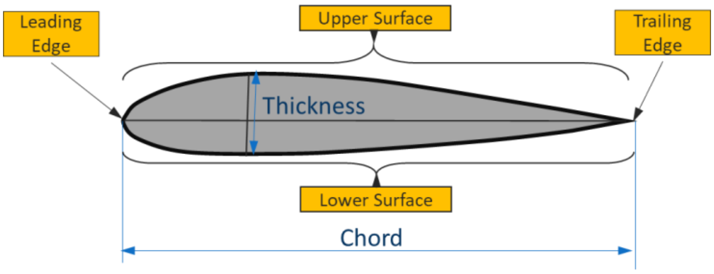


Figure 31. Airfoil main dimensions

Bernoulli's principle. Bernoulli's principle is used to explain the generation of the lift force. It can be derived from the principle of conservation of energy, which states that in steady flow, the sum of all forms of energy in a fluid along a streamline is the same at all points on that streamline:

$$E_c + E_p = k \tag{2}$$

Where

E_C - kinetic energy

E_P - potential energy

k - constant

Due to the curvature of the upper surface of the airfoil, the air speed increases (kinetic energy) and the pressure (potential energy) has to decrease. A lower pressure is created at the upper surface. The difference of pressures between the upper surface and the lower surface are related with the lift force (Figure 32 and Figure 33).

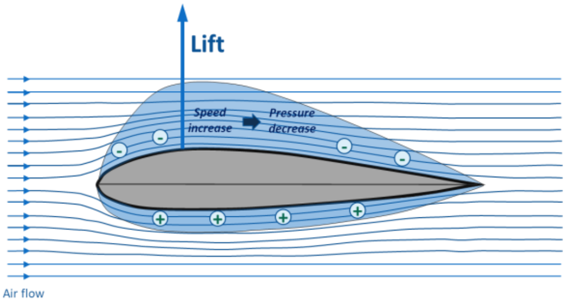


Figure 32. The lift generation in an airfoil

Lift Equation

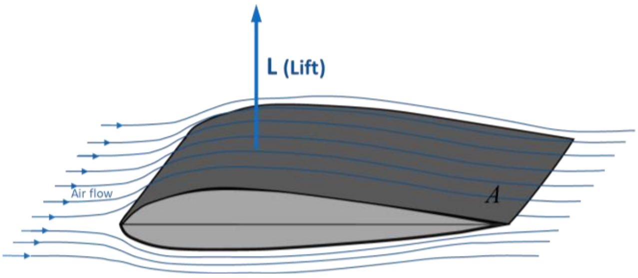


Figure 33. Wing specimen for Lift calculation

The lift force L of an airfoil can be achieved by the equation:

$$L = \frac{1}{2}\rho v^2 A c_L \tag{3}$$

Where

L – Lift force (N – Newton)
ρ – Air density (1.225 kg/m^3 at 15°C and 1013 hPa)
v – Velocity of the air flow (m/s)
A – Wing area surface (m^2)
C_L– Lift Coefficient (dimensionless)

Lift Coefficient C_L. The lift coefficient C_L is obtained experimentally. It depends on the airfoil shape and the angle of attack α (Figure 34 and Figure 35). The angle of attack α (also known as AoA) is the angle between airfoil chord and the air flow direction.

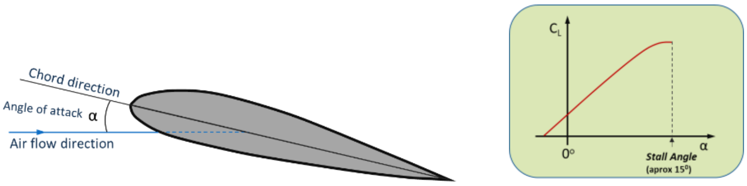


Figure 34. Angle of attack (AoA) and C_L function of the AoA

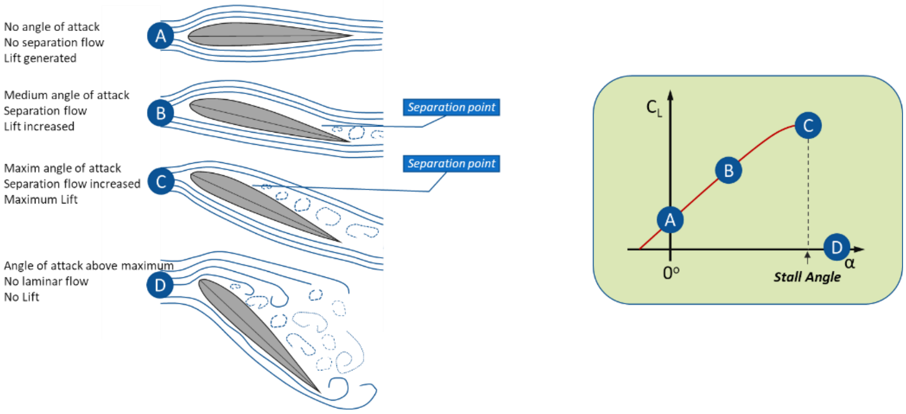


Figure 35. Max angle of attack, stall angle

Drag force. Drag is the aerodynamic force that opposes an aircraft's motion through the air. Drag is generated by every part of the airplane. Drag acts in a direction that is opposite to the motion of the aircraft. The drag equation is similar to the lift equation and given by:

$$D = \frac{1}{2}\rho v^2 A c_D \tag{4}$$

Where

D – Drag force (N - Newton)

ρ – Air density (1.225 kg/m^3 at 15°C and 1013 hPa)

v – Velocity of the air flow (m/s)

A – Wing area surface (m^2)

C_D– Drag Coefficient (dimensionless)

3.3 AXES OF AIRCRAFT MOTION

Whenever an airplane changes its flight attitude or position in flight, it rotates about one or more of three axes, which are imaginary lines that passthrough the airplane's center of gravity. The axes of an airplane can be considered as imaginary axles around which the airplane turns. The axis, which extends lengthwise through the fuselage from the nose to the tail, is the *longitudinal axis*. The axis, which extends crosswise from wingtip to wingtip, is the *lateral axis*. The axis, which passes vertically through the center of gravity, is the *vertical axis* (Figure 36).

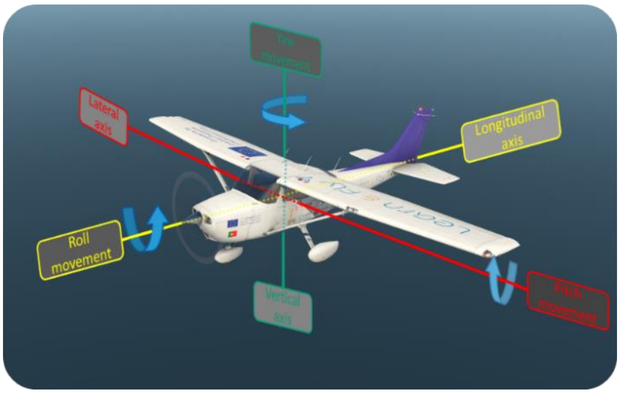
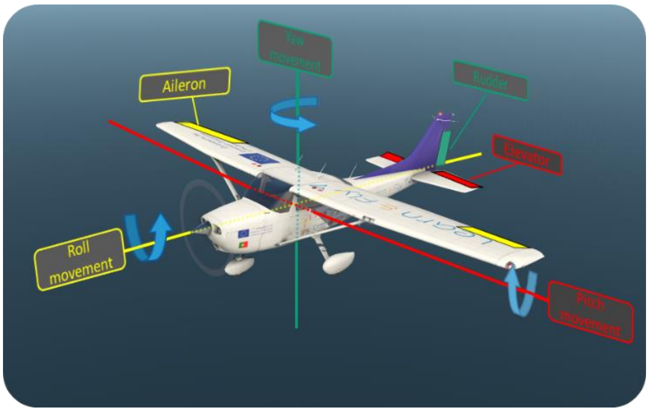


Figure 36. Three axis of an aircraft

Axis	Movement
Lateral	Pitch
Longitudinal	Roll
Vertical	Yaw

In light of the adoption of nautical terms [26], the motion about the airplane's longitudinal axis is called "roll"; motion about its lateral axis is referred to as "pitch." Finally, an airplane moves about its vertical axis in a motion, which is termed "yaw"—that is, a horizontal (left and right) movement of the airplane's nose.



Movement	Surface Control
Pitch	Elevator
Roll	Aileron
Yaw	Rudder

Figure 37. Flight control movements of an aircraft

Aircraft flight control surfaces are aerodynamic devices allowing a pilot to adjust and control the aircraft's flight attitude around the three axes (Figure 37). To control the pitch movement the pilot use the elevators surface. If the pilot pulls back the stick, the elevator moves up and the aircraft rotate around the transversal axis and the aircraft climb (Figure 38).

Figure 38. Elevator surface control position climb up

If the pilot pull push the stick, the elevator moves down and the aircraft rotate around the transversal axis and the aircraft descend (Figure 39).

Figure 39. Elevator surface control position climb down

When the pilot wants to right roll bank, moves the stick to right. The left aileron goes down and right aileron goes up. As a result, the lift force on the left wing increase and on the right wing the lift force decreases. The aircraft rolls to the right (Figure 40).

Figure 40. Roll movement to the right

If the pilot wants to left roll bank, moves the stick to the left. The ailerons movement are showed on Figure 41. As a result, the lift force on the right wing increase and on the left wing the lift force decreases. The aircraft rolls to the left.

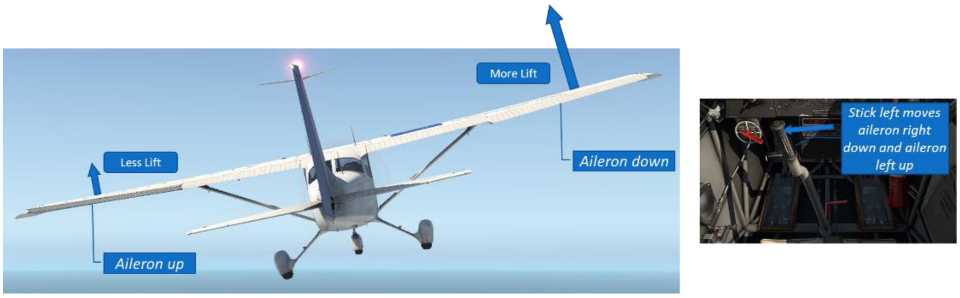


Figure 41. Roll movement to the left

When the pilot wants to rotate the aircraft around vertical axis (yaw movement) uses the pedals that are connected to the rudder. If he wants turn to left, he press the left pedal, the rudder goes left, push the tail to the right and the aircraft yaw to the left (Figure 42).

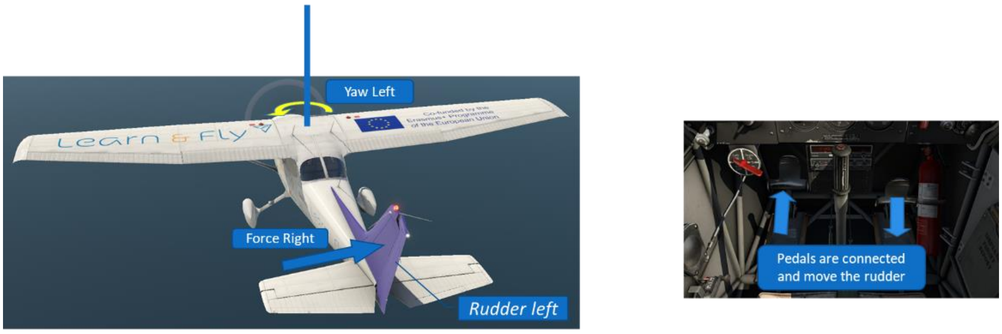


Figure 42. Left yaw movement

If the pilot wants to yaw right, he press the right pedal, the rudder goes right, push the tail to the left and the aircraft yaw to the right (Figure 43).

Figure 43. Right yaw movement

3.4 MASS AND BALANCE

Weight is a major factor in airplane construction and operation, and it demands respect from all pilots and particular diligence by all maintenance personnel. Excessive weight reduces the efficiency of an aircraft and the available safety margin if an emergency condition should arise [27].

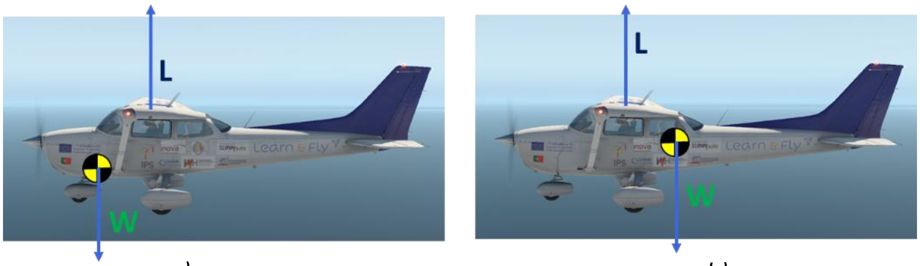
One important pre-flight consideration is the distribution of weight in the aircraft. Loading the aircraft so that the gross weight is less than the maximum allowable is not enough. This weight must be distributed to keep the Centre of Gravity (CG) within the limits (Figure 44).

Figure 44. Center of Gravity and a balanced aircraft

The Centre of Gravity of a body is the theoretical point at which the entire weight of that body is assumed to be concentrated. It should be noted that if the body is suspended by the CG, it will remain in balance. If the Centre of Gravity (CG) of an aircraft is completely out of limits, situations such as the shown in Figure 45 can occur.

Figure 45. Unbalanced aircraft on the ground

To ensure the aircraft is safe to fly, the CG must fall within specified limits, established by the aircraft manufacturer. Before flight, the pilots must ensure that the CG is within limits.



a) *b)*

Figure 46. Examples of unbalanced aircraft

If the CG lies too far forward, the aircraft tends to nose down (Figure 46 *a)*. If the CG is far behind, aircraft tends to nose up. (Figure 46 *b)*.

Before starting a flight, the pilot must calculate the total weight of the aircraft (aircraft empty weight, fuel, passengers and cargo) and whether the CG is within limits.

Figure 47. Several components for calculate the total weight

There are several forces to consider for the calculation of the CG (Figure 47). The Datum Line is a reference line to establish the arms of the several forces required to determine the CG. For example, in the Cessna as shown in the picture the Datum Line rest over firewall engine. On other aircrafts is usually the Datum Line match the leg nose landing gear. The position of the CG must be calculated and verified if are inside limits, and can be achieved by the equation:

$$CG = \frac{\sum Weight \times d}{\sum Weight} = \frac{W_1 d_1 + W_2 d_2 + W_3 d_3 + \cdots + W_n d_n}{W_1 + W_2 + W_3 + \cdots + W_n} \tag{6}$$

in which:

W… is the individual weight of each component (n components)

d is the distance from each weight to the datum line (n arms)

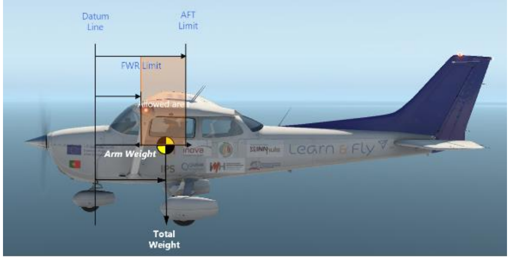


Figure 48. Forward and Afterward limits

The CG must always remain between the FWR (Forward) and AFT (Afterward) limits in order to operate the aircraft safely.

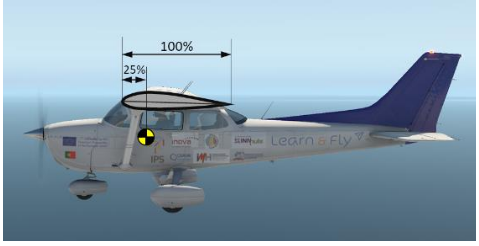


Figure 49. Optimal position for CG

The longitudinal location of the CG should be found at 25% of the chord wing.

The magnitude of the FWR limit is normally 10% of the wing chord and the AFT is 30%.

4 PROCESSES AND TECHNOLOGIES

4.1 INTRODUCTION

The processes and technologies proposed in the Learn&Fly Students Kit to build the glider for the challenge are close to traditional handcraft techniques used in the construction of model airplanes. They are explained step-by-step in the corresponding slides, allowing to fulfil the desired goal. However, they do not actually reflect the complex processes, the sophisticated equipment and the required facilities' specialization by which aerospace products are made, nor the huge challenges put forward by the complexity involved in design and manufacture of aerodynamic contour with weight control [28]. It was thus considered useful to give some insight into the industry's manufacturing strategies.

4.2 THE AEROSPACE INDUSTRY

The aerospace industry concerns the manufacturing strategies related to vehicular flight within and beyond Earth's atmosphere [7]. It is engaged in the research, development, and manufacture of manned and unmanned flight vehicles, including unpowered gliders and sailplanes, lighter-than-air craft (e.g. balloons and airships), heavier-than-air craft (both commercial and military aircraft), missiles and rockets, space launch vehicles, and spacecraft [7]. Also includes major flight-vehicle subsystems such as propulsion and avionics (aviation electronics) and key support systems necessary for the testing, operation, and maintenance of flight vehicles [7]. In addition, the industry is engaged in the fabrication of non-aerospace products and systems that make use of aerospace technology [7].

The product line of the aerospace industry is broad because its primary products, flight vehicles, require up to five millions of individual parts [7]. In addition, many support systems are needed to operate and maintain the vehicles. Military aircraft have the largest market share, followed by space systems and civil aircraft, while missiles and other unmanned aerial vehicles (UAV) are still modest groups [7]. The industry's customers range from private individuals to large corporations and commercial airlines, telecommunications companies, and military and other government agencies [7].

4.3 PROCESSES AND TECHNOLOGIES IN AIRCRAFT ENGINEERING

Aircraft and the processes by which they are made are complex, and involve specialized personnel and sophisticated equipment and facilities (the size of the products themselves demands massive structures to house their assembly) [7]. The development and productivity of the industry critically depends on substantial investment in research, while subsequent product development and the transition of new technologies to production through design and testing also involve numerous processes and practices [7].

4.3.1 Research

Technological progress is the basis for competitiveness and advancement in the aircraft industry. As a result, this industry is a world leader in advancing science and technology [7]. Because of the complexity of the end products, advances commonly require improvements across many technological disciplines, including materials science, electronics, automation and control, fluids mechanics, among many others. The world's aircraft industry undertakes research and development alone and in conjunction with governmental agencies and academia. The ultimate aim of the effort is the creation of flight vehicles more advanced than their predecessors [7].

Current focus of aircraft research includes [7]: weight reduction of aircraft structures, through ongoing research into composite materials and investigation of aluminium-lithium and other aluminium alloys; materials research for supersonic and hypersonic vehicles focused on high-temperature polymers, lightweight metals and high-temperature polymer-matrix composites; enhanced vision systems using video and infrared cameras or millimetre-wave radar technology to improve the all-weather operation of commercial aircraft; fly-by-light techniques that transmit commands through fibre-optic cables rather than electrically; increased vehicle lifetime predictability through the development of non-destructive evaluation techniques; and miniaturization of instruments, propulsion systems, power sources, and other components. Important research directions also include vehicle autonomy, microelectronic and microelectromechanical systems, modular architecture and multifunctional systems, and high-efficiency solar arrays [7].

4.3.2 Product development

The development process of aircraft differs between the military and commercial sectors. In the civil aircraft sector, manufacturers conduct detailed market studies to determine the need for new vehicle designs, then define specifications, announce to potential customers their intention to develop the new product, and solicit orders [29]. When sufficient orders are obtained from the launching customers, the program is officially initiated. The customers' engineers generally work together with the manufacturers to influence the final design to their specific needs [7]. Aircraft design is thus a compromise between many competing factors and constraints and accounts for existing design and market requirements to produce the best aircraft [29].

In the early years of aircraft design, designers used analytical theory to do the various engineering calculations that go into the design process along with a lot of experimentation. These calculations were labour-intensive and time-consuming. In the 1940s, ways to automate and simplify the calculation process and many relations and semi-empirical formulas were developed [29]. Even after simplification, the calculations continued to be extensive. With the invention of the computer, a majority of the calculations could be automated, but the lack of design visualization and the huge amount of experimentation involved kept the field of aircraft design stagnant, but the rise of programming languages, allowed engineers to write programs tailored to design an aircraft. Originally this was done with mainframe computers and used low-level programming languages; with the introduction of personal computers, design programs began employing a more user-friendly approach [29].

The design cycle of a new flight vehicle has changed radically since the 1980s because of new methods, tools (including computers), and guidelines available [7]. Traditionally, the cycle begins with a conceptual design of the overall product followed by the preliminary design, in which most or all subsystems take shape. Several iterations regarding stress analysis, aerodynamics and materials analysis must be carried out before a final design is achieved. Since not all production issues can be anticipated by designers and engineers, substantial design rework is common. Despite the apparent simplicity of the initial conceptual design phase, 70-80 % of the aircraft cost is determined in this stage. The use of the computer has fundamentally changed the development process and cost. All details, from the airframe to the electric subsystem, are stored in the computer and by creating 3D models (i.e., virtual flight vehicles) of prospective candidates based on the data sets entered the computer eliminates the requirement for full-size physical models (known as mock-ups) on which engineers verify design layouts [7]. By enabling rapid examination of several candidate configurations under the effect of flight conditions, it also replaces a portion of costly wind-tunnel testing [7]. (Wind-tunnel testing is a very important part of the development process in the aerospace industry: air is blown over a test section of an aircraft model, or over a test models of reduced scale, creating an effect comparable to flight at a selected Mach number). The computer has thus fundamentally changed the development process by permitting digital modelling and simulation as well as computer-aided design in conjunction with computer-aided manufacturing (CAD/CAM) [7] (§ Module 5).

The phase of prototype construction and testing follows [7,28]. A customary procedure is to build several test airplanes solely to verify the design. The structural integrity of the aircraft is evaluated in static and dynamic tests. Ground testing requires an array of facilities, including ovens for applying high temperatures to materials, acoustic chambers to permit study of the effect of high-frequency engine noise on structures, rigs for measuring landing impacts, and variable-frequency vibrators for investigations of vibration and utter characteristics of structures [7]. Test fixtures verify that the ultimate load factor called for in the design has been met or exceeded; for example, the wings may be loaded until they break. In dynamic or fatigue tests, the life of the aircraft is simulated in time-lapse fashion [7]. Thus an airplane may go through more than 100,000 equivalent “flight hours” before it is taken apart and examined completely in every detail. Tests are also conducted on auxiliary equipment. Structural and mechanical systems are tested in similar fashion to that described for aircraft structures, whereas electrical and electronic equipment is exhaustively checked by electronic testing. As the equipment is run through its performance cycle, monitors confirm or detect and isolate faults for correction. In many cases, complete systems are further checked in altitude chambers that simulate operating environments [7]. Engines are tested in a test cell capable of simulating flight conditions: to qualify for installation, a new engine undergoes several hundred hours of testing that embraces the entire intended range of speed, altitude and endurance capacity of the airplane; bird-strike is also simulated. Test engines are heavily instrumented, and the recorded data are transmitted to a computer for processing. After the test runs, the engines are completely disassembled and inspected. Flight testing is then necessary to validate the individual results, although modern procedures of computerized design and wind-tunnel testing are so thorough and extensive that the results of the flight-test phase rarely dictate major design changes [7].

Aircraft certification takes approximately one year, where all aircraft must demonstrate capabilities in numerous performance tests under all anticipated conditions, including emergency braking, stall trials, loss of engine thrust, and take-off and landing in extremely hot, cold, high-altitude, and low-altitude environments [7].

Once a civil aircraft has demonstrated its airworthiness in the flight certification program, it can enter regular service. The necessary certificate (called Type Certificate, TC)[2], is issued by the national authorities of the aircraft constructor’s country – the National Aviation Authority (NAA). In Europe the TC for Airbus aircraft are issued by the NAA-European Aviation Safety Agency (EASA); in the United States the TC for Boeing aircraft are issued by the NAA-Federal Aviation Administration (FAA) [7]. These certificates are required for any aircraft purchased within Europe or the United States, respectively, and serve throughout the world as the basis for

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[2] The *Chicago Convention on International Civil Aviation* established the *International Civil Aviation Organization* (ICAO) as the specialized agency of the United Nations in charged with coordinating and regulating international air travel [67], including establishing rules for aircraft registration and safety, and the rights of the signatories in relation to air travel. Virtually all countries (192 as of 2017) have signed the Chicago Convention, pledging to enforce that legislation. This is a guarantee that aircraft will be designed, manufactured and operated safely if run within the defined limits. The Chicago Convention also stipulated that each country has a National Aeronautical Authority (NAA) responsible for implementing and enforcing ICAO regulations [67].

certifying civil aircraft that are to enter service in those countries. Russia and China have certification processes largely modelled on American and European standards. The most significant aircraft suppliers from Brazil, Japan and Indonesia use American and European certification standards [7].

4.3.3 Manufacturing

Modern aircraft manufacture has been described as a craft process with a mass production mentality. In fact, large aircraft consist of the assembly of one to five million separate parts and each different type demands unique skills and manufacturing methods [7].

Historical context. Modern aerospace manufacturing processes evolved in the context of the historical development of aircraft vehicle design briefly summarised in (§ Module 1). The wood frames of aircraft through World War I required skilled woodworkers and their equipment, coupled with crafters (often women) who laced or sewed fabric to the frames. This skin was painted with acetone-based lacquers to tighten and toughen surfaces, thus factories had large brush or spray areas with natural or induced air circulation to enhance drying and dissipation of fumes [7]. At the same time, with the exception of the air-cooled engine designs developed by the Wright brothers, aircraft engine manufacturing was an extension of the production of liquid-cooled automobile motors requiring refined machining techniques for the cylinder head fins, which provided the extensive cooling surfaces needed.

The advent of metal airframes changed both the character of manufacturing processes and the skills required of production workers [7]. At first, only the wood framework of fuselages was replaced by tubular aluminium trusses connected with mechanical fasteners or welding; coverings were still sewn and glued fabric. In the mid 1930s, as thin rolled aluminium alloys became available, all-metal structures for fuselages and then wings became prevalent. Skilled craftsmen were required to operate the metalworking machines, and new emphasis was placed on riveting and welding and on hard tooling of fixtures to facilitate alignment and assembly. At the same time, the forging of landing-gear components and major structural fittings and the forming of sheet metal grew to resemble processes in the automobile industry. This affinity became particularly close as all-metal bombers and transports revolutionized airplanes manufacturing. It was not surprising, therefore, that the mass producers of automobiles and related equipment became manufacturers of military aircraft during WW II.

After the war, jet propulsion and other technical advances led to further changes in manufacturing techniques and processes [7]. Commercial air travelling required increased passenger capacity and bigger aircraft. This required in turn expanded facilities, and a community of structural subassembly contractors building wings, sections of fuselages and horizontal surfaces started to relieve some of the space and tooling needs of prime contractors. Nowadays, aircraft production programs incorporate a complete range of hardware and software from suppliers that operate as subcontractors to the prime contractor or systems integrator, covering the onboard equipment but also major elements of the airframe itself. Because of the extensive range of skills and facilities required, companies don’t build an entire flight vehicle [7].

Fabrication processes and technologies. Fabrication involves the manufacture of individual components that make up larger assemblies or end products. This activity encompasses the working of metals and the incorporation of electrical and electronic devices into processors, circuit boards, and subassemblies for the components of navigation, communication, and control systems [7]. Manufacturing in the aircraft industry crosses nearly all construction boundaries - for example, conventional machine shops for mechanical components, clean rooms for electronic parts, and unusually large final-assembly facilities for multi-hundred-ton aircraft [7].

Materials (§ Module 2) play an important role in the fabrication methods [7]. Most of the basic metal-fabrication methods have been employed since World War II [7]. Metals are cut, shaped, bored, bent, and formed by tools and machines operated manually or, increasingly, under the control of computers programmed (CNC) to guide the necessary operations consistently and with greater precision than can normally be provided by humans [7]. Modern differences, such as tighter metal-cutting tolerances, are related to advances in the capabilities of machines and tools. The manufacture of new metals such as aluminium-magnesium alloys and titanium alloys and their products has created new challenges, requiring specialized machining and grinding [7] (§4.4).

In the production of components that must bear high loads yet as light as possible, aerospace fabricators have evolved engineering techniques for modifying materials properties. Composites are increasingly becoming staples of aircraft outer surfaces, thus most structure manufacturers incorporate the necessary fabrication technology in their factories [7]. A notable example are honeycomb sandwiches, far lighter than a metal plate of comparable thickness and with higher resistance to bending. Laminated polymer-matrix composites are valued in the aerospace industry for their stiffness, lightness, and heat resistance. They are fabricated in polymer resins in which carbon fibres are bonded together either in laminated or sandwich form. To achieve required strengths, laminates must be resin-cured within a vacuum, obtained within evacuated rubberized bags or in autoclaves (temperature- and pressure-controlled chambers).

Assembly. Assembly is the gathering of the aircraft constituent units, the sub-assemblies [7]. An example of a typical sub-assembly for a commercial aircraft is the rear fuselage section, which is itself composed of several segments. (These segments are often built by subcontractors, who in turn deal with their own suppliers of the segments' constituent elements). The segments are taken to the sub-assembly area, where teams of workers take them into support jigs or fixtures and join them into a unit, within which the interior equipment is installed [7]. In similar manner, teams put together other sub-assemblies such as the remaining fuselage sections, wing sections, tail sections, and engine nacelles. Integration of the components of a sub-assembly most often takes place in black boxes enclosing electronic and electrical sub-elements, with connectors that interface with various systems in the aircraft [7].

The performance of sub-assemblies as units is verified prior to their integration into final assemblies. In the case of structural sub-assemblies, verification usually refers to load testing, alignment and assurance of dimensions and tolerances, and electrical conformity checks for installed cabling [7]. For sub-assemblies with electrical and electronic, hydraulic, and mechanically actuated components, extensive tests are usually carried out in simulated flight environment [7].

The various sub-assemblies are then taken to the main assembly line, where final integration takes place. This requires a facility furnished with a network of overhead rails on which ride heavy-lift cranes capable of moving large portions of the plain; facility size is governed by aircraft dimensions [7]. Aircraft assembly usually starts with the joining, or mating, of fuselage sub-assemblies that have been craned into a supporting jig. As the vehicle is assembled, it is moved through a succession of work stations, acquiring additional sub-assemblies and accumulating its onboard systems, ducts, control cables, and other interior plumbing. Major assembly steps include the additions of nose and tail sections, wings, engines, and landing gear. At the last station, the airplane is rolled out of the assembly plant to the flight line for a production flight test, a process that involves a thorough checkout of specified performance [7]. A critical verification step for every aircraft once they are assembled follows, for ensuring the quality of the manufacturing and assembly processes. This involves extensive inspections of structural and mechanical items, including functional verification of equipment such as control surfaces and systems, landing-gear operation, avionics performance, and crew and passenger environmental conditioning [7].

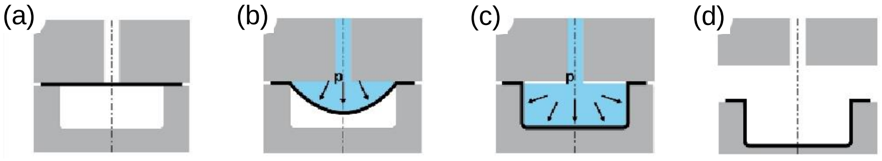
4.4 ADVANCED MANUFACTURING PROCESSES IN THE AIRCRAFT INDUSTRY

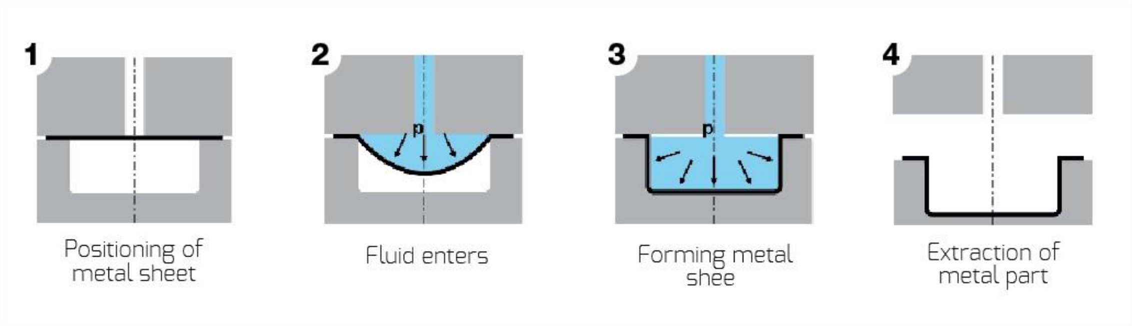
Over the past few years, the aerospace industry has seen countless innovations coming to readiness, with emerging technologies and innovative manufacturing processes being developed. Aircraft construction requires state-of-the-art manufacturing processes and assembly techniques to achieve improved build quality and increased rate of production [28]. Manufacturing in the aerospace sector involves the assembly of components with large dimensions and shapes that cause significant deformations under their own weight. Therefore, the tolerances of the physical part-to-part interface differ from the estimated during the design process [30]. Advanced manufacturing processes and technologies simplify the production processes, improve the production rate, quality and repeatability, and reduce rejection through automation. They are applied both for prototype development as well as series production [28].

4.4.1 Hydroforming of Sheet Metal parts

While aircraft performance is governed by its aerodynamic contour, achieving the complex contour profile is a challenge [28]. Sheet metal forming is traditionally used to shape several components of the airframe: the workpiece is permanently shaped to reach the required geometry through mechanical deformation, without adding or removing material through the process [31]. Deformation can be imposed either mechanically (bending and die forming are the most common technologies in aircraft manufacturing), or by hand (using rubber pad or drop hammer processes). All aircraft parts are afterwards subjected to inspection for detection of eventual wrinkles, thickness variation and cracks [7]. Considering the complexity of the contour and the sheet metal forming processes limitations, designers consider the split design philosophy, approaching complex geometries through the production of individually designed parts. This leads to increased number of parts and tools, and to increased cost and time of manufacturing. Split results in more joints, requiring more rivets and subsequent increase in overall weight.

The described issues can be eluded by the use of hydroforming, a process that was primarily developed for the needs of the aircraft and aerospace industry [32]. Hydroforming is a variation of the die forming process that uses a hydraulic fluid under ultra-high pressure to force the working material into a die with desired shape, at room temperature. It is classified into sheet hydroforming and tube hydroforming processes [32]. Sheet hydroforming uses one die and a sheet of metal, which is driven into the die by high pressure water on one side of the sheet, forming the desired shape (Figure 50). Tube hydroforming is an expansion of metal tubes into a shape using two die halves, which contain the raw tube. Hydroforming allows complex shapes with concavities to be formed, which would be difficult or impossible with standard forming processes [7,28,32]. It is capable of producing parts with stringent tolerance requirements and allows a smoother finish as marks resulting from shaping tools are eliminated [7].This process is ideal for prototyping and low volume production of aluminium, titanium, stainless steel and other ductile aerospace alloys, and also of metal-composite panels [32].





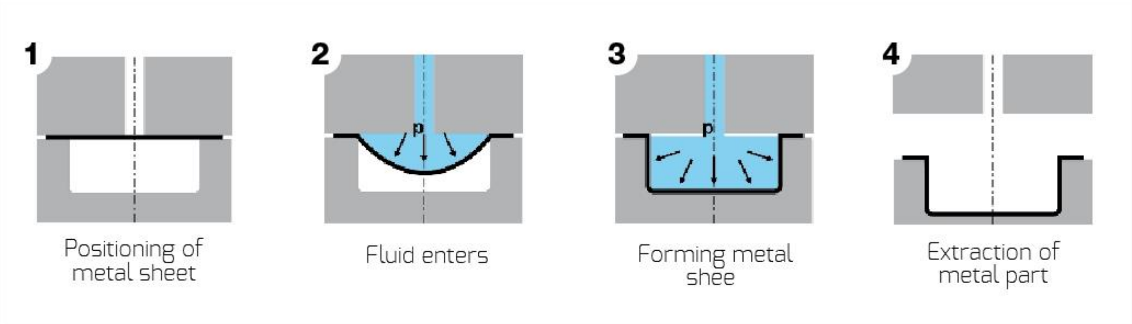


Figure 50. Schematic representation of metal sheet hydroforming: (a) positioning of metal sheet; (b) fluid entry; (c) metal shaping against the die; (d) extraction of the formed metal part after fluid removal.

4.4.2 High speed machining of lengthy components

Long and slender components in aircraft (such as longerons, stingers and spars) are usually machined from billets, involving removal of considerable amounts of material [7]. High speed machining is well suited for such thin-wall machining [7,33]. It consists in an operation or a combination of operations where machining takes place at a high cutting speed, high spindle speed, high feed rate, and high removal rate [33].

Besides providing increased metal removal rate, it ensures feed with low depth of cut, fast heat dissipation because of faster chip removal, improved surface finish, lower deflection of thin walls due to reduced cutting force, reduced warpage and virtually stress-free components, and better surface finish and dimensional accuracy [33]. Compared with conventional machining, high speed machining allows to increase efficiency, accuracy and quality of workpieces, and at the same time decreasing costs and machining time [33].

4.4.3 CNC pipe bending

Rigid pipe assemblies are used extensively in aircraft fluid systems to transfer oil, fuel and air throughout the airframe and engines. They are produced in a range of stainless steel, aluminium, titanium and high-temperature alloys and the majority is still fabricated through manual pipe bending and welding, resulting in insufficient quality [28]. Also, pipelines having multiple bends cannot be bent with a single pipe: the component must be split up into multiple pieces which are individually bended, and then joined by welding; welded pipeline joints result in pipe distortion, prone to crack at joint location and difficult to achieve interchangeability [28].

CNC bending of pipes for system pipelines and conducts is currently being introduced in the aircraft industry [28]. The pipe is positioned between two dies and a mechanical force is applied to push the material, forcing it to conform to the shape of the die. The stock pipe is held firmly in place and the end is rotated and rolled around the die, while a mandrel is placed inside to prevent it from collapsing during bending [28]. Over conventional pipe manual bending, CNC bending results in better accuracy and repeatability, less human intervention/low skill set, higher degree of control, change-over flexibility and speed, and the possibility to produce complex bend radii and angles [28].

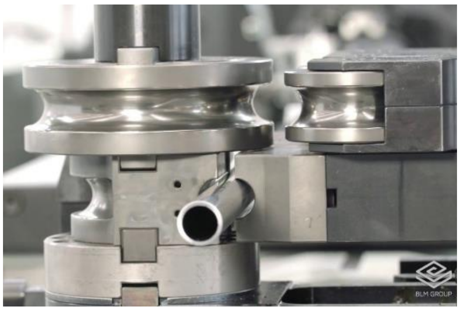


Figure 51. CNC metal tube bending.

4.4.4 Multi-pass EDM of complex components

Electrical discharge machining (EDM) is a manufacturing process where the desired shape is obtained by removing material from the work piece by a series of rapidly recurring electrical discharges (sparks) between two electrodes [31]. Two major factors have been contributing to establish EDM as a mature production process in the aircraft industry [34]. First, the industry's requirement for high-volume manufacture of precision components using unusual materials such as nickel superalloys and titanium alloys, difficult to machine by conventional metal cutting methods [34]. Secondly, the development of advanced innovative systems providing the capability of high productivity, with economy in space and manpower [28,34]. In particular, computer numerical control of the discharge parameters and accurate sensing devices provide the means to fully-automate machining cycles [34], rendering a more stable and predictable process [28].

In the aircraft industry EDM is particularly suitable for machining complex contours and cavities, long aspect ratio drilling, complex profile cutting, and grooves through cut, which traditionally would require complex and expensive tooling, large cycle times for setting and machining and finally resulting to an expensive process [28]. EDM is invaluable to fulfil one particular need of the industry: to drill a large number of small, not always circular, holes (often thousands) in a single component. Using conventional machining, the drill breakage is unacceptably high, and when the hole needs to be at an acute angle to the surface, drilling is virtually impossible [34].

EDM has not only solved the problem, but has given high production rates for precision components [28,34].

4.4.5 Multi-Tasking machining

After the advent of CNC in the 1960s, milling machines evolved into machining centres: milling machines augmented by automatic tool changers, tool magazines, CNC capability, coolant systems, and enclosures [31]. These multi-tasking machines (MTM) enable to integrate different family of operations – e.g. turning, milling, grinding, inspection - within the same work envelope in a single set-up, without manual intervention [28]. There are many advantages to multitasking, since it delivers considerable savings: combining operations can dramatically reduce setup and other non-value-added time, improving the process and cycle time to produce a complete part; also it reduces opportunities for error and eliminates work-in-process inventory that usually lingers between standalone machine tools [28].

4.4.6 Automated layup of composite parts

Composite fabrication requires the placement of the fibre reinforcement to place. This involves the laying down of reinforcing fibres along predefined trajectories in the component, with the goal of maximise the performance of a particular part by using the highly directional strength of fibre reinforcement (for example to improve stiffness and strength of components, or to locally reinforce holes and cut outs) [35]. Hand layup of prepreg fibre reinforcements has long been a standard of aerospace composites fabrication processes. This has suited the industry's relatively low build volumes, while the 100 % inspection requirement imposed by the aerospace original equipment manufacturers ensures that any error introduced by humans during hand layup will more than likely be caught and corrected before delivery to the customer [36]. However, the definition of "high-volume" in the aircraft industry is getting higher, placing pressure on composites fabricators to be faster and more efficient. Automation is evolving to meet that challenge [37] and automated fibre placement (AFP) and automated tape laying (ATL) are currently allowing to automate placement: they are the manufacturing processes that enabled widespread application of composites in the Boeing 787 and Airbus A350 [37].

Automated tape laying is a well-established automated manufacturing techniques to form composite layups. Wide unidirectional tapes are laid onto a part mould using a loaded roller system with varying degrees of articulation, depending on the complexity of the part being manufactured. ATL essentially replicates the manual deposition of unidirectional tape but can do so at higher speeds, on larger parts, with greater process control with precise control of tape start, cut, and orientation [35].

The automated fibre placement process (Figure 52a) involves computer-controlled laying of prepreg, allowing highly automated, high-speed production of laminates with double curvature [35]. Wide unidirectional prepregs are laid and compacted onto a part mould using a loaded roller system with varying degrees of articulation, depending on the complexity of the part being manufactured. A key aspects is the ability to allow individual tapes in the band to be stopped, cut, and restarted during the laying process. As a result, it is possible to do cut out windows, to layup various sizes of ply doublets with close tolerance accuracy on the ply boundaries, and lay up a constant ply thickness on tapered shapes. It is also possible to lay up plates in any orientation (Figure 52b), and several machines currently available will do simultaneous bidirectional lay up of material [35]. This technology allows better precision and increased deposition rates when compared with experienced laminator workers, but while allowing for more complex layup geometries than ATL, it does not reach the same deposition rates [35].

Automated fibre placement can be used to manufacture complex structures that are not possible to manufacture with any other methods [29,35].

Despite their productivity advantages, these technologies are not cost-effective or efficient for all prepreg placement operations, particularly for parts with highly contoured deeply drawn parts, where human fingers are so capable [37]. This means that automation technology must be developed in order to keep up with the quality and production rate requirements of next-generation aircraft [37]. Further improvements and progress in both techniques are thus claimed by the aircraft industry, including increasing layup speeds, improving mould surface tack, increase force applied by the robotic system, optimization of the end effector geometry, and multiple robots [36,37].

Figure 52. Automated fibre placement [35]: (a) example of commercial equipment (MTorres Machine Company, Spain); (b) Robotic AFP in several orientations (Coriolis Composites, France).

4.4.7 CNC machining of composite parts

Fibre-reinforced plastics have high specific strength, high stiffness or modulus, and good dimensional stability. This combination of properties is unusual and not easily obtained in metallic alloys. In the present aircraft scenario, the majority of skin and spars have been replaced with carbon fibre-reinforced composite parts with considerable reduction in part counts and weight [28]. The composite parts are processed through the manual layup of prepregs upon a mould with desired geometry and cured mostly through autoclave process. However, certain machining procedures, such as milling and drilling are needed to obtain close fits and tolerances, as well as to achieve near-net shapes and uniform thickness in classical production processes. Manual procedures are being replaced by machining using computer numerical control (CNC) of composites, which provides better control of thickness and sizes, improving aircraft construction [7].

4.4.8 Additive manufacturing

Additive manufacturing (AM)[3] covers a variety of processes in which material is joined or solidified under computer control to create a three-dimensional object, with material being added together layer-by-layer [38]. This is unlike conventional machining, casting and forging processes, where material is removed from a stock item or poured into a mould and shaped by means of dies, presses and hammers [38].

The generic AM process ultimately involves seven steps [38]. (i) CAD: All AM parts start from a software model that fully describes the external geometry of the 3D solid. (ii) File conversion: the CAD file is converted to STL file format (or similar), that describes the external closed surfaces of the original CAD model and forms the basis for the calculation of the slices. (iii) Transfer to AM machine and STL file manipulation: corrections of size, position and orientation for building. (iv) AM machine setup: definition of operational parameters such as materials constraints, energy source, layer thickness, and timings. (v) Build: building the part is an automated process. (vi) Removal. (vii) Post-processing: parts may require removal of support structures, additional cleaning, and/or any form of surface treatment before ready to use.

Additive manufacturing technologies present unique advantages that are revolutionising product development and manufacturing. One of its key advantages is the ability to produce and/or integrate complex geometries, allowing cost-effective small series production of customised parts. Other benefits include smaller processing time and lower time-to-market, lower raw materials and consumables consumption, less production steps and adequacy to produce very small and complex shapes. A wide range of polymers, polymer composites, metals and ceramics have been demonstrated, but only a subset of these are commercially available; other concerns involve intrinsically low mechanical properties resulting from poor surface finish compared to conventional technologies [38,39].

Additive technologies can be classified in three categories regarding the starting form of the raw material [38] (Table 9): liquid-based, including vat photopolymerization and material jetting; solid-based, including material extrusion and sheet lamination; and powder-based, namely binder jetting, powder bed fusion and directed energy deposition.

Table 9. Materials for AM technologies (adapted from [38]).

Technology	**Materials**			
	starting state	**plastics**	**metals**	**ceramics**
vat photopolymerization	liquid	✓ (photosensitive)	×	×
material jetting				
material extrusion	solid	✓	×	✓
sheet lamination		✓	✓	✓
binder jetting	powder	✓	×	✓
powder bed fusion		✓	✓	✓
directed energy deposition		✓	✓	✓

Vat photopolymerization. In the photopolymerization processes a vat of liquid polymer is exposed to controlled lighting under safelight conditions [38]. The exposed liquid photopolymer hardens through cross-linking mediated by its chromophore groups, that react with the solution to begin polymerization. Polymerization of monomers lead to cross-linking, which creates a polymer. After one layer is finished, the build plate moves vertically in small increments and the liquid polymer is again exposed to light. The process repeats until the part is completed. The

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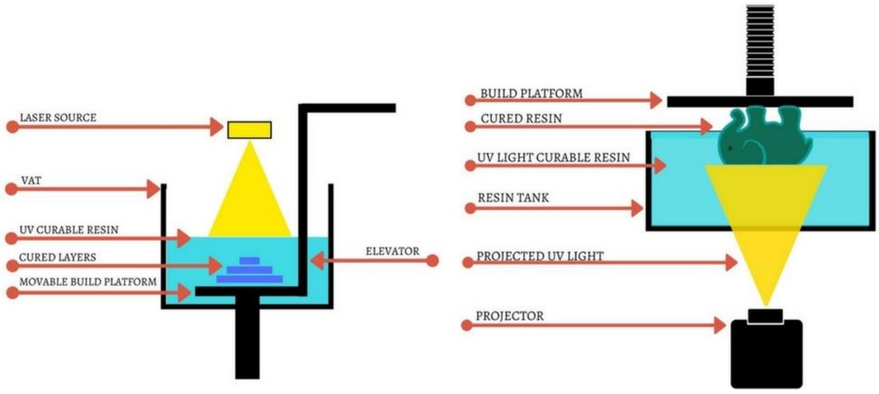
[3] *Additive manufacturing* is the formal term for what is popularly known as *3D printing*. Although the popular vernacular has started using the term to encompass a variety of additive-manufacturing techniques, *3D printing* specifically refers to a process that deposits a binder material onto a powder bed with inkjet-printer heads, layer-by-layer [12].

liquid polymer is then drained from the vat, leaving the solid model [38]. Both stereolithography (SLA) and digital light processing (DLP) fall into the vat polymerisation category of 3D printing. Yet, a key difference between the two technologies is the type of light source used to solidify the material: SLA uses ultraviolet (UV) or visible light laser beam (Figure 53a) and the beam moves from point to point on one resin layer, passing to another layer after the former layer is cured; in DLP a digital light projector screen remains stationary to flash an image of each layer at once, curing a complete layer of resin at a time (Figure 53b). Thus DLP is typically a faster process than SLA, but since the digital light projector delivers light in pixels, it results in a pixelated shape projected in the resin that prevents smooth edges. Since the hardening of the resin in SLA is done from point to point, it is more accurate and the quality of the print is better in comparison to DLP. Material jetting (MJ) operates in a similar fashion to 2D printers: a printhead (similar to the printheads used for standard inkjet printing) dispenses droplets of a photosensitive material in a line-wise fashion. After the all layer is solidified under UV light, the build platform moves downwards one layer height and the process repeats until the whole part is complete. The possibility to attach multiple inkjet printheads allows different heads to dispense different material, so multi-material printing and full-colour printing is straightforward and widely used. Key drawbacks of MJ include that the liquid resin must be heated to 30-60 ºC to achieve optimal viscosity for printing, and that support structures are always required and need post-processing to be removed; all vat polymerisation process are limited by the requirement of suing photosensitive resins [38].



(a) (b)

Figure 53. Schematic of vat polymerisation processes: (a) SLA; (b) DLP (image credits: 3DMag).

Material extrusion. This is currently the most popular technology on the market [38]. Pressure is applied to draw the material through a nozzle, where it is heated, and is then deposited layer by layer. The nozzle can move horizontally and a platform moves up and down vertically after each new layer is deposited [38]. The applied pressure must be kept stable and at constant speed to enable accurate results regarding cross-sectional diameter. The following layer is added on top of the previous one. Material layers can be bonded by temperature control (layers are fused together upon deposition as the material is in melted state) or through the use of chemical agents [38]. Material is often added to the machine in filament form (**Error! Reference source not found.**). While this technology is mostly used for plastics, it can also be used for metals and ceramics (Table 9). In this case, the feedstock materials are mixtures of a polymeric binder (from 40% to 60% by volume) and a fine grain solid powder of metal or ceramic material. However extrusion of plastics is much more common, under the fused filament fabrication (FFF) technique, that accounts for almost 50 % of all AM [38][4].

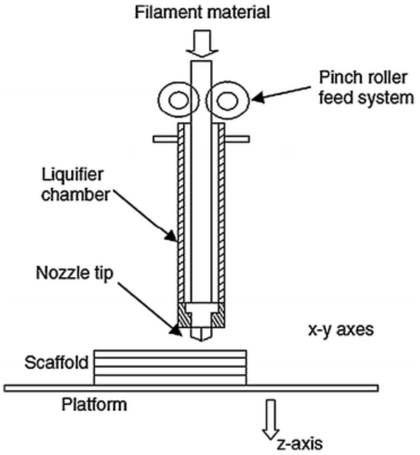


Figure 54. Schematic representation of the FFF technique of plastic filament extrusion [38].

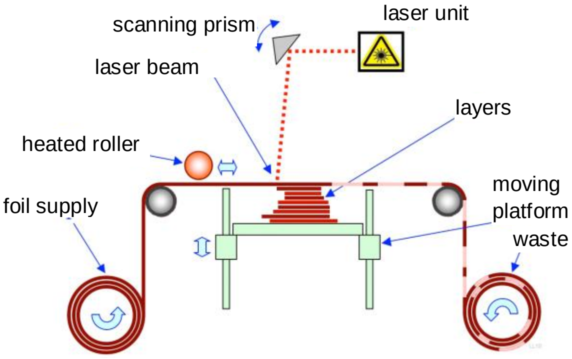


Figure 55. Schematic representation of the LOM sheet lamination process (image credits: wikipedia).

Sheet lamination. In this technology, known as laminated object manufacturing (LOM), layers of paper, plastic, ceramic or metal laminates are successively bonded together and cut to shape with a laser cutter [38]. Each sheet represents a sectional layer of the CAD model of the part. Because of the construction principle (**Error! Reference source not found.**), only the outer c ontours of the part are cut, and the sheets can be either cut and then stacked, or stacked and then cut. The mechanism employed to achieve bonding between layers can be adhesive bonding (gluing), thermal bonding, clamping or ultrasonic welding [38].

Binder jetting. Binder jetting is the AM technology properly corresponding to the expression 3D printing. A binder is printed onto a power bed to form cross-sections. Only a small portion of the part material is delivered through the printing head; most of the part material is comprised of powder in the powder bed [38]. Typically, binder droplets form spherical agglomerates of binder liquid and powder particles, providing bonding to the previously printed layer. Once a layer is printed, the powder bed is lowered and a new layer of powder is spread on it (usually via a counter-rotating rolling mechanism). This process is repeated until the part is completed [38].

Powder bed fusion. Selective laser sintering (SLS) was the first commercialised powder bed fusion (PBF) process (Figure 56), and all other PBF procedures - e.g., direct metal laser sintering (DMLS), selective laser melting (SLM) and electron beam melting (EBM) - modify its basic approach in one or more ways to enhance machine productivity, enable different materials to be processed, and/or avoid specific patented features [38]. Nevertheless, the basic set of characteristics is the same. The approach consists in the selective melting of materials in a granular bed, fusing only prescribed regions of each layer; the working area then moves upward adding another layer of granules and repeating the process until the piece has built up; a mechanism for smoothing powder layers is necessary [38]. A cool down period is usually required to allow the parts to uniformly cool to room temperature before handling.

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[4] FFF is also the technology corresponding to the printers you probably used through the **Learn&Fly** challenge to produce some of the glider parts and connectors.

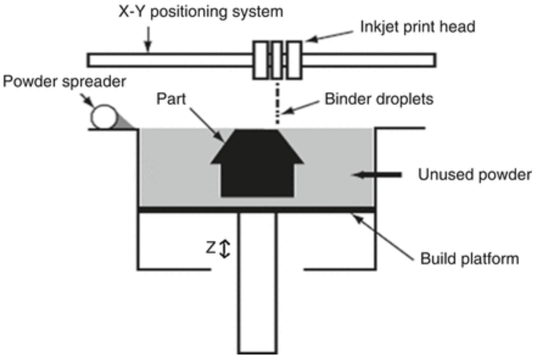


Figure 56. Schematic of binder jetting process [38].

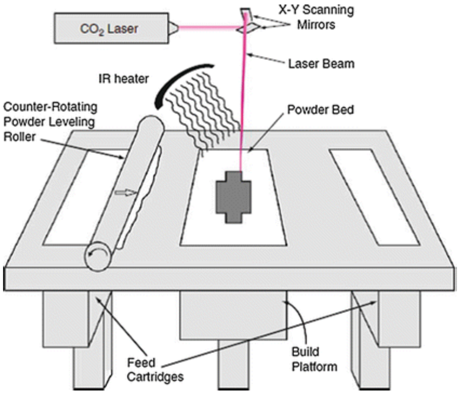


Figure 57. Schematic of the SLS powder bed process [38].

Directed energy deposition. Directed energy deposition (DED) processes (Figure 58) enable the creation of parts by melting material as it is being deposited [38]. A focused heat source (typically a laser or electron beam) is used to heat and melt the substrate material, and simultaneously melts the material that is being deposited into the substrate's melt pool. Each pass of the DED head creates a track of solidified material, and adjacent lines of material make up layers and build up three-dimensional objects in a manner similar to the extrusion-based processes described before [38]. Unlike powder bed fusion techniques, DED processes are not used to melt a material that is pre-laid in a powder bed but are used to melt materials as they are being deposited [38]. Although this approach can work for polymers, ceramics, and metal matrix composites, it is predominantly used for metal powders (Table.1), and this technology is often referred to as metal deposition.

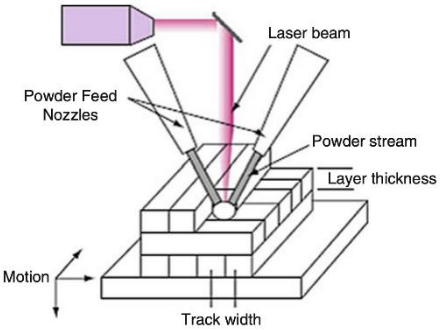


Figure 58. Schematic of the DED procedure [38].

Figure 59. A320 nacelle hinge bracket redesigned for AM [38].

AM in the aircraft industry. AM has been applied in aircraft since it was first introduced in the 1980s [38], because of the opportunity window it opens with respect to several features and needs of the industry. One of those features is the complex geometry of aircraft applications, often requiring components to have more than one function (for example, engine turbine blades may also have an internal structure for passing coolant through it). This can be addressed by AM's ability to generate complex engineered geometries with a limited number of processing steps [38]. Also, AM brings about the opportunity to completely rethink how components are shaped in order to best fulfil their functions: integrated designs can be produced that combine several parts, eliminate assembly operations, improve performance by designing parts to utilize material efficiently, eliminate shape compromises driven by manufacturing limitations, and completely enable new styles of products to be produced [38]. Figure 4.10 displays the example of the A320 nacelle hinge bracket: the new optimised design made possible by AM resulted in 64 % part weight reduction, allowing to save a total of 10 kg per plane, which results in carbon emissions reduction in by about 40 % when considering the total number of A320 planes produced so far [39]. AM also toils regarding the lightweight requirement of aircraft structures. This can be achieved by the use of low density materials with high strength to weight ratio, as is the case of titanium alloys, aluminium alloys, and composite materials (§ Module 2). But it can also be addressed by creating lightweight structures with hollow or honeycomb internal cores, which is the kind of topology optimisation quite easy to achieve using AM [38]. AM enables cost saving since it is particularly qualified for the economical production of small series, which are common in aircraft, since hard tooling is not necessary. This dismisses the design and fabrication of moulds, dies and fixtures, and avoids time spend on the complex process planning required by conventional manufacturing processes [38]. AM technologies also enable companies to maintain digital models of parts, which are much easier and less expensive than warehousing physical parts or tools during all the aircraft useful live (20-50 years or longer) [38].

In summary, advantages of the AM approach over aircraft conventional manufacturing processes include a more compact design, weight reduction, and integral features [38]. Reportedly, 200 parts are flying on at least eight different military and eight different civilian models of aircraft[38,39]. Until recently, all of these were non-structural polymer parts: polymer parts for aircraft need to satisfy flammability requirements, so their adoption needed to wait until flame retardant polymer materials were developed. For metals, material qualification and part certification took many years to achieve. In addition to parts manufacturing, aerospace companies are also developing new higher-performance materials in both metals and polymers, as well as processing methods [38,39]. Some of the first large scale, metal part production manufacturing applications are emerging in the aerospace industry. New design concepts can be expected for not only piece parts, but entire modules. Also, AM vendors are developing larger frame machines so that larger parts can be fabricated, opening up new opportunities for structural metal components and functional polymer parts [38]. In as much, many more production applications of AM in aircraft can be expected in the very near future as materials advance and production methods become standardized, repeatable, and certified.

5 TECHNICAL DRAWING

Drawing is a form of visual art in which an instrument is used to mark paper or another two-dimensional medium leaving visible signs, either permanent or temporary. Drawing has been a popular and fundamental means of expression throughout human history, and is one of the simplest and most efficient resource for communicating ideas [40].

5.1 TECHNICAL DRAWING AS A COMMUNICATION TOOL

Technical drawing is the act of composing images that visually transmit how something functions or is constructed, essential for communicating ideas in industry and engineering. The need for precise communication in the preparation of a functional document distinguishes technical drawing from the expressive drawing of the visual arts. Artistic drawings are subjectively interpreted; their meanings are multiply and subjectively determined. Technical drawings are understood to have one intended specific meaning, and accurately and unambiguously capture all the geometric features of a product or a component. The end goal of an engineering drawing is to convey all the required information that will allow a manufacturer to produce that component [40].

To make technical drawings easier to understand, the drafting technician uses familiar symbols, perspectives, units of measurement, notation systems, visual styles, and page layout. Together, such conventions constitute a visual language and help to ensure that the drawing is unambiguous and relatively easy to understand. Many of the symbols and principles of technical drawing are specified in the ISO 128 international standard (§ Module 5.4).

Technical drawing has become gradually more accurate and rigorous over time, in tight relation with the evolution of the instruments used in its execution [40]. Manual technical drawing requires a drawing board, a T-square and a technical pen, along with mastering the mechanics of drawing lines, arcs, circles and text onto a sheet of paper. It also requires a thorough understanding of geometry and trigonometry, spatial comprehension, and precision, accuracy, and attention to detail. For centuries, until the post-World War II, all engineering drawings were done manually by using pencil or pen on paper. After the 1980s [40], the mechanics of the drafting task has largely been automated and accelerated through the use of computer-aided design (CAD) systems in the representation of orthographic projections (§ Module 5.4.1). In the 1990s, CAD systems evolved to a new philosophy based on parametric representation of three-dimensional models, meaning that all information regarding individual parts and part assembly is kept, with geometrical or dimensional constraints or restrictions, with parametric drawings updating themselves if any a restriction is changed [40]. Parametric models allow to generate 2D or 3D representations, making easy to obtain detailed part images in any position without increased drawing hours [40]. Most engineering drawings are now done with CAD, although pencil and paper have not entirely disappeared.

5.2 INFORMATION CONTAINED IN TECHNICAL DRAWINGS

Technical drawings intend to accurately and unambiguously represent products and components. In aeronautics, they are the best communication tool between design engineers and the workers who build, maintain and repair an aircraft. For that purpose there are several representation techniques, depending for what purpose the drawing is used (§ Module 5.5.1). The most usual for manufacturing and assembly purposes is the multiview projection system, which includes information about the whole component (assembly drawings) with an associated Bill of Materials (BOM) (§ Module 5.5.6). From the BOM you can find the drawings detailing each part or subassemblies. Each part must have a corresponding drawing, identifying every detail of the geometry an any other information necessary to accurately produce the part, including: surface condition (painting or other surface treatments); all the dimensions and corresponding dimensional and geometrical tolerances (to ensure that part size and shape is correct within a limits (for example a cylinder has a circular shape and not an elliptical one, etc…); all required processes, including welding, fastening, riveting; and notes necessary for full understanding of the part.

For other purposes, including representation of the electrical system or the pipe system, drawings can be more schematic, as long as they include all the information to assemble the equipment. Representations in perspective are also common accompanying an explaining text, for example showing how to carry out a procedure in operation manuals and maintenance manuals.

5.3 PRODUCT DEVELOPMENT

Product development follows a series of stages, bringing the product from a concept or idea, through certification and use. Product development incorporates a product's entire journey. The development of aeronautical components usually go through the concept, preliminary design, development, production, and certification stages, each one with a number of milestones. These include the System Concept Review (which focuses on design goals, requirements definition, design concepts, project feasibility, and overall schedule and budget), the Preliminary Design Review (in which the initial design of subsystems, interfaces, and configuration items is reviewed considering design requirements), and the Critical Design Review (a most important multi-disciplinary technical review to ensure that a system can proceed into fabrication, demonstration and test, and that it can meet performance requirements within cost, schedule, and risk). Afterwards, production is able to start, in the frame of a Production Review milestone. It finally comes to the First Article Inspection, a part of the purchasing and design control requirements where supplier and purchaser ensure that the production process reliably produces what is intended [41].

5.4 NORMALIZATION

All drawing elements are subjected to normalisation, i.e., to specifications imposing the general principles of presentation and graphical representation of objects, ensuring that technical drawings conform to the minimum standards set internationally, and are thus reliable and comparable. Different standards for drawings are used in industry, the more common being the ones published by the International Organization for Standardization (ISO) (customary in Europe) and the American National Standards Institute (ANSI) (customary in the US). The ISO 128 standard (in fifteen parts) approaches the general rules for the execution and structure of technical drawings [42]. Further, it describes basic conventions for lines [43], views [44], cuts and sections [45], and different types of engineering drawings, such as those for mechanical engineering [46,47], architecture, civil engineering, and shipbuilding. It is applicable to both manual and computer-based drawings, but it is not applicable 3D CAD models [43]. Other important international specifications regarding technical drawing regard normalised paper size (ISO 216:2007) [48], standard folding sizes (ISO 5457:1999) [49], lettering (ISO 3098/1:1974)

[50], and tolerances (ISO 129) [51]. Any book on technical drawing, presents extensive lists of standards.

5.5 TYPES OF REPRESENTATION

Graphical projections are drawing methods by which an image of a three-dimensional object is projected onto a planar surface (such as drawing paper or the computer screen). Nowadays, with computers and CAD systems advance, some drawings are available only in digital format (3D representation), which includes all technical information contained in the representation. Projections can be divided into parallel projection (the observer is placed in an infinite position relative to the object/plane) and central projection (the observer is placed in a finite position relative to the object/plane) (§ Module 5.5.1 and 5.5.2), which in turn can be orthogonal or oblique to the plane of representation (§ Module 5.5.3).

In most cases, a single view is not sufficient to show all necessary features, and several views are used [40]. The most used representation technique for manufacturing and assembly is the multiview projection system. The object is projected upon the six faces of a cube, as watched by an observer positioned orthogonally to each one of those sides. When the cube is “opened” a planar representation is created. This is thus a mean of representing three-dimensional objects in 2D, in which all the projection lines are orthogonal to the projection plane. As a result every plane of the object appears correspondingly transformed upon the viewing surface. The views are default positioned relatively to each other according to the rules of the first-angle projection (in Europe), where the parallel projectors originate as if radiated from behind the viewer and passing through the 3D object to project a 2D image upon the orthogonal plane behind it. The 3D object is projected into 2D surface as if the observer was looking at a radiograph of the object: the top view is under the front view, the right view is at the left of the front view. Not all views are mandatorily used: only as many views as are necessary to convey all needed information clearly and economically. The front, top, and right-side views are commonly considered the core group of views included by default, but any combination may be used depending on the needs of the particular design. In addition to the six principal views (front, back, top, bottom, right side, left side), any auxiliary views (not presented in the slides) or sections may be included as serve the purposes of part definition and its communication.

An auxiliary view is an orthographic representation that is projected upon any plane other than one of the six primary views. They are typically used when an object contains some sort of inclined plane. Using the auxiliary view allows for that inclined plane (and any other significant features) to be projected in their true size and shape. The true size and shape of any feature in an engineering drawing can only be known when the line of sight is perpendicular to the plane being referenced.

A section drawing (§ Module 5.5.4) shows a view of a structure as if it had been sliced in half or cut along another imaginary plane. The sectional view is applicable to objects where the interior details are intricate (Figure 60 a) and would be very difficult to understand through the use of "hidden" lines (Figure 60 b) on an orthographic or isometric drawing. This can be bypassed by pretending to cut the object on a plane (Figure 60 c) and showing the resulting internal view (Figure 60 d), visualizing what the part looks like after it is cut open.

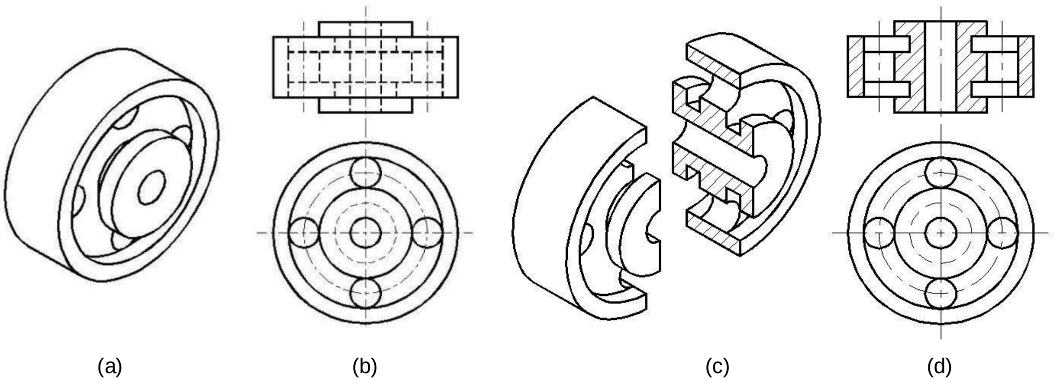


Figure 60. Sectional views: (a) intricate part; (b) part representation using conventional orthographic drawing; (c) cut plane; (d) sectional view showing interior details [40].

The cut is called a “cutting plane”, and can be done in several ways. A full section view is used when the interior construction or hidden features of an object cannot be shown clearly by exterior views. In a full section, the cutting plane line passes fully through the part [40]. Usually one of the conventional views is replaced with the corresponding full section view. The section-lined areas are those portions that have been in actual contact with the cutting-plane.

In a half section, the cutting plane extends only halfway across the object, leaving the other half of the object as an exterior view [40]. Half sections are used to advantage with symmetrical objects to show both the interior and exterior. A removed section drawn directly on the exterior view shows the shape of the cross section of a part. A removed section illustrates particular parts of an object [40]. It is drawn like revolved sections, except it is placed at one side and, to bring out pertinent details, often drawn to a larger scale than the view on which it is indicated. A broken-out section is part of an existing drawing view, that is used to remove material to a specified depth in order to expose inner details of a model [40].

Assembly drawings detail how certain component parts are assembled. They typically include three orthographic views of the system, overall dimensions, identification and weight of all the components, quantities of material, supply details, list of reference drawings, and notes. An assembly drawing also shows in which order the product is put together, presenting all the parts as if they were stretched out. When a section is represented in an assembly (§ Module 5.5.5), different hatch (angle or direction) is used to represent different parts; connecting elements like bolts, rivets or shafts are not sectioned [40].

A sketch (§ Module 5.5.6) is a quickly executed, freehand drawing that is usually not intended as a finished work. It is a quick way to record an idea for later use, or a way to try out different ideas before a more finished work, especially when the finished work is expensive and time-consuming.

Another type of representation, quite frequent in diagrams, manuals, and maintenance instructions, is the isometric (axonometric) (§ Module 5.5.7 and 5.5.8). Isometric drawing is the most commonly used method of pictorial drawing [40]. An isometric view is a representation of an object that uses a combination of the orthographic views and tilts them forward so that portions of all three can be seen in one image, providing the observer with a 3D view of the object. Isometric drawings are built on three lines, called isometric axes: one is drawn vertically and the other two are shown at 30º to the horizontal (the angle between axonometric axes is 120^{o}, Figure 61).

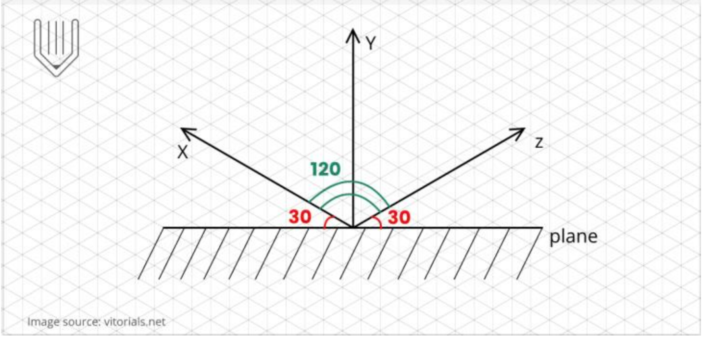


Figure 61. Features of isometric representation.

Unlike perspective drawing, where lines converge and dimensions are not true, lines in an isometric drawing are parallel and the true dimension of the object is used to build the drawing. These dimensions can be taken from either orthographic drawings or by direct measurement. Isometric drawings or images have become the aircraft industry standard for part manuals, technical proposals, patent illustrations, and maintenance publications, due to their use of true length and their ability for being understood by untrained people.

It is also frequent to represent exploded views (§ Module 5.5.9) of assemblies in isometric view. An exploded view shows the individual parts that constitute an object and their relative position before they are assembled, together with the relationship or order of assembly. The object components are shown slightly separated by distance, or suspended in the surrounding space in the case of a 3D exploded diagram. An object is represented as if there had been a small controlled explosion emanating from the middle of the object, causing the object parts to be separated by an equal distance away from their original locations. This drawing helps to assemble mechanical systems (usually the components closest to the centre are assembled first), but also represents the disassembly of parts, where the parts on the outside normally get removed first [40].

Dimensioning (§ Module 5.6.8) is fundamental to provide a clear and complete description of an object. A complete set of dimensions will render only one possible interpretation to construct the part. ISO 129 [51] establishes the general principles of dimensioning applicable to all types of technical drawings. Books of technical drawing, such as [40], general contain information about how to properly apply dimensions to a drawing. Some dimensions may also include the associated tolerance, but even if it doesn’t, the title block must have indication about the general tolerances to apply.

A pictorial drawing (§ Module 5.6.9) usually provides a perspective image to help to understand the shape of an object or to assist in interpreting a drawing. It shows an object as it appears to the eye, but it is not satisfactory for showing complex forms and shapes. Pictorial drawings corresponds closely to what is actually seen when viewing the object from a particular angle. Yet, although they can show the overall arrangement clearly, they do not show details (including inner details) nor dimensions. Pictorial drawings are useful in showing the general appearance of an object and are used extensively with orthographic projection drawings. They are used in aircraft maintenance, overhaul, and part numbers.

5.6 CAD SYSTEMS

There are two types of computer-aided design systems used for the production of technical drawings: bidimensional (2D) and three-dimensional (3D). Both 2D and 3D CAD systems can be used to produce technical drawings for any discipline; each one (electrical, electronic, pneumatic, hydraulic, ...) have industry recognized symbols to represent common components (§ Module 5.6.1).

2D CAD systems such as *AutoCAD* or *MicroStation* replaced the paper drawing discipline (§ Module 5.6.1). The necessary lines, circles, arcs, and curves are created within the software, but it is down to the skill of the user to produce the drawing. A 2D CAD system is merely an electronic drawing board, and there is still much scope for error when representing orthographic projections, auxiliary projections and cross-section views. Its greatest strength over paper drawing is in the making of revisions. Whereas in conventional hand drawing a new drawing must be made from scratch if a mistake is found or a modification is required, in 2D CAD the system allows a copy of the original to be modified, saving considerable time. 2D CAD systems can be used to create plans for large projects such as aircraft but do not provide an easy way to check if the various components will fit together.

3D CAD systems (such as *CATIA*, NX Graphics, CREO, *Autodesk Inventor*, or *SolidWorks*) first produce the 3D geometry of the part, and the technical drawing comes from user defined views of that geometry. Any orthographic, projected or sectioned view is created by the software. There is no scope for error in the production of those representations. The main scope for error comes in setting the projection parameters and in displaying the relevant symbols on the technical drawing. Nowadays AutoCAD and other traditional 2D software also have the capability to build 3D parametric drawings, however they were not originally developed for this kind of work. On its turn, 3D CAD allows for individual parts to be assembled together to represent the final product. Buildings, aircraft, ships, and cars are modelled, assembled, and checked in 3D before technical drawings are released for manufacture. Widely used CAD/CAM software packages in the aerospace industry include *CATIA* from Dassault Systemes. The biggest companies operating in the sector use CATIA to do design, and most of them also to manage, the project [7].

3D CAD models can be wireframe, surfaces or solid (§ Module 5.6.2). The final model is usually a solid, but most of the solids in advanced modeling are generated stating from a wire-frame, then to a surface model, that is finally transformed in a solid model. Nowadays, some companies are working only with 3D electronic versions of the drawings (with no need to produce 2D drawings). In this case, the 3D drawings are annotated with symbols and notes to include all the information necessary for production. The 3D model can be used for a large variety of disciplines such as *rendering*, 3D-animation, ergonomic studies, calculation (CAE, Computer Aided Engineering), manufacturing (CAM, Computer Aided Manufacturing) and for machine numerical control (CNC, Computer Numerical Control) (§ Module 5.6.3).

6 AIRCRAFT DESIGN

6.1 PROJECT MANAGEMENT

Project management is much more than simply planning the activities of the project like wproposed for Learn&Fly. The main objective of project management is to initiate, plan, execute, control, close the project and to allocate the teamwork to achieve specific goals at the specified time. These goals are the project requirements, which must comply with the client's objectives. Nowadays, the principles from lean manufacturing has been introduced in project management, focusing in the value to the client with less waste and reduced time.

A Gantt chat is one of the tools generally used to plan, show the dependency relationships between the activities and allocate people to a project [52]. Henry Gantt first implemented it around the years 1910–1915. In that time Gantt charts were drawn in paper, limiting its update when is necessary to adjust schedule changes. Nowadays Gantt charts are drawn in a computer, using specific software (some of it freeware), or implemented in simple spreadsheets (with much less managements tools). Computer software based in Gantt chats is nowadays one of the most widely used management tools for project scheduling and control [52]. With the advance of internet, these charts can become easily available online for the team, allowing collaborative work.

The figure presented in slides (Section 6.2) exemplifies one Gantt charts were it is possible to create all the tasks, the dependency between them and to allocate resources. Most of these allows analysing in real time the progress of the project in proportion to the degree of their completion and provide visual representation of how the project and its tasks are ahead or behind schedule.

6.2 PRODUCT DEVELOPMENT

Every product that must be developed following a series of stages involved in bringing a product from concept or idea, through certification and beyond. Product development incorporates a product’s entire journey. In general is usual to have several stages in product development like: concept, preliminary design, development, production and certification. Before starting concept is necessary to stablishing design requirements and conducting requirement analysis, sometimes termed problem definition. These include basic things like the functions, attributes, and specifications. The concept stage is often a phase of project planning that includes producing ideas and taking into account the pros and cons of implementing those ideas. There are several used techniques to help generating these concepts [53]. The preliminary design is some way between concept and development stages. In this phase the ideas form conceptualization are someway detailed with the help of some schematics, diagrams, and layouts of the project to provide the early project configuration. After this the development starts, detailing every feature of the project, which includes procurement of materials. In this phase technical drawings are produced through solid modelling (3D drawings), including assemblies, detailed 2D drawings for manufacturing, simulations, documentation, etc.. Computer-aided design software (CAD) can provide the designer all the required tools integrated to perform all these tasks with only one product. After development stage, starts production with planning. This consists of planning how to produce the product and which tools should be used in the manufacturing process. This step includes determination of the sequence of operations, selection of tools such as jigs, fixtures, cutting and forming tools. After planning, tools, jigs, molds etc.. are designed, produced and tested to give support for production.

Qualification and Certification is the last stage and one of the most important ones in products for aeronautical industry. This stage is only represented at the end, but all stages from concept to production must have in mind all the certification requirements.

For each stage, there are a series of milestones. This includes the System Concept Review (focuses on design objectives, requirements definition, design concepts, project feasibility, and overall schedule and budget), the Preliminary Design Review (reviews the initial design of subsystems, interfaces, and configuration items relative to the design requirement), the Critical Design Review (is one of the most important milestones and reviews of all the design for production). After this, starts the production and sometimes a production review is necessary. At the end comes the First article inspection (FAI) that involves supplier and purchaser to ensure that the production process reliably produces what is intended. The AS9102 standard [41], provides the requirements for aerospace components First Article Inspection. FAI must be repeated whenever there is a change in design that affects the fit, form, function of the product or if the production process used to make the part changes manufacture (e.g. tooling, processes, machine, location, sequence of manufacture).

6.3 PRODUCT SUSTAINABILITY

Any designer or engineer must have in mind that the world has a limited number of resources and that any decision may cause serious environmental impacts in the future. He must be able to continuously look for new products where new materials and production methods can be used together with a sustainable design. According to Ljungberg [54], the resources of energy will probably be more critical in the future than probably the availability of materials. In addition, the relation between material and energy is obvious. There are thousands of different materials involved in simple products that are used every day. Estimations indicated that are probably over than 100.000 commercial materials on the market with respect to the great amount of variants. This causes extremely complex the products life cycle from extraction of material to waste or deposition of the used product [53].

The product development for successful products can be strengthened following seven principles as follows [53]:

- Material. Minimise the material use and try to use renewable materials. Minimise the energy consumption during the LCA and avoid toxic materials, etc.
- Economy. Product and service must be cost efficient and comparable with similar products. Consider the total cost during the life cycle including the cost for restoring environmental impacts. What about ownership, serviceability, PSS?
- Design. Design for the environment and the product user as well as for recycling!
- Market. Develop products and design them according to the needs from the specific market and target group.
- Equity. Is the trading equitable and what is the impact on the local and global community? What about
- Employee conditions of work?
- Technology. Optimise the extraction of raw materials, production, lifetime and quality and functionality of the product.
- Ecology. Eliminate emissions and waste and minimise the environmental impact.

6.4 TECHNICAL REQUIREMENTS

Aspects such as performance, reliability, cost, availability must be considered to successfully complete a project. However, technical requirements can be much more than this and the project manager must select witch ones real matters for the consumer. The Kano model, developed by Professor Noriaki Kano in the 1908s, can be used for product development and customer satisfaction, classifying the customer preferences along five attributes, namely, “Attractive”, “Onedimensional”, “Must-be”, “Indifferent”, and “Reverse” [55].

Slides from section 6.4 identify some of these attributes applied to the aircraft that students must develop for Learn&Fly challenge.

- Must-be attributes: these attributes are expected to be implicitly present in the product. When these are not present or presented at a poor level then the customer may become extremely unsatisfied. For Learn&Fly Challenge these are explicit in the Regulations - Aircraft Requirements. Nor fulfilling all these requirements penalties should apply or even disqualification;
- One-dimensional attributes: these are the attributes which are linearly correlated with satisfaction. Also called performance features. i.e. as better you execute these, better it will be the customer satisfaction. Some examples are provided in the slides like: light construction; small drag or mass and balance well done;
- Attractive attributes: these are attributes which are unexpected or innovations. However, absence of these attributes do not dissatisfy a supplier. Examples are provided like: new wing shape, different stabilizer shape, solution for easy wing disassembly;
- Indifferent attributes: these are attributes with which customers will become neither satisfied not dissatisfied with their performance level. Examples: nice painting, all made from carbon fiber;
- Reverse attributes: these are attributes whose presence result in dissatisfaction like standing support attached to the aircraft or even for example landing gear that will increase weight and drag force, unless it is essential for example to avoid the aircraft to get damaged when landing.

6.5 TOOL TO CONCEPT A GLIDER MODEL

Section 6.5 of the slides provides a spreadsheet tool to concept the glider model. Engineers in the early stages of product development usually use simple tools to concept their models and to have a general idea how the product should be to meet the requirements. These tools are in general implemented in spreadsheets and most of the time are based in empirical models that were developed from previous knowledge or modelling some basic physical aspects with many assumptions to keep it simple.

The spreadsheet available together with the slides “Tool do Concept Glider Model”, was developed taken in account general dimensions that are empirically used in the development of aircraft models. The initial dimensions of the glider/aircraft can be obtained using this tool, however these many not be the optimal ones. The intension of this tool is to provide a simple way for the students to define the first iteration of its glider, that has a big probability to fly, and for the students to get used to a spreadsheets.

Almost of all the dimensions of the glider are directly related to the wing chord “C” (imaginary straight line joining the leading edge and trailing edge of an aerofoil, as provided in the images of the slides and in Figure 62). This means that if students define the wing chord all the other dimensions become defined, between certain limits. The limits are indicative and are indicated in column Min and Max, becoming the column "Value used" green if inside the limits and yellow if outside. If some dimensions passes the limits provided does not means that the aircraft does not fly. Sometimes, for an optimum design, it is necessary to pass some of these limits. Some longitudinal dimensions are relative to the centre of pressure of the wing that is close to ¼ of the leading edge of the wing, according to Figure 62. In Table 10 you can find some explanations of some parameters provided in the "Tool do Concept Glider Model". Most of these parameters are required for the students to simulate da glider in X-Plane (§ Module 7) or to build the glider (§ Module 6).

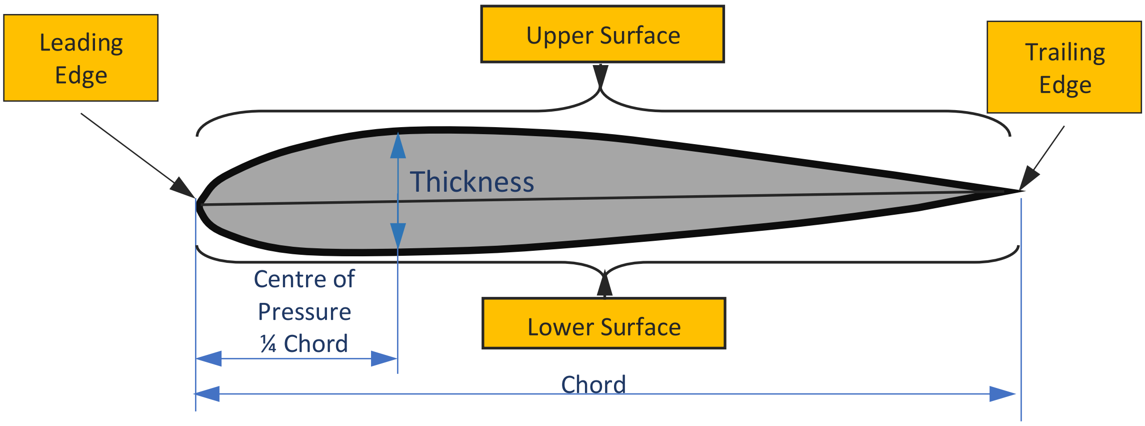


Figure 62. Airfoil profile, identifying the wing chord.

Table 10. Explanations of the spreadsheet "Tool do Concept Glider Model"

	Symbol	Formula	Obs.
Wings			
Root Chord (C)	C	C	Average chord of the wing
Wingspan (if glider 8 to 10C or more)	E	E/C	The wingspan (total dimension of the wing)
Incidence angle of wing [º]	AI		This is the angle that the wing must have when assembled, relative to the fuselage
Longitudinal position of wing	La	N + 1/4 C	This is the position of the wing (centre of pressure) relative to the nose of the aircraft. For balance proposes sometimes is better to have a bigger nose.
Area of wing [unit]^2	A	C x E	The area of the wing has a limit, which must be fulfilled, specified by the Learn&Fly Challenge Regulations.
Fuselage			
From wing leading edge to nose (1C)	N	C	Position of the wing (leading edge) relative to the nose of the aircraft.
From wing tail to leading edge of stabilizer (1,5 to 2C)	F	2 x C	Size from the wing trailing edge to the leading edge of stabilizer

Fuselage total length (N+C+F+Ch)	L	N+C+F+Ch	Total size of the fuselage
Fuselage diameter	D		Diameter of the fuselage, required for simulation purposes in X-Plane.
Horizontal stabilizer			
Chord of horizontal stabilizer (2/3 to 3/4 of C)	Ch	¾ x C	Average chord of the horizontal stabilizer
Length of horizontal stabilizer (2 to 2,5C)	Eh	2 x C	Total length of the horizontal stabilizer
Incidence angle of horizontal stabilizer (0º to 5°) [º]	Ih	-5	This is the angle that the hor. stab. must have when assembled, relative to the fuselage. It can be positive if the centre is gravity is behind the centre of pressure.
Longitudinal position of horizontal stabilizer (of C)	Lh	N+C+F+¼xCh	This is the position of the hor. stab. (centre of pressure) relative to the nose of the aircraft.
Vertical stabilizer			
Chord of vertical stabilizer (3/4 to 1C)	Cv	¾ x C	Average chord of the vertical stabilizer
Height of vertical stabilizer (1C)	Ev	C	Height of vertical stabilizer
Longitudinal position of vertical stabilizer	Lv	N+C+F+¼xCv	This is the position of the vert. stab. (centre of pressure) relative to the nose of the aircraft.
Control Surfaces (optional)			May be necessary for X-Plane modeling
Chord of horizontal stabilizer (1/3 of stabilizer chord)	Clp	1/3 x Ch	This is the average chord of the rudder
Chord of vertical stabilizer (1/2 of stabilizer chord)	Cld	1/2 x Cv	This is the average chord of the elevator
Aileron chord (1/3 of C)	Cla	1/3 x C	This is the average chord of the aileron
Aileron length (2C)	Ela	2 x C	This is the length of the aileron
Centre of gravity position (CG) ((N + 0.1 C) to (N + 0.3 C))	CG	1.23 x C	This is the recommended centre of gravity position, relative to the nose.

6.6 GLIDE RATIO

Glide Ratio, also called Glide Slope Ratio indicates how well a glider flies through the air. Generally, this also applies to aircrafts (heavier than the air) that are flying like a glider (aircraft unpowered). This indicates how far did the glider travel forward for every foot or meter it dropped in altitude.

Glide Ratio = Horizontal Distance Traveled divided by the Altitude Lost.
(§ Module 6.6)

There are several parameters that influence the glide ratio. One of the most important is the aerodynamics, strongly influenced by the speed. The best speed for range corresponds to an angle of attack, which gives the best lift-to-drag ratio. As better is the relation of Lift/Drag (see

Module 3 and next section) better it will be the glide ratio. Wing drag can also be reduced increasing the aspect ratio of the wing and changing the shape of the wing at the wing tip, according to section 6.8. Obviously, everything matters, including the aerodynamics of the fuselage (that must have the lowest drag possible) and of the stabilizers. Note that the weight of the aircraft will also influence, being necessary to determine the best speed taking in account that the forces acting in the aircraft also changed. A well balanced aircraft will reduce the forces induced in the stabilizers, reducing drag.

6.7 AIRFOIL DESIGN

The airfoil design has a strong influence in the aerodynamics, creating the lift force (L) to sustain the weight, but also creating a drag force (D) that must be reduced as possible. To calculate the lift and drag forces, the C_L and the C_D coefficients must be obtained for each specific airfoil. In internet, searching for example for “airfoil profile” you will find a lot of tools available, most of them free, to determine the values of C_L and C_D and the shape for thousands of airfoil profiles. The site http://airfoiltools.com is one of these examples. The best airfoil profile dependents on many parameters, including the type of aircraft, the wing shape and the usual speed of the aircraft. For the aircraft you are designing, that flies like a glider, it is very important to achieve the highest possible relation of C_L/C_D with a certain angle between the chord and the airflow, incidence angle (alpha angle). Most of the airfoil profiles were developed by the National Advisory Committee for Aeronautics (NACA), being organized by NACA numbers. The parameters in the numerical code followed by NACA can be entered into equations to generate the cross-section of the airfoil and calculate its properties [56]. Each NACA airfoil series has its ideal range of operation as it can be seen in [56].

Slides present as an example two common profiles for general aviation (NACA 2412 and Clark Y (non NACA profile)). With these profiles a Glider can fly well but there are better profiles for low speed that students may found. The best profile should have the highest relation as possible of C_L/C_D for a specific alpha angle (angle between the chord and the air flow). In general an alpha value of 2º is recommended for aircrafts.

In section 6.7 the formulas to calculate C_L and C_D are provided, including the values of some required parameters.

The 2D geometry of the airfoil can be downloaded from web sites like http://airfoiltools.com, in a form of coordinates, that can be used in a spreadsheet of a CAD software. This geometry can then be printed on paper to cut the wing ribs with the right section or in a 3D printer. To generate the 3D drawing for 3D printing students can use freeware software like Fusion 360® (from Autodesk®) or FREECAD. To import points to CAD software you can find in internet to do it by searching for “Importing XYZ into …”.

6.8 WING DRAG

The parameters of C_L and C_D, and consequently lift and drag, calculated in last section, are valid for an infinite wing. If the wing has finite dimensions, corrections must be done that are out of the scope of this project. However, students must be aware about this problem and can improve the wing to increase its efficiency. The wing tip is the most problematic factor affecting the behaviour of the wing. Due to the difference in pressure between the lower and upper parts of a wing, unwanted airflow and vortexes tends to be created according Figure 63, losing energy.

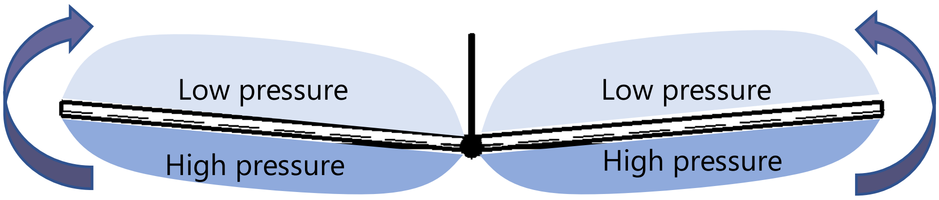


Figure 63. Difference in pressure between the lower and upper parts of a wing.

To reduce this problem, designers try to reduce the wing tip size by increasing the aspect ratio of the wing (wing span/chord), Figure 64, or by changing the wing shape (to elliptical or tapered), or create a wing winglet like Figure 65. However all this features are sometimes difficult to produce increasing the productions costs.

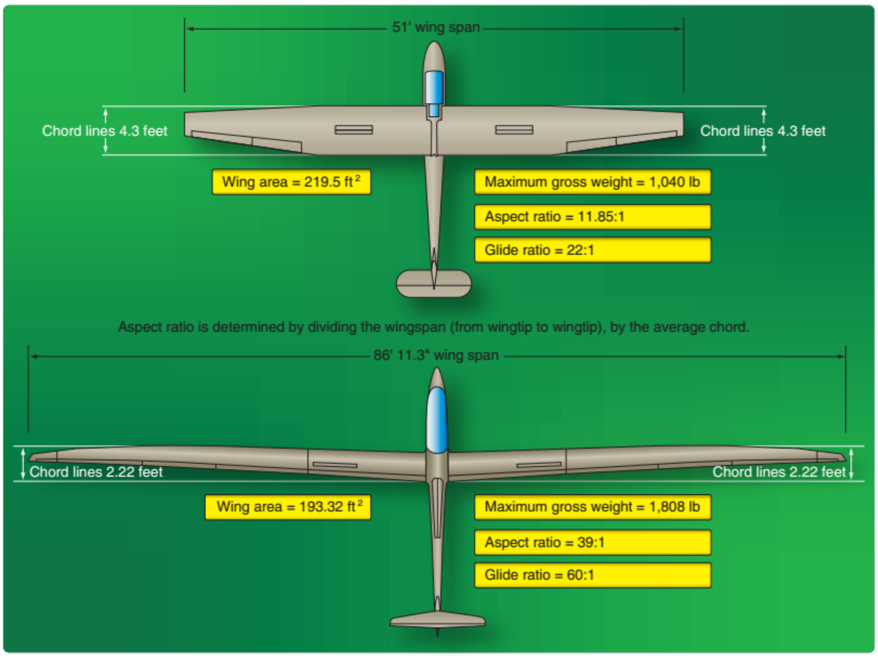


Figure 64. Influence of Aspect Ratio in Glide Ratio [57].

Figure 65. Boeing 737-700 with winglets.

6.9 LATERAL STABILITY

The glider developed has no control surfaces that can control the movement of the aircraft like the rudder, elevator or flaps. To ensure a proper flight and to fly a longer distance according to Learn&Fly Challenge, the glider shall fly as straighter as possible. However due to some unbalance in the aircraft or even some wing or changes in pressure from left part of wing to the right part of the wing, the aircraft can have a tendency to turn to one side. To reduce this behaviour a dihedral angle, Figure 66, can be added improving considerably the tendency to return to wings-level flight. In Figure 67 is shown that adding some dihedral when the aircraft tends to turn to one side, the lift force increases in the wing that lowers turning it back to wings-level flight.

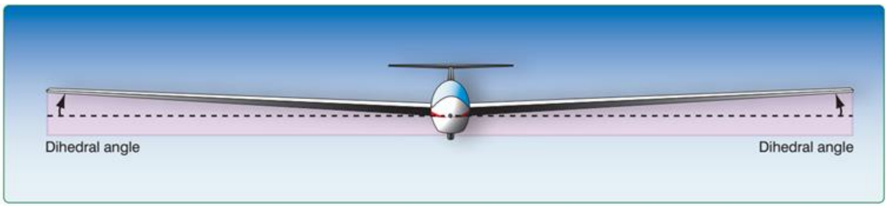


Figure 66. Dihedral angle

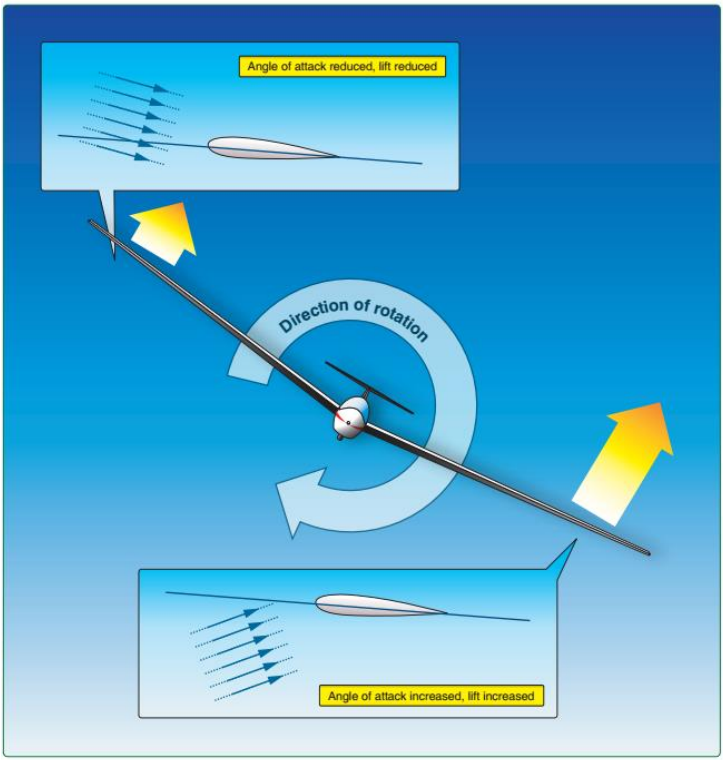


Figure 67. Lateral stability

6.10 MATERIALS SELECTION

Module 2 provides and overview of the materials used to build aircrafts (§ Module 2). To build model aircrafts the materials are different form the ones applied in real aircrafts because the requirements are others, at least in terms of scale. For example in most aircrafts the skin is made from thin aluminium sheet. It would be impracticable to produce extremely thin aluminium sheet for the model aircraft, so other materials may be used.

For Learn&Fly challenge there is a base kit of materials proposed. These are easily found in the market at a low cost and that can be used as first approach to build a good aircraft. However, students are free and should be encourage, to use different materials that can be more appropriated than the ones presented.

6.11 FUSES

In many situations, aircrafts have fuses to protect some mechanical systems from damage. For example is failure occurs in an engine and this creates excessive vibrations to the wings, it may damage also the wing. In this case the engines are supported by fuses, losing the engine and avoid extending the damage to the wings. So the aircraft can fly without the engine (in the limit like a glider if no other engine is working) but the aircraft cannot fly of be controlled without wing.

For Learn&Fly Challenge, in order to fulfil all the requirements of the regulations, fuses can be applied to sustain some structural parts of the aircraft. These can break under certain circumstances, for example during the drop test or when the aircraft crashes in the ground, and must be reassemble in a limit time, as specified in the regulations.

6.12 DRAWINGS

Chapter 5 provides and overview about technical drawing that must be studied to provide some background for students to be able to produce the required drawing for the report that they should submit for the Learn&Fly Challenge.

Drawings for the report can be made by hand, or using CAD software, like AutoCAD® or parametric 3D native software. Orthogonal projections (multiview) should be provided with details of some features like attachments, wings, stabilizers, etc… with dimensions. It is recommended to add also an isometric view, with balloons, to identify each part that should be listed in the bill of materials (BOM).

The BOM in technical drawings as a lot of relevant information about each part or assembly, like quantities, part number, description, materials used, applied standards, moulds, etc. For Learn&Fly challenge this list does not require to be so complete, however the cost of materials should be included as the regulations impose a limit in terms of budget.

6.13 MASS AND BALANCE

An aircraft is in equilibrium when all of its forces are in balance (§ Module 3). One of the most important factors to ensure longitudinal stability is the position of the centre of gravity (CG). The CG is the point at which the total force of gravity is considered to act. Experimentally, the position of the CG can be determined by attaching the aircraft to a simple point (the CG) with a flexible cable. If the attachment point coincides with the CG then the aircraft remains in the horizontal position. If not, it is necessary to move the attachment point to find the correct CG position.

In an aircraft the CG position should be a bit forward in relation to the lift force (L) (located at approximately at position ¼ of the wing chord). The pitch moment created between the L force is equilibrated by the horizontal stabilizer that must produce a down force (F). For this to happen, the horizontal stabilizer must have a negative incidence angle (angle relative to the fuselage). Depending in the relative position of the L to W, F must increase or decrease. This compensation is made in real aircrafts with small trim adjustments, that depending on the aircraft, can introduce a small movement in the elevator to introduce this compensation. However this compensation is limited, meaning that the CG only can change within certain limits, as explained in slides from Module 3.

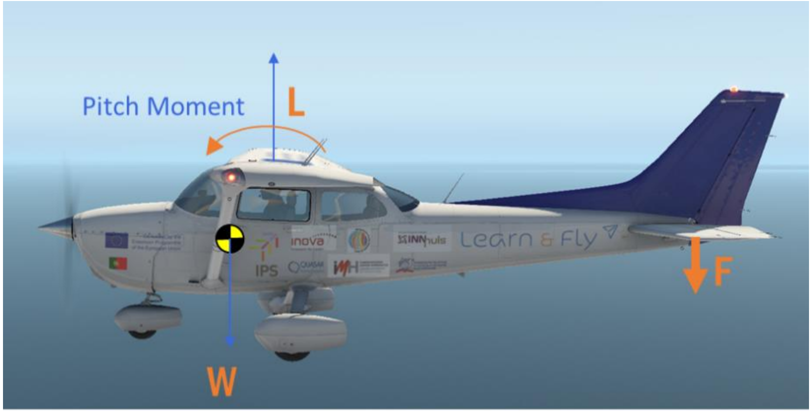
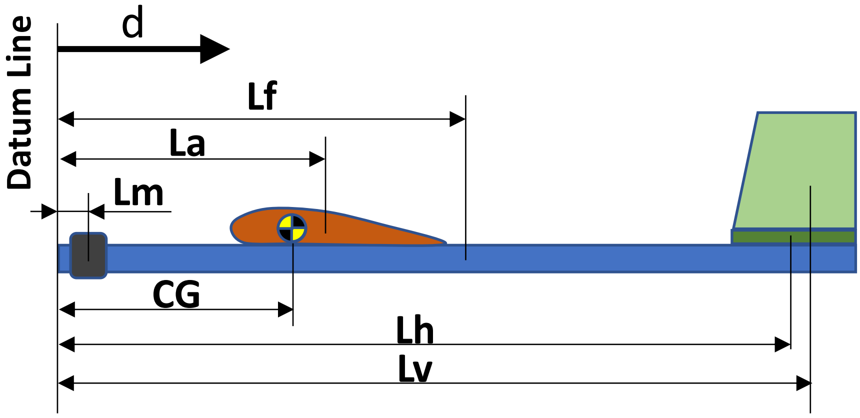


Figure 68. Principal Vertical forces acting in and aircraft.

For students to understand physics it is required that they can estimate the position of the CG mathematically. As explained in Slides, module 3.4.1, the CG can be determined, knowing that the total moment relative to a point must be zero.

Particularizing for the case of a model aircraft, students must develop their model in such way that the center of gravity must be close to the L force (1/4 of the wing chord). For this to happen, in general, they must add some weight (that they have to calculate) in the nose of the aircraft. According to Figure 69, they should find the mass in Lm position (nose) to put the CG at about 1/4 of the wing chord or a bit to the front.



CG – Centre of gravity position
Lf – Longitudinal position of fuselage
La - Longitudinal position of wing
Lm - Longitudinal position of added mass
Lh - Longitudinal position of horizontal stabilizer
Lv - Longitudinal position of vertical stabilizer

Figure 69. Nomenclature to calculate the CG position.

The CG position can be calculated by the formula, derived from moment equilibrium:

$$CG = \frac{\sum(Weight\ x\ d)}{\sum Weight} \tag{5}$$

Being:

the Weight the individual weights of each component and d the distance of each component (Lf, La, Lm, Lh, Lv …) to the datum line (CG position of each one) . $\sum Weight$ represents the weight of the whole aircraft.

The weight of each component (fuselage, wing, added mass, horizontal stab. Vertical stab. and others) can be calculated using the table with materials densities at the end of slides (§ Module 6.13).

To verify and adjust experimentally the CG of the aircraft (by adding or removing mass in the nose), students must support the aircraft in two points close to ¼ of the chord (or a bit to the front) and check is it remains horizontal (§ Module 6.13).

6.14 HOW TO LAUNCH YOUR AIRCRAFT

The launching technique is of major importance to have a good flight. Slide in section 6.14 provides some basic recommendations to perform a good launching. Better than everything is to test launching several times to improve the technique.

During flight, students must understand if the glider is flying or not properly. In general the usual problem is that the glides is not in balance, causing the glider to stall or dive according to last slide of sections 6.14.

This behaviour can also be adjusted by increasing or decreasing the incidence angle of the horizontal stabilizer (angle relative to the fuselage). In general optimum and stable configuration can be achieved having the CG a bit to the front of the centre of pressure (L force position) (¼ of the chord) and a small negative incidence angle (force down in the horizontal stab.).

6.15 HOW TO MEASURE TRAVELLED DISTANCE

In order to evaluate the flight distance and beauty of flight, in Learn&Fly challenge, the only distance accounted (measured travelled distance) is projected to the ideal flight distance, as shown in Figure 70. This can be done simply by extending the Launching Line (blue line in Figure 70) and measure directly the distance from the CG of the aircraft (even if this disassembles) to that line (blue dimension).

However, to introduce some mathematical concepts, it is recommended to use Pythagorean Theorem.

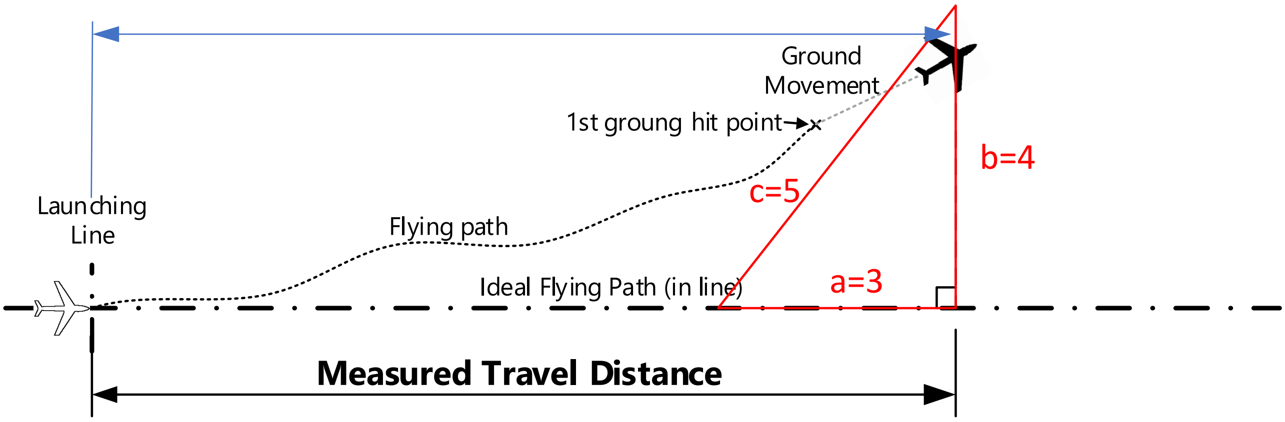


Figure 70. How to measure travelled distance

According to Pythagorean Theorem, the triangle is rectangle (has one angle with 90º), if the sum of the sides square 2 are equal to the hypotenuse square 2. From Figure 70 this means that:

$$a^2 + b^2 = c^2$$

If students cut a thread with size (3+4+5 = 12 meters) and make a mark with 3 meters, 4 meters and remain one will have 5 meters. They can use multiples of the side dimensions to define the triangle. For example 1.5 X more will have (4.5 + 6 + 7.5 = 18 meters)

$$3^2 + 4^2 = 5^2$$
$$9 + 16 = 25$$

Verified!

7 SIMULATION

7.1 INTRODUCTION

Computer simulation is the reproduction of the behaviour of a system using a computer to mimic the outcomes of a mathematical model associated with that system. Since it allows to check the reliability of chosen mathematical models, computer simulations have become a useful tool for the study of many natural and human systems [58], including aircraft design and engineering. Simulation of a system is represented as the running of the system's model output by providing input data. It can be used to explore and gain new insights into new technology and to estimate the performance of systems too complex for analytical solutions [58].

In this context, a flight simulator is a device that artificially recreates aircraft flight and the flight environment, aimed for pilot training, aircraft design, or other purposes [59]. It includes replicating the equations that govern how aircraft fly, how they react to applications of flight controls, the effects of other aircraft systems, and how the aircraft reacts to external factors such as air density, turbulence, wind shear, cloud, and precipitation. Flight simulation is used for a variety of reasons, including flight training (mainly of pilots), the design and development of the aircraft itself, and research into aircraft characteristics and control handling qualities.

The European Aviation Safety Agency (EASA) defines several categories and levels of flight simulators (§ Module 7.1): the more basic is the Flight Navigation and Procedures Trainer (FNPT) level, followed by the Flight Training Devices (FTD) level; the most advanced simulators are classified as Full Flight Simulators (FFS).

7.2 THE X-PLANE FLIGHT SIMULATOR

X-Plane [60] is a commercially available program, produced by Laminar Research (USA), which can be run on about any home computer. It is packaged with several commercial, military and other aircraft, as well as with basic global scenery which cover most of the Earth surface (from 74° north to 60° south), including over 33,000 airports [61]. The programme includes several aircraft in the base package and additionally, more than 1,400 other models can be downloaded from the internet [61], many of which for free.

The X-Plane simulator has several features that make it useful as an engineering tool, since the way it computes the trajectory of a flying machine (§ Module 7.2) allows users to design and test their own aircraft [61]. X-Plane can create complex aircraft designs, including helicopters, rockets, rotorcraft, and tilt-rotor craft. The program then models the forces and moments acting upon the aircraft and individually evaluates their effect on the parts that constitute it, both in subsonic and supersonic flight dynamics. The lift and drag of each section are calculated, and the resulting effect is applied to the whole virtual aircraft. The simulated aircraft is then put to fly. This approach allows users to quickly and easily design an aircraft, as the simulator engine immediately illustrates how an aircraft with a given design might perform in the real world.

The Demo package of X-Plane is completely free for home users. It has some limitations but none of them invalidates it’s use in the frame of the Learn&Fly Challenge. Home users or users under K12 institutions can buy X-Plane for $69 (2018 value) if they want to use X-Plane for other purposes.

In the Learn&Fly Challenge students will use the X-Plane flight simulator to design and optimize the glider that they must develop and build. The tasks required to simulate the model are:

1. Define the model to be simulated (§ Module 6.5). The provided spreadsheet tool (§ Module 6) can be used to conceptualize the glider model.

2. Create the model in the Plane Maker developer (§ Module 7.3) [62].
3. Run the model in X-Plane simulator (§ Module 7.4).

The X-Plane includes some development tools to create custom scenery, airports and aircrafts. These tools are free and no experience is required to handle them.

7.3 WORLD EDITOR AND PLANE MAKER

X-Plane also includes some development tools to create custom scenery, airports and aircrafts. These tools are free and no experience is required.

7.3.1 World Editor

Is a tool that can be used to create custom scenery and airports. In fact, X-Plane is designed specifically to enable users to create and modify scenery themselves, which can include essentially everything outside the aircraft, [63].

7.3.2 Plane Maker

The Plane Maker is a program bundled with X-Plane that allows users to design their own aircraft. Using this software, nearly any imaginable aircraft can be built. Once all the physical specifications of the aircraft have been entered (e.g., weight, wing span, control deflections, engine power, airfoil sections), the X-Plane simulator will predict how that plane will fly under imposed real world conditions, evaluating its performance just like it does for the program's built-in aircraft [60].

The slides (§ Module 7.3.2) provide step-by-step information how to create a simple glider, according to the instructions provided in section 6 (Aircraft Design). The Plane Maker Manual [62] supplies the workflow to create a model, as follows. Because students will be creating a model glider, most of these tasks (striken out) are not required:

1. Decide on a design (§ Module 6.5).
2. Create the fuselage, wings, and tail of the aircraft.
3. Create secondary objects, such as landing gears and engine nacelles.
4. ~~Set up the systems and internal properties, including the engines, electrical systems~~, weight and balance, ~~and viewpoints.~~
5. ~~Set up any additional features of the aircraft, such as added weapons or special controls.~~
6. Create a 2D instrument panel (optional but recommended).
7. Test-fly the aircraft in X-Plane and fine-tune the features of the aircraft from steps 2 to 6 as needed.
8. ~~Add textures, 3-D objects, extra liveries, etc~~.

The free-access Plane Maker Manual [62] contains more detailed and complete information about the software.

7.4 X-PLANE

Similarly to the last section, the Module 7 slides provide step-by-step information on how to fly the glider. Since it is only a model glider, to be launched be hand, the simulation must be paused (by pressing “p”) as soon as X-Plane start to put the glider in the air and give it the launching speed. This is the way how we put the glider in the air and launch it (by pressing “i”). In the Challenge conditions the altitude at which the gliders are launched is about 2 meters. However, in simulation 2 metres would result too slow and it would be difficult to evaluate glider behaviour. In as much, it is recommend to add 100 ft to the altitude (about 33 meters), or more, for simulation purposes. For more detailed and complete information about simulation using the X-Plane, the X-Plane11 User’s Manual should be consulted [61].

After modelling and simulating the first approach to the glider, the students must improve the model. It is recommended to give them some support in planning their tries and to report them to the Learn&Fly Report Template available in the Moodle platform.

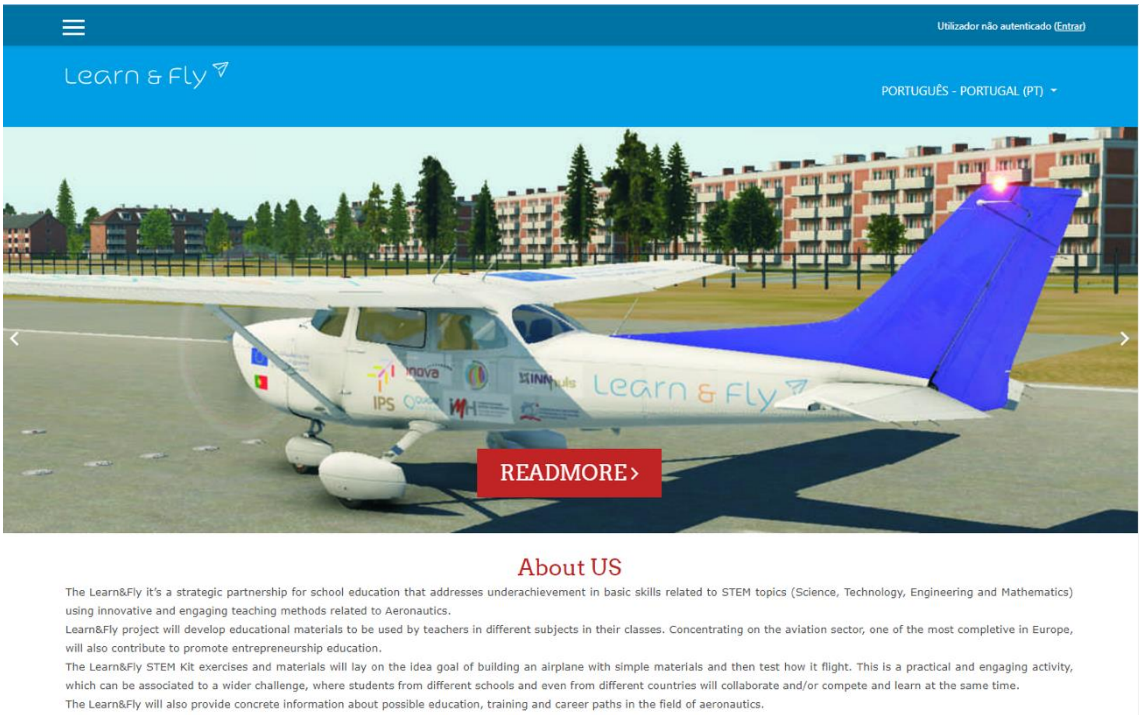
8 MOODLE

8.1 INTRODUCTION TO THE MOODLE PLATFORM

Moodle is an Online Learning Management System designed to provide educators, administrators and learners a robust, secure and integrated system to create personalised learning environments. Educators can create their own courses, extending learning to anytime and anywhere. Its development was guided by social constructionist pedagogy and delivers a powerful set of learner-centric tools and collaborative learning environments that empower and support both teaching and learning [64]. Additionally, it has multilingual capabilities [64].

8.2 STEM KIT AND MOODLE

The Moodle platform was used in the context of the Learn&Fly Project to deliver the teaching/learning materials produced (STEM Kit). For this purpose, a course was created and structured to include all digital resources (including the STEM Kit slides and all sharable documents), to support the teachers' in delivering contents, communicating with the students and creating learning and assessment activities, and also to toil as a communication forum.
The Learn&Fly Moodle Platform (Figure 71) is available from: http://elearning.learn-fly.eu.

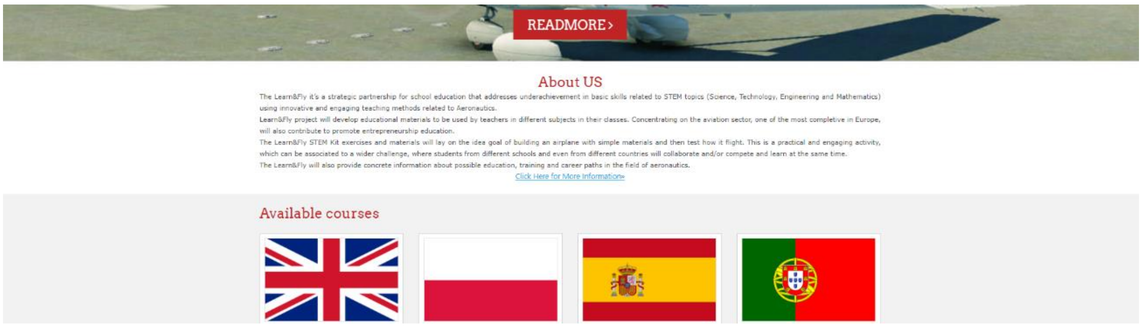


About US

The Learn&Fly it's a strategic partnership for school education that addresses underachievement in basic skills related to STEM topics (Science, Technology, Engineering and Mathematics) using innovative and engaging teaching methods related to Aeronautics.
Learn&Fly project will develop educational materials to be used by teachers in different subjects in their classes. Concentrating on the aviation sector, one of the most completive in Europe, will also contribute to promote entrepreneurship education.
The Learn&Fly STEM Kit exercises and materials will lay on the idea goal of building an airplane with simple materials and then test how it flight. This is a practical and engaging activity, which can be associated to a wider challenge, where students from different schools and even from different countries will collaborate and/or compete and learn at the same time.
The Learn&Fly will also provide concrete information about possible education, training and career paths in the field of aeronautics.

Figure 71. The front page of Learn&Fly in the Moodle platform.

All contents are available in four languages (Figure 10.2) and can be accessed by teachers and students through the front page.



About US

The Learn&Fly it's a strategic partnership for school education that addresses underachievement in basic skills related to STEM topics (Science, Technology, Engineering and Mathematics) using innovative and engaging teaching methods related to Aeronautics.
Learn&Fly project will develop educational materials to be used by teachers in different subjects in their classes. Concentrating on the aviation sector, one of the most completive in Europe, will also contribute to promote entrepreneurship education.
The Learn&Fly STEM Kit exercises and materials will lay on the idea goal of building an airplane with simple materials and then test how it flight. This is a practical and engaging activity, which can be associated to a wider challenge, where students from different schools and even from different countries will collaborate and/or compete and learn at the same time.
The Learn&Fly will also provide concrete information about possible education, training and career paths in the field of aeronautics.
Click Here for More Information»

Available courses

Figure 72. The STEM KIT is available in four languages.

8.2.1 Accessing Moodle

To access Moodle valid credentials are required from students and teachers (they will be sent by email to all enrolled students and teachers). After accessing to http://elearning.learn-fly.eu, the user must click the upper left side weblink - LOG IN (**step 1**), and afterwards fill the window form with username and password (**step 2**) and click the LOG IN button (Figure 73).

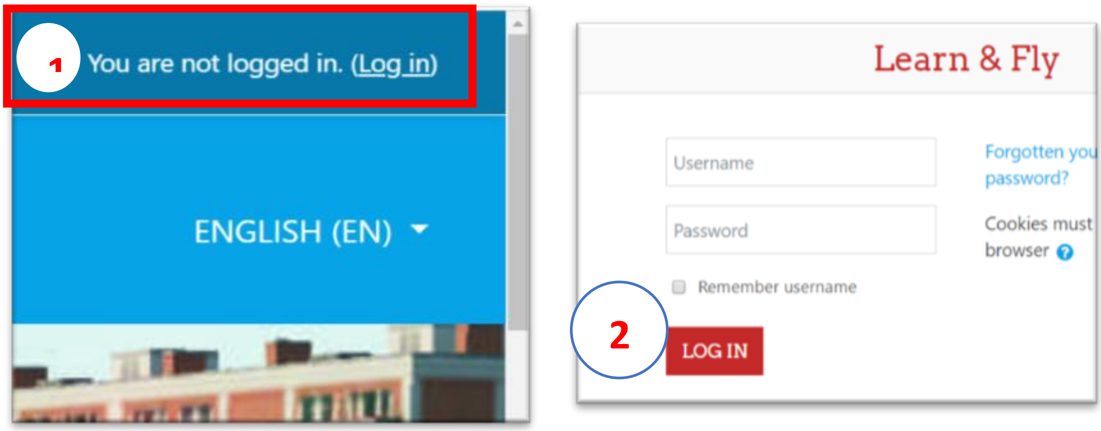

You are not logged in. (Log in)

Figure 73. Access procedure with valid credentials.

After valid login, users will see the authenticated main page (Figure 10.4).

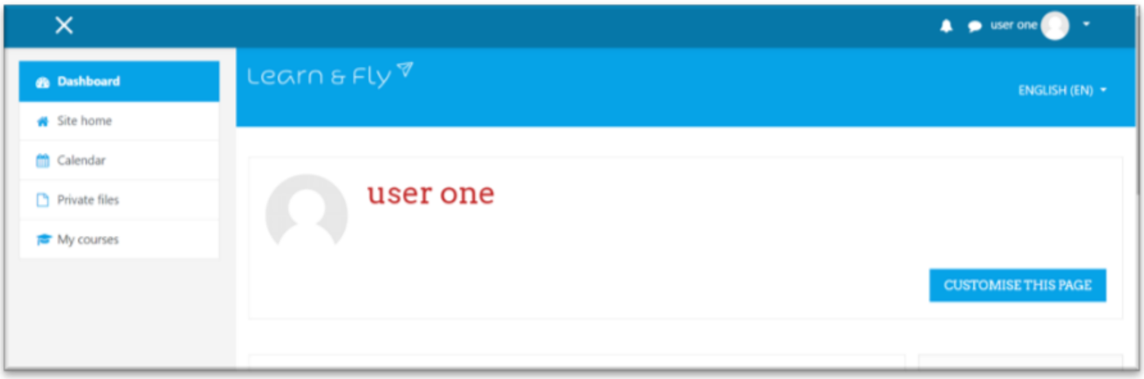


Figure 74. User authenticated main page.

After authenticating users have access to the Dashboard and to their User Profile (Figure 75), where is possible to make some personal configurations.

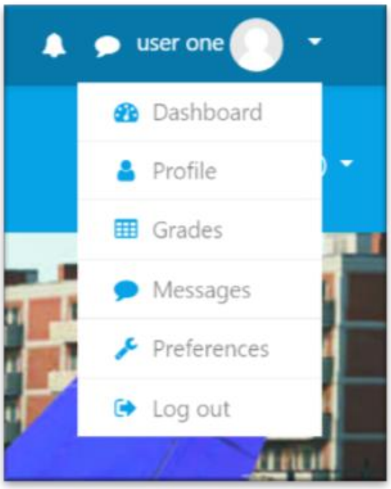


Figure 75. User Profile.

Courses are available from the Dashboard by clicking on Site Home option (Figure 10.6). By clicking on the correspondent course users' have access to the STEM Kit course main page, as shown in Figure 10.7.

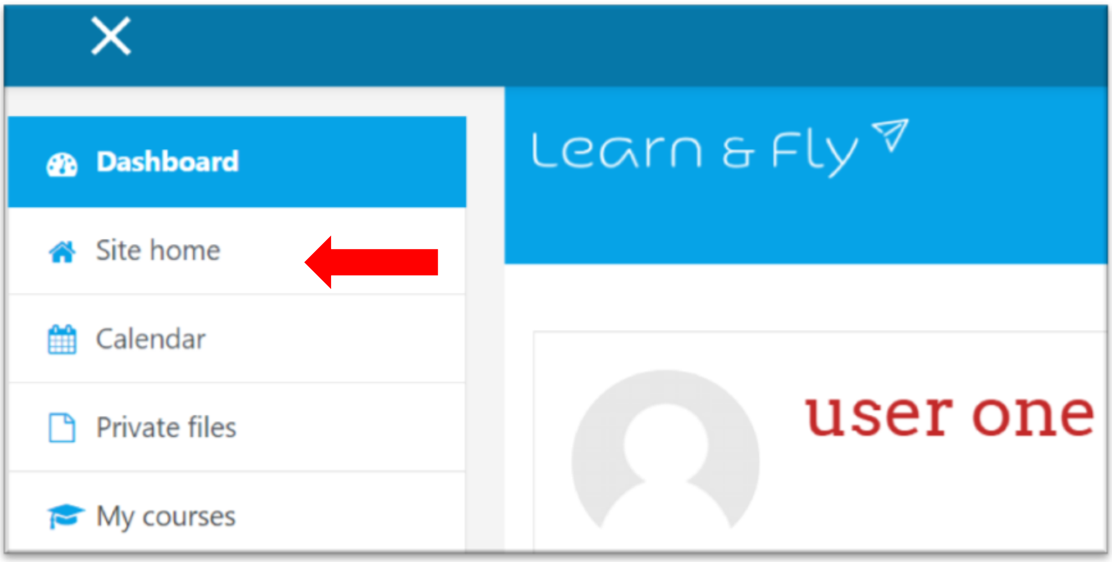
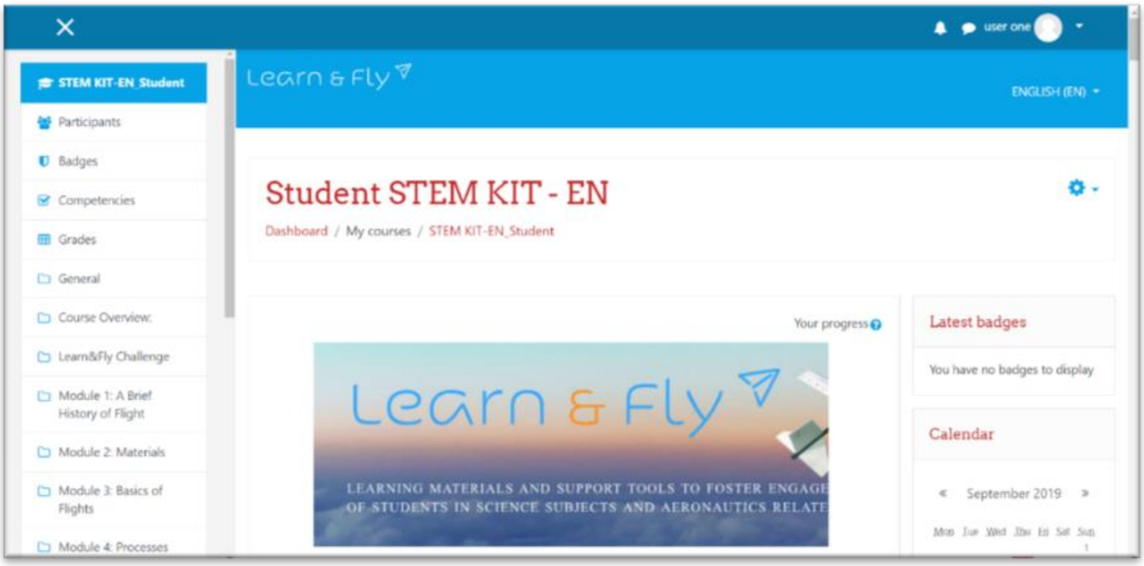


Figure 76. Dashboard Options



Student STEM KIT - EN

Dashboard / My courses / STEM KIT-EN_Student

You have no badges to display

Figure 77. Main page of the STEM Kit course

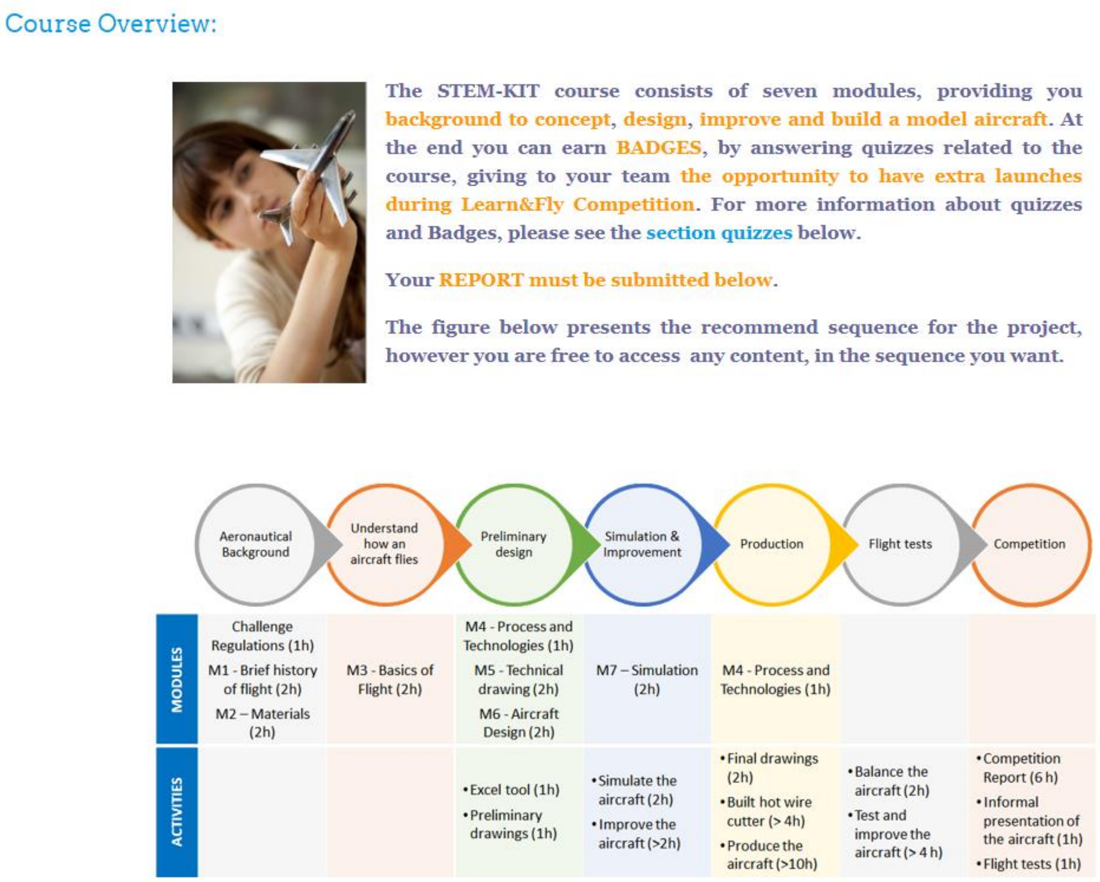
8.3 STRUCTURE OF THE STEM KIT COURSE IN MOODLE

The Course is structured in the following sections:

- Course Overview
- Learn&Fly Challenge
- Module 1: A Brief History of Flight
- Module 2: Materials
- Module 3: Basics of Flights
- Module 4: Process
- Module 5: Technical Drawings
- Module 6: Aircraft Design
- Module 7: Simulation
- Quizzes
- Get Social

8.3.1 Course overview section

Course Overview is the first section (Figure 78). Useful information about the course and Moodle are available on this section.



Course Overview:

The STEM-KIT course consists of seven modules, providing you **background to concept, design, improve and build a model aircraft**. At the end you can earn **BADGES**, by answering quizzes related to the course, giving to your team **the opportunity to have extra launches during Learn&Fly Competition**. For more information about quizzes and Badges, please see the **section quizzes** below.

Your **REPORT must be submitted below**.

The figure below presents the recommend sequence for the project, however you are free to access any content, in the sequence you want.

	Aeronautical Background	Understand how an aircraft flies	Preliminary design	Simulation & Improvement	Production	Flight tests	Competition
MODULES	Challenge Regulations (1h) M1 - Brief history of flight (2h) M2 – Materials (2h)	M3 - Basics of Flight (2h)	M4 - Process and Technologies (1h) M5 - Technical drawing (2h) M6 - Aircraft Design (2h)	M7 – Simulation (2h)	M4 - Process and Technologies (1h)		
ACTIVITIES			• Excel tool (1h) • Preliminary drawings (1h)	• Simulate the aircraft (2h) • Improve the aircraft (>2h)	• Final drawings (2h) • Built hot wire cutter (> 4h) • Produce the aircraft (>10h)	• Balance the aircraft (2h) • Test and improve the aircraft (> 4 h)	• Competition Report (6 h) • Informal presentation of the aircraft (1h) • Flight tests (1h)

Figure 78. Section regarding Course Overview.

8.3.2 Learn&Fly challenge regulations section

The second section gives to students and teachers information about the Learn&Fly Challenge Regulations and lists the materials necessary to build the aircraft. The mandatory reports to access the national and international challenges must be submitted online by the students in this section. Uploading takes place by clicking on the corresponding option from those available: Challenge Report – Upload or International Challenge Report (Figure 79).

Learn&Fly Challenge

Below, you can find information about Learn&Fly Challenge Regulations and the kit of materials necessary to built an aircraft.

- Challenge Regulations and Report Template
- Base Kit of materials recommended to build a model aircraft
- Kit of materials supplied for the international challenge
- Challenge Report - Upload

  Submit your Challenge Report in **PDF Format until 17th May at 23h55m.**

  - LearnFly Challenge - Portuguese Teams Results
- International Challenge Report - Upload

  Submit your International Challenge Report in English (PDF Format) **until 15th September at 23h55m.**

Figure 79. Section regarding the Learn&Fly Challenge.

8.3.3 Section corresponding to modules

Sections 1 to 7 deliver the STEM KIT slides. All sections present the same structure: **Module Objectives** and **Contents** related to the module (Figure 80). The contents are available in two formats: SCORM[5] and PDF File. SCORM content (Figure 81) is only accessible online; PDF can be accessed online but can also be downloaded.

Module 1: A Brief History of Flight

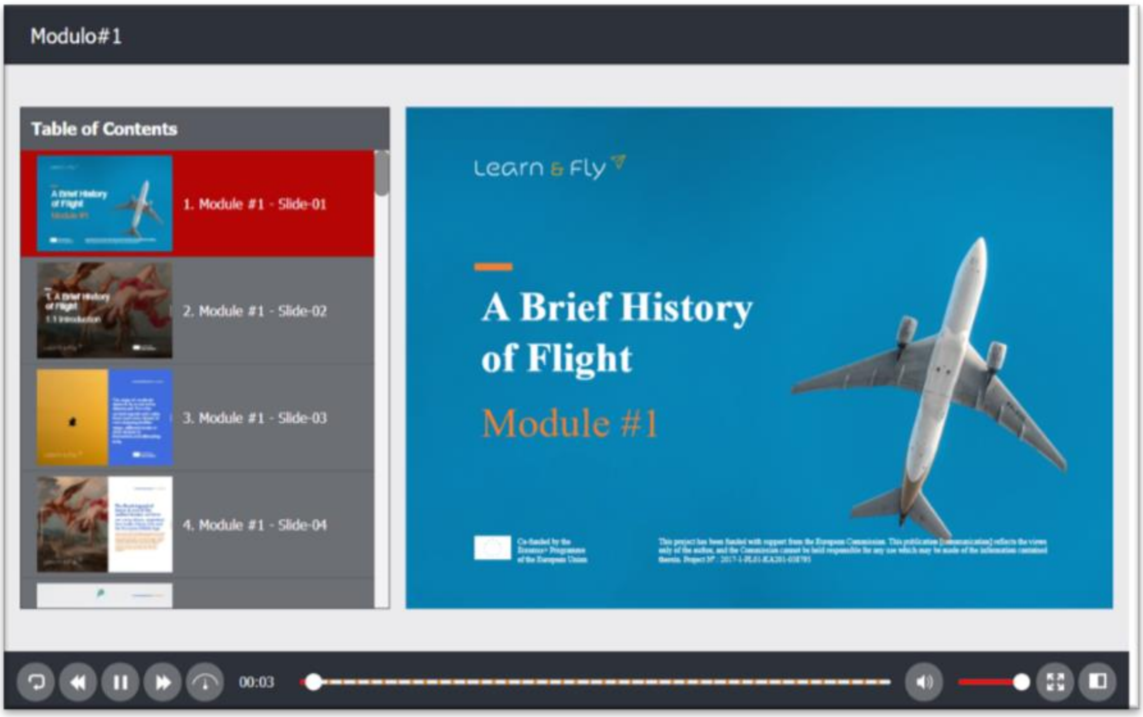
Module Objectives:

The overall objective of this module is to provide a concise perspective about flight pioneers, the aviation saga and flying machines technological evolution, approaching its impact on human life and society to the present.

Contents

- A Brief History of Flight - Scorm content
- A Brief History of Flight
- A Brief History of Flight - Notebook

Figure 80. Section referring to Module 1 - A Brief History of Flight.



Modulo#1

Table of Contents

1. Module #1 - Slide-01
2. Module #1 - Slide-02
3. Module #1 - Slide-03
4. Module #1 - Slide-04

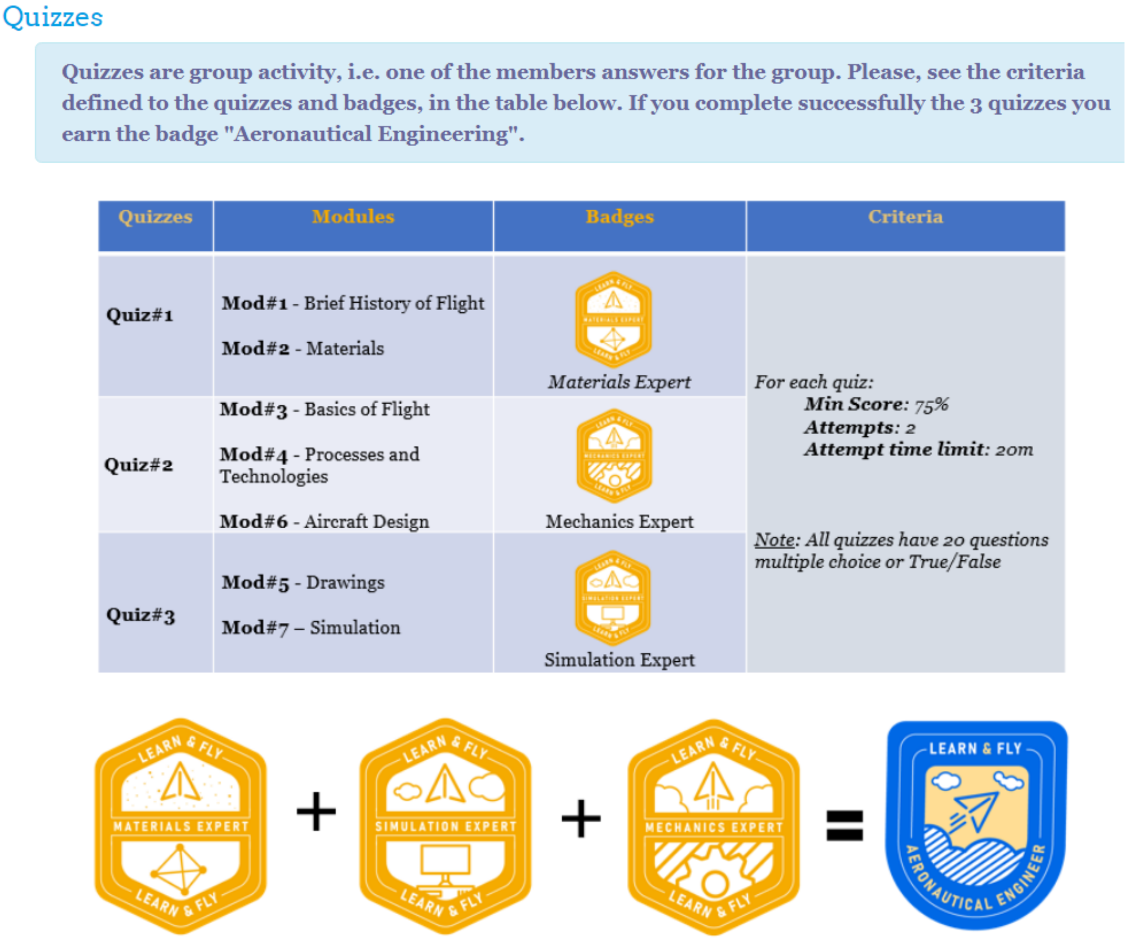
Figure 81. Module 1: contents available in SCORM format.

---

[5] *Sharable Content Object Reference Model* (SCORM).

8.3.4 Section: quizzes

Section **Quizzes** have three quiz activities (Figure 10.12), where students are invited to answer several questions to test their knowledge about the STEM KIT modules. Figure 10.13 shows an example.

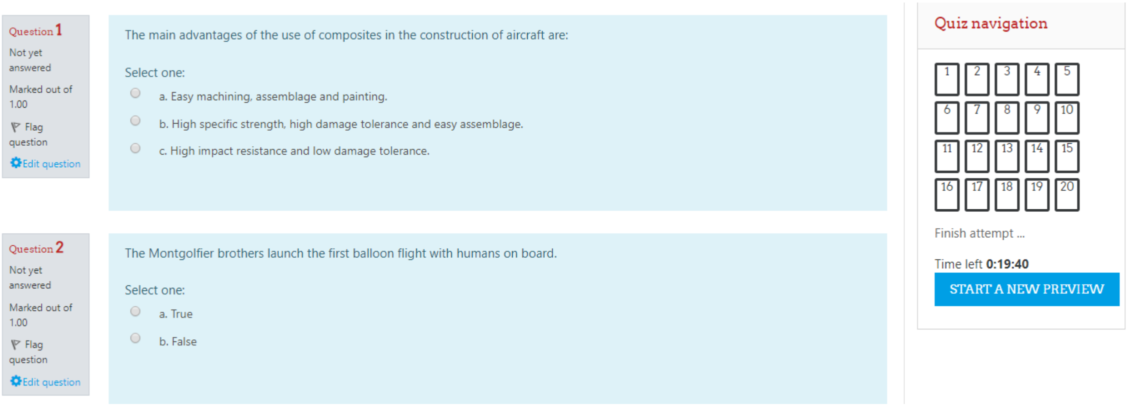


Quizzes

Quizzes are group activity, i.e. one of the members answers for the group. Please, see the criteria defined to the quizzes and badges, in the table below. If you complete successfully the 3 quizzes you earn the badge "Aeronautical Engineering".

Quizzes	Modules	Badges	Criteria
Quiz#1	**Mod#1** - Brief History of Flight **Mod#2** - Materials	*Materials Expert*	*For each quiz:* ***Min Score:*** *75%* ***Attempts:*** *2* ***Attempt time limit:*** *20m* *<u>Note</u>: All quizzes have 20 questions multiple choice or True/False*
Quiz#2	**Mod#3** - Basics of Flight **Mod#4** - Processes and Technologies **Mod#6** - Aircraft Design	Mechanics Expert	
Quiz#3	**Mod#5** - Drawings **Mod#7** – Simulation	Simulation Expert	

Figure 82. Section regarding Quizzes. The list of attainable badges is also shown.



Question 1
Not yet answered
Marked out of 1.00

The main advantages of the use of composites in the construction of aircraft are:

Select one:

○ a. Easy machining, assemblage and painting.
○ b. High specific strength, high damage tolerance and easy assemblage.
○ c. High impact resistance and low damage tolerance.

Question 2
Not yet answered
Marked out of 1.00

The Montgolfier brothers launch the first balloon flight with humans on board.

Select one:

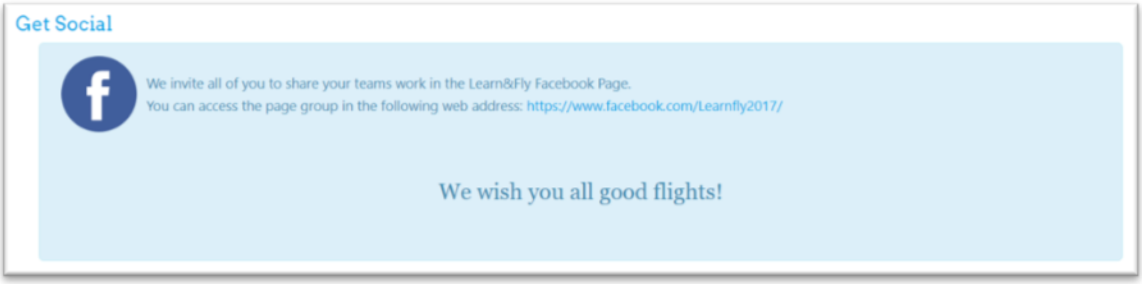
○ a. True
○ b. False

Time left **0:19:40**

Figure 83. Quiz Example

8.4 GET SOCIAL SECTION

The final section invites students to share their achievements and activities on social networks (Figure 84).


Get Social

We invite all of you to share your teams work in the Learn&Fly Facebook Page.
You can access the page group in the following web address: https://www.facebook.com/Learnfly2017/

We wish you all good flights!

Figure 84. Section Get Social.

8.5 STEM KIT COURSE AND GAMIFICATION

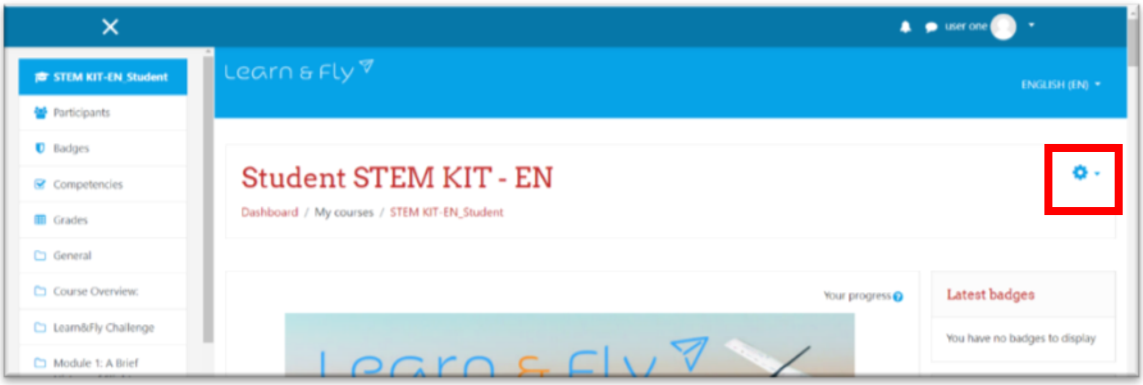
Gamification is the process of incorporating game elements in a non-game context [65]. Game elements are characterized by the use of points, medals, levels, progress bars, virtual currency, avatars, among others, and common gamification implementations apply these elements in a learning context [65]. In the last few years gamification has attracted the attention of many researchers from different areas such as marketing, health, sports and education. Its use in education aims to increase users' engagement in learning activities [66].

In this sense, the badges element (Figure 82) was integrated in the quiz activities as a reward to knowledge pursue in Learn&Fly. The main objective was to motivate students to interact with the online STEM KIT contents. In each quiz, students have two attempts and twenty minutes limit to submit their answers. If a minimum score of 75 % is attained in a quiz, the students team earns a badge. If students are successful in achieving the 3 badges, they earn a final "Aeronautical Engineering" insignia that renders extra-launches in the challenges. All this information is described in the Challenges Regulations document available.

All winning Badges will be visible for students in their Moodle Profile.

8.5.1 Badges – How can teachers consult badges earned by students

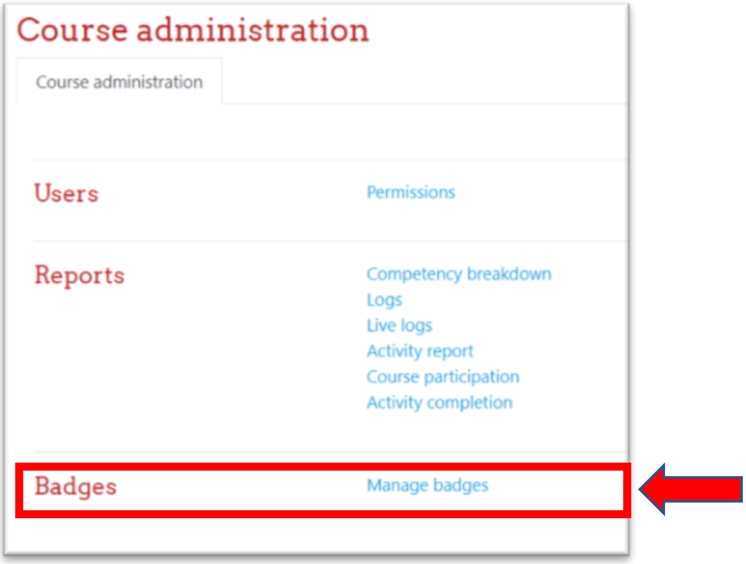
- On the course main page click on ⚙ (Figure 85).



You have no badges to display

Figure 85. How to access Badges on the Course Main Page.

- Then, on the course administration page select the option **Manage Badges** (Figure 86).

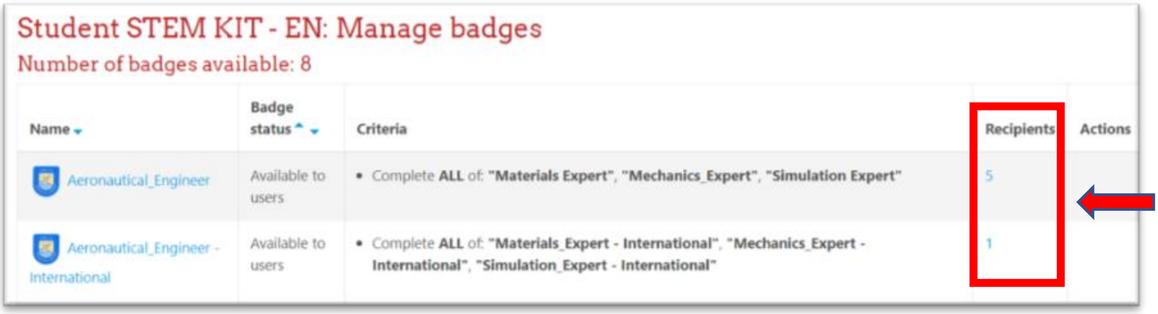


Course administration

Users	Permissions
Reports	Competency breakdown Logs Live logs Activity report Course participation Activity completion
Badges	Manage badges

Figure 86. How to manage Badges on the Course Administration Page.

- After clicking on **Manage Badges**, a table with all available Badges becomes visible (Figure 10.17).
- To visualize the student's names, click the number (Figure 87) to get a page with all students, (Figure 88).

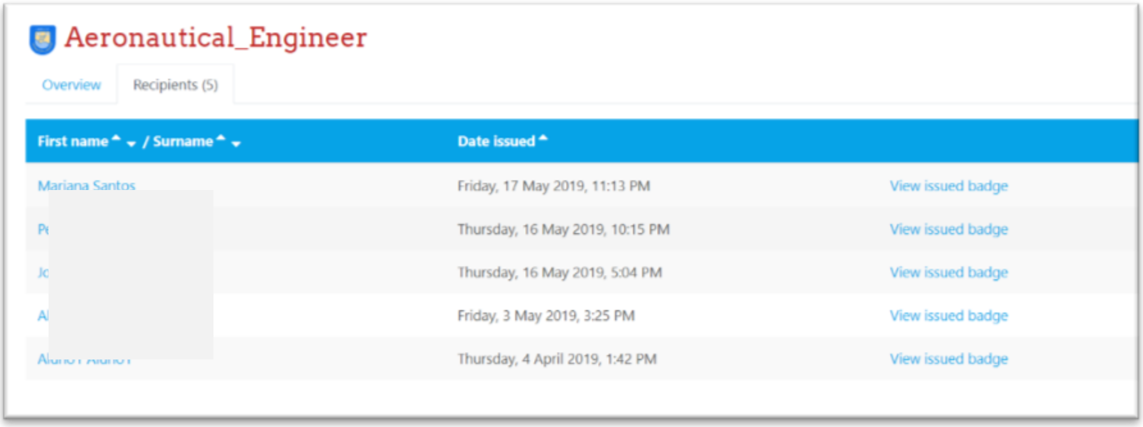


Student STEM KIT - EN: Manage badges

Number of badges available: 8

Name	Badge status	Criteria	Recipients	Actions
Aeronautical_Engineer	Available to users	• Complete **ALL** of: **"Materials Expert", "Mechanics_Expert", "Simulation Expert"**	5	
Aeronautical_Engineer - International	Available to users	• Complete **ALL** of: **"Materials_Expert - International", "Mechanics_Expert - International", "Simulation_Expert - International"**	1	

Figure 87. Available Badges.



Aeronautical_Engineer

First name / Surname	Date issued	
Mariana Santos	Friday, 17 May 2019, 11:13 PM	View issued badge
[redacted]	Thursday, 16 May 2019, 10:15 PM	View issued badge
[redacted]	Thursday, 16 May 2019, 5:04 PM	View issued badge
[redacted]	Friday, 3 May 2019, 3:25 PM	View issued badge
[redacted]	Thursday, 4 April 2019, 1:42 PM	View issued badge

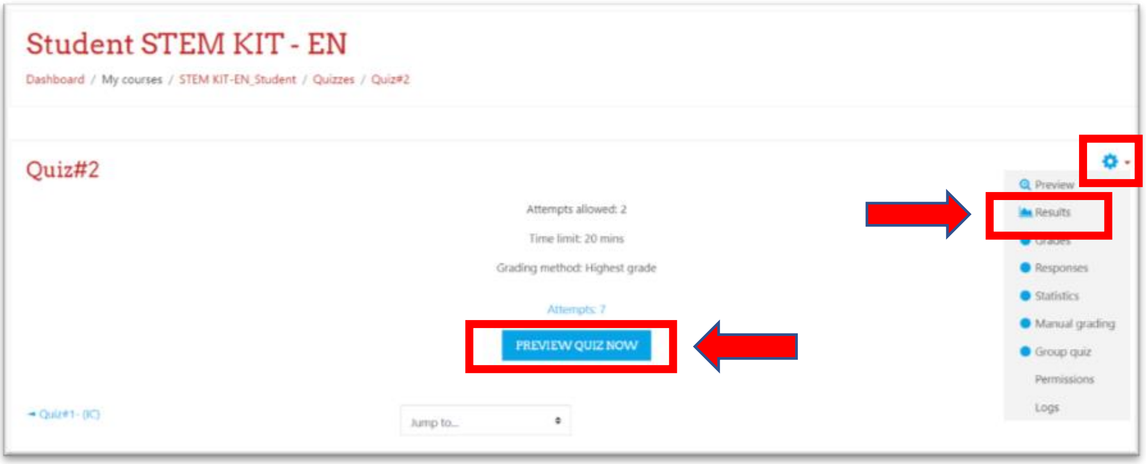
Figure 88. List of students awarded with Badges.

8.5.2 Quizzes – How can teachers consult quiz results

To access the quiz results window, teachers must select the correspondent activity (Quiz#1, Quiz#2, or Quiz#3) on the quiz section. The **Attempts** window then becomes available, displaying two options to access results (Figure 89):

- Clicking on **Attempts** option or
- Clicking on ⚙ ▾

A dropdown menu with several options then becomes visible. Click on **Results Option**.



Student STEM KIT - EN

Dashboard / My courses / STEM KIT-EN_Student / Quizzes / Quiz#2

Quiz#2

Attempts allowed: 2

Time limit: 20 mins

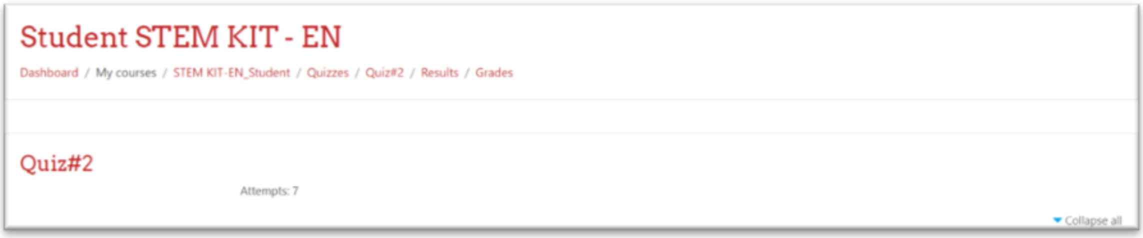
Grading method: Highest grade

Attempts: 7

Figure 89. *Quiz* results.

After selecting the options to access results, the window Grades will be displayed, were results are shown by student's name (Figure 90)

Teachers have the option to download the results in excel format or in other formats available. Teachers must select in which format they want the download to be carried out and then click **Download.**

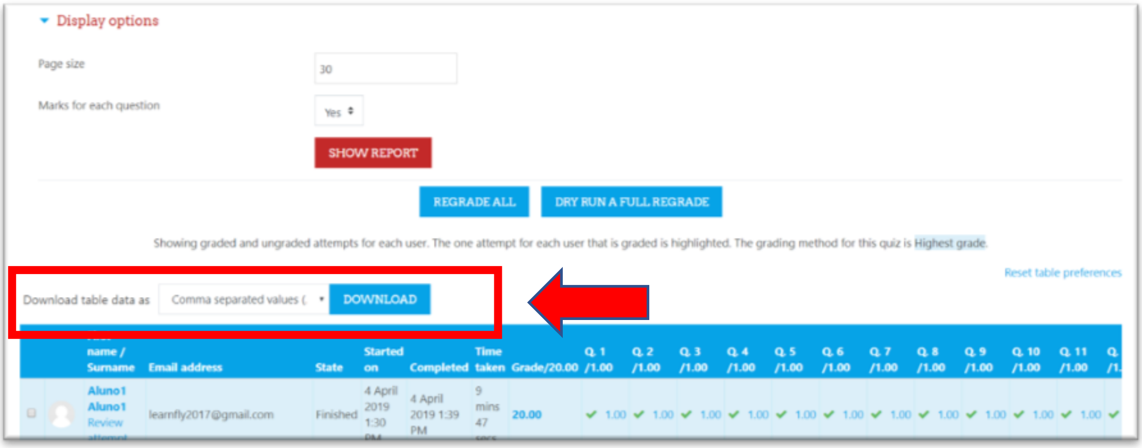


Student STEM KIT - EN

Dashboard / My courses / STEM KIT-EN_Student / Quizzes / Quiz#2 / Results / Grades

Quiz#2

Attempts: 7



Page size: 30

Marks for each question: Yes

Showing graded and ungraded attempts for each user. The one attempt for each user that is graded is highlighted. The grading method for this quiz is Highest grade.

Download table data as: Comma separated values (

		name / Surname	Email address	State	Started on	Completed	Time taken	Grade/20.00	Q. 1 /1.00	Q. 2 /1.00	Q. 3 /1.00	Q. 4 /1.00	Q. 5 /1.00	Q. 6 /1.00	Q. 7 /1.00	Q. 8 /1.00	Q. 9 /1.00	Q. 10 /1.00	Q. 11 /1.00	Q. /1.
☐		Aluno1 Aluno1 Review	learnfly2017@gmail.com	Finished	4 April 2019 1:30	4 April 2019 1:39 PM	9 mins 47	20.00	✓ 1.00	✓ 1.00	✓ 1.00	✓ 1.00	✓ 1.00	✓ 1.00	✓ 1.00	✓ 1.00	✓ 1.00	✓ 1.00	✓ 1.00	✓

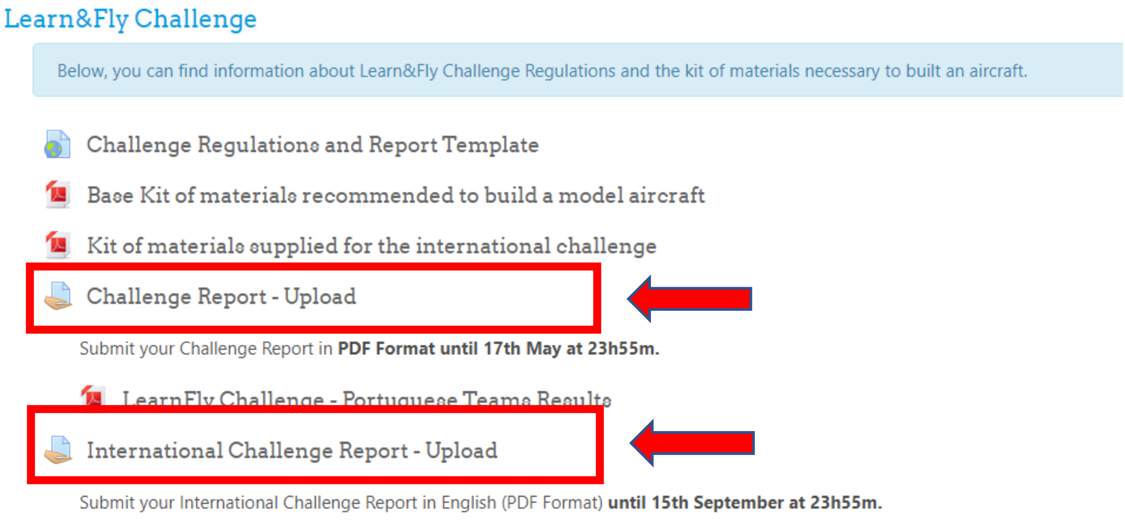
Figure 90. Quiz results by students name.

8.6 CHALLENGE REPORTS - UPLOAD AND DOWNLOAD CHALLENGE REPORTS

This section shows how can students upload their reports to Moodle, and how can teachers access the students reports.

8.6.1 Reports upload by the students

To access, click on the activities available in the section **Learn&Fly Challenge** (Figure 91).



Learn&Fly Challenge

Below, you can find information about Learn&Fly Challenge Regulations and the kit of materials necessary to built an aircraft.

Challenge Regulations and Report Template

Base Kit of materials recommended to build a model aircraft

Kit of materials supplied for the international challenge

Challenge Report - Upload

Submit your Challenge Report in **PDF Format until 17th May at 23h55m.**

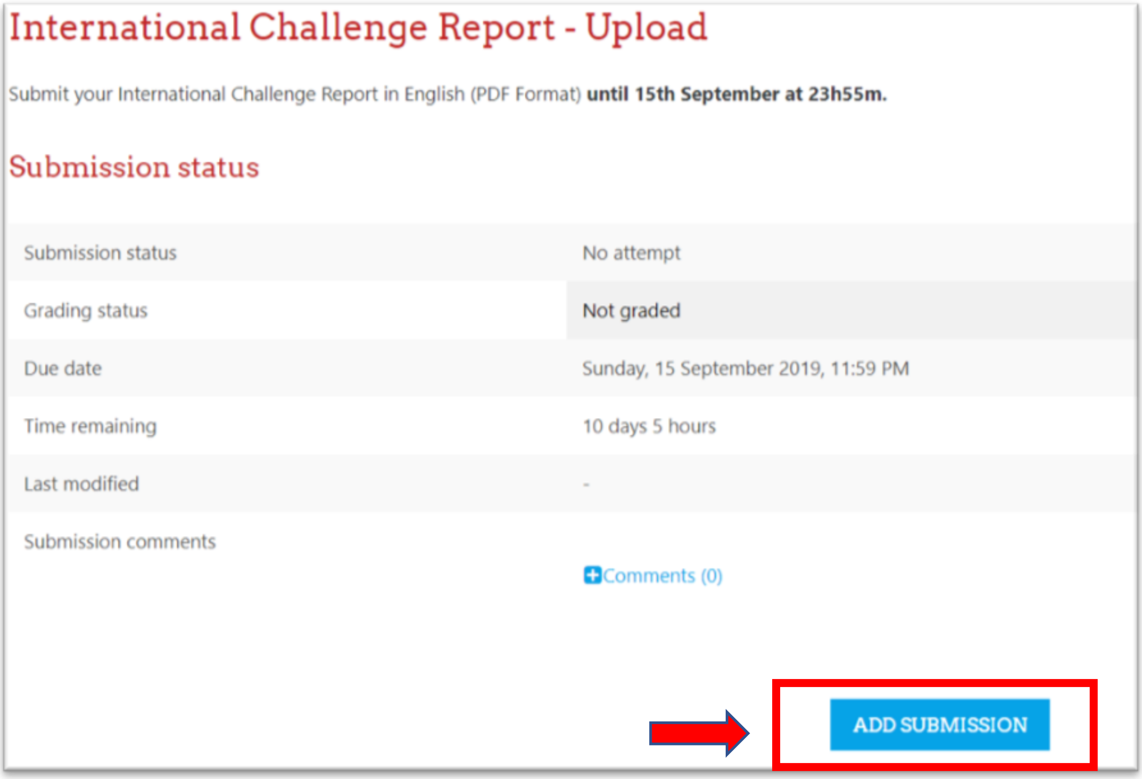
LearnFly Challenge - Portuguese Teams Results

International Challenge Report - Upload

Submit your International Challenge Report in English (PDF Format) **until 15th September at 23h55m.**

Figure 91. Uploading Challenge reports.

If students are uploading the International Challenge report, they should click the button Add Submission (Figure 92).



International Challenge Report - Upload

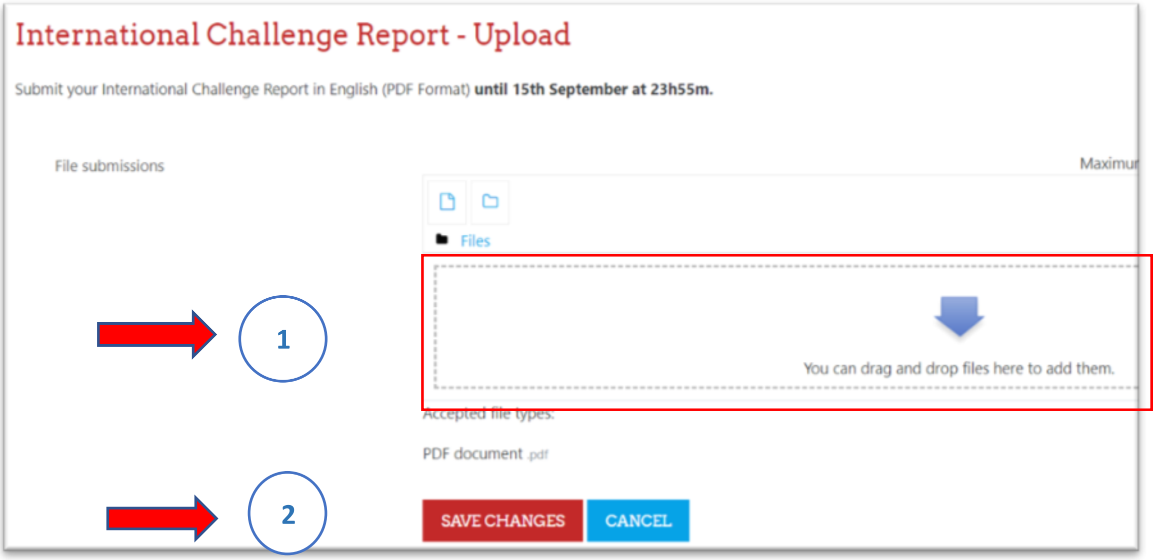
Submit your International Challenge Report in English (PDF Format) **until 15th September at 23h55m.**

Submission status

Submission status	No attempt
Grading status	Not graded
Due date	Sunday, 15 September 2019, 11:59 PM
Time remaining	10 days 5 hours
Last modified	-
Submission comments	Comments (0)

Figure 92. Adding a new submission – step 1.

- On the **File Submissions Window** students should drag and drop files to the text area (Figure 10.23). The number of allowed files depends the type of activity.
- To finalize the submissions students should click on the button **Save Changes.**



International Challenge Report - Upload

Submit your International Challenge Report in English (PDF Format) **until 15th September at 23h55m.**

File submissions

Maximu

Files

You can drag and drop files here to add them.

Accepted file types:

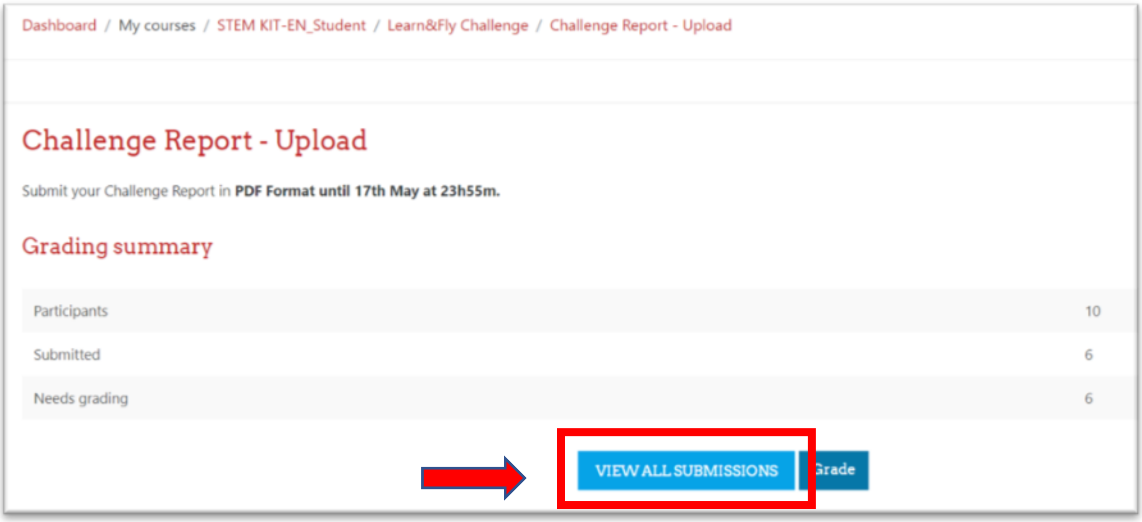
PDF document .pdf

Figure 93. Adding a new submission – step 2.

The **Submission status** can be visualized in the **Challenge Report – Upload window**.

8.6.2 Download report files by the teachers

On the Challenge Report Window, click on the **View All Submissions,** (Figure 94).



Dashboard / My courses / STEM KIT-EN_Student / Learn&Fly Challenge / Challenge Report - Upload

Challenge Report - Upload

Submit your Challenge Report in **PDF Format until 17th May at 23h55m.**

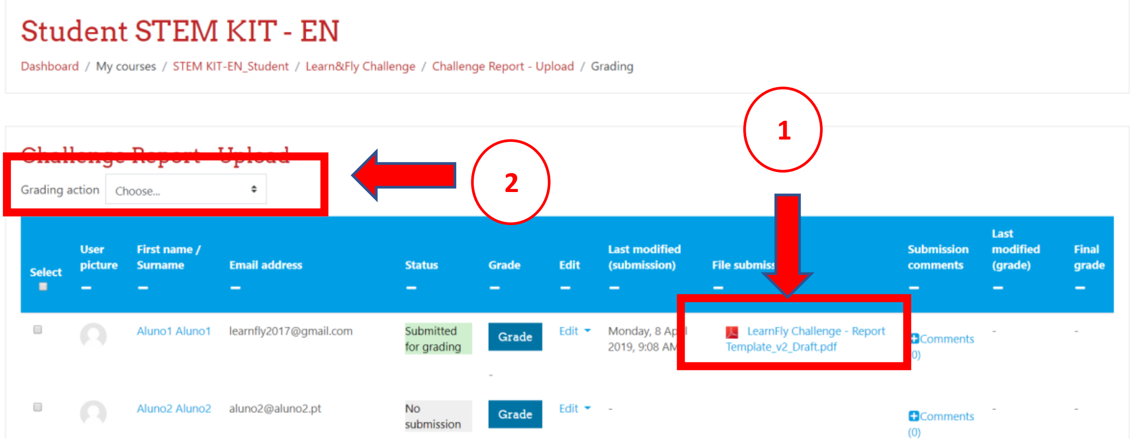
Grading summary

Participants	10
Submitted	6
Needs grading	6

Figure 94. Downloading Challenge reports by teachers. Step 1: view submissions.

On the following window, Grading Window, the teacher has two options to download the Reports (Figure 95):

- By clicking directly on file ①;
- By clicking on Grading action and choosing the option Download all submissions ②.



Student STEM KIT - EN

Dashboard / My courses / STEM KIT-EN_Student / Learn&Fly Challenge / Challenge Report - Upload / Grading

Challenge Report - Upload

Grading action: Choose...

Select	User picture	First name / Surname	Email address	Status	Grade	Edit	Last modified (submission)	File submiss	Submission comments	Last modified (grade)	Final grade
☐		Aluno1 Aluno1	learnfly2017@gmail.com	Submitted for grading	Grade	Edit	Monday, 8 Ap 2019, 9:08 AM	LearnFly Challenge - Report Template_v2_Draft.pdf	Comments (0)	-	-
☐		Aluno2 Aluno2	aluno2@aluno2.pt	No submission	Grade	Edit	-		Comments (0)	-	-

Figure 95. Downloading Challenge reports by teachers. Step 2: grading reports.

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