



# ObservatoryNANO

Economic Assessment  
Aeronautics and Automotive sectors  
Final Report  
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## Chapter 1 Introduction

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### 1.1 Executive Summary

Potential applications of nanotechnology in the transport sector are enormous. The match between the advantages derived from using nanotechnology (e.g. new, improved or tailored properties) and the market needs in the transport sector such as (more) sustainable, safer and economic transport modes has triggered huge public and private investments in the field.

As a result, a (small) percentage of today's new cars and aircrafts already incorporate nanotechnology. From nanotubes into cars' fuel lines, to nanoparticles in scratch resistant glass coatings or as fuel additives to improve fuel combustion efficiency, nanotechnology has started to enter the transport sector. Thus, cars and aircrafts have mostly benefited from the development of nanomaterials production technologies (e.g. providing benefit/cost attractive nanoparticles) and from better characterisation tools and control of processes that were already widely established in industries (e.g. PVD and CVD processes for coatings).

However, nanotechnology has not significantly contributed to lighter vehicles structures and powertrain systems nor to more efficient or alternative propulsion systems. Failing to meet the full set of industrial requirements (e.g. production volumes, automation and / or quality assurance) is preventing further deployment into mass-markets whereas stringent performance requirements (e.g. stiffness, strength, wear-resistance) at reasonable cost has limited its use on vehicle parts such as windows or bumpers. Stringent certification requirements derived from transporting human beings but also long development times and costs (especially relevant in the aeronautics sector) do not ease the situation.

Looking into the future, nanotechnology will keep penetrating into the transport sector provided that it delivers clear advantages as compared to competing solutions that still offer room for significant improvements. Despite the long lifetimes of transport vehicles (from 10 to more than 30 years) results in a slow market penetration rate, it also results in potentially huge advantages (e.g. 99.9% of the energy consumption during an aircraft lifetime is consumed during use) that could justify investments in new materials, processes or tools.

Specifically, coatings and surface treatments are likely to continue to be the fastest growing sectors both in vehicles' parts and in tooling and production equipment. Coating technologies are more mature, can benefit from developments in other sectors and can offer clear benefits in the short term (e.g. increased tooling lifetime). Besides, the increasing use of composites foreseen in the transport sector will favour the use of nanoparticles (e.g. reducing costs or weight) and, as technologies mature, nanofibres (e.g. improving mechanical performance). In terms of metals, new technologies to produce nanostructured metals are likely to have limited applications mainly due to the limited size of the parts that can be produced. Nevertheless, metals can benefit from improved modelling and simulation tools that could lead to a tremendous impact at a fraction of the cost as they would have little interference on existing processes.

## 1.2 Scope of this report

This report focuses on providing an overview of existing and potential applications on the transport sector while paying specific attention to the following application areas: airframes and car structures and propulsion systems for both types of vehicles. Applications of nanotechnology such as batteries, fuel cells, fuels or electronic equipment are addressed in the reports prepared for the energy or ICT. Over the coming 3 years, additional domains will be added to the different sectors to expand the scope of these analyses.

## 1.3 Definitions and Methodology

### 1.3.1 What is nanotechnology?

ObservatoryNANO defines nanotechnology as:

1. Products with a functional component with controlled geometry size below 100 nanometres in at least one dimension, and innovative characteristics caused by this critical dimension.
2. Equipment for analytical or manipulatory purposes that allows controlled fabrication, movement or measurement resolution with a precision below 100 nanometres.

Obviously, only in few cases such a product consists of nanoscale building blocks alone, without any macroscopic element. Since the value of the nanotechnology contribution to such a product is difficult to estimate, whenever possible, the market price value of the end product will be considered.

Therefore, the smallest unit that can be commercially sold in the marketplace is defined as a “nanotechnology product”. Consequently, the market figures in this study are based on the market price of the smallest commercially available units with functional nanotechnology components.

### 1.3.2 Methodology for preparing the report

The market figures for the nanotechnology world market, as covered in this report, were predicted on the basis of available market data from press releases, company reports and Internet websites including so far unpublished market research studies. Market estimations of the authors are clearly marked in the text. However, it should be taken into account that the reported market figures are only estimates. Moreover, in some cases it has not been possible to estimate the market for nanotechnology products. Instead, the report contains the markets for materials and/or parts that nanotechnology-enabled solutions could replace.

For an analysis of the present status, future visions and economic perspectives of nanotechnology, expert interviews either personally or via on-line questionnaires were carried out. Organisations and/or experts were identified via various sources such as partners’ contacts, databases, previous reports, conferences and Internet researches.

The answers to the future predictions and future products are at least regarded as a good indicator of future developments from the present point of view. The results were cross-checked with experts. Furthermore, the interviews and questionnaires included some open questions concerning the most important products and main innovation barriers. Naturally, the answers to this type of questions resulted in dispersed opinions that clearly reflect the difficulties to predict future developments.

## Chapter 2 Aeronautics sector

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### 2.1 General market description

The European aerospace industry is a high-tech industry which develops and manufactures a broad range of products: civil and military aircraft, aero-engines, helicopters, launchers and satellites, unmanned aerial vehicles, missiles as well as systems and equipment. In 2004 the European aerospace industry employed about 445,200 directly and had a turnover of €77 billion. It invested about 14.4% of its turnover in research and development. Exporting more than half its output, the industry provided a positive trade balance of €31.8 billion for the EU as a whole.

Aircraft development and production is by far the largest component of the aerospace industry (with space activities accounting for less than 10% of the activities). In total, the European aerospace industry accounted for around € 26 billion value-added (out of above € 90 billion in production value) and around 2.200 enterprises in 2003. Nevertheless, the market is dominated by a small number of large firms with more than 1.000 employees that account for 3% of the total number of enterprises but for above 80% of the turnover and SMEs accounting just for 7% of the industry added-value [2].

The success of the industry depends on twin pillars, civil (64%) and defence (36%). They are both complementary and mutually dependent. Operating in civil and defence markets allows companies to share know-how, skills and products and benefit from the economies of a broad product range. Both areas rely on the application of advanced technologies while serving private and public customers with different needs. For the long-term, forecasts indicate an increase in overall growth in the civil market while the defence market growth is expected to be flat.

In Europe three countries (Germany, France and the UK) account for more than 80% of the added value and more than 85% of the turnover [2]. The global aerospace sector was formerly dominated by US companies, which traditionally accounted for two thirds of the industry's global turnover. Largely due to the success of Airbus, this picture has changed in recent years in favour of the European aerospace industry, which accounted for 36.4% of the € 284 billion in global sales in 2007 (US: 51.1%) [4]. Europe is claimed to be a world leader in large civil aircrafts, business jets, helicopters, aero-engines and defence electronics [2].

However, emerging markets such as China, Russia or India are expected to play an increasing role in civil aircraft manufacturing and assembling initially on the business jet sector and the single-aisle aircrafts lately. This growth will be fueled by low-cost labour (leading to manufacturing costs around 20-25% cheaper for typical aircraft structures), the purchase of more than 3.500 planes (roughly 15% of global demand) over the next 20 years and the related offset requirements set by governments (by which local suppliers must be involved in aircraft manufacturing) and know-how gains derived from existing alliances between western OEMs and local suppliers [5].

#### 2.1.1 Aeronautics Market segmentation and forecasts

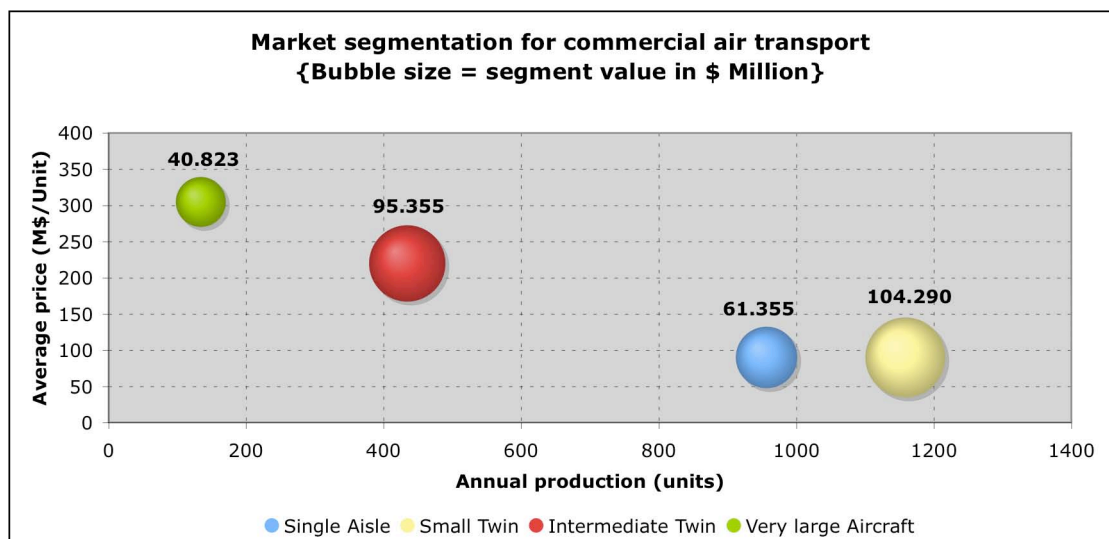
The world market for aerospace and defence in 2006 was \$ 918 billion, of which \$ 121 billion corresponded to civil aeronautics and space applications [18]. For the purpose of this report, the aeronautic industry is segmented into airframes and propulsion systems. Within these segments a further distinction is made between civil aircrafts and business jets. Military aircrafts are excluded from the scope of this report; however, it is important to

notice that in 1992 about 18% of the world's aircraft fleet were military aircrafts and this is estimated to decrease to 7% by 2015 [7].

The European Aerospace and defence industry had a turnover of € 132.2 billion in 2007, of which around 52% was related to military applications [4]. Excluding defence, the European Aerospace industry had a turnover of around € 90 billion in 2004, of which 91% came from aircraft manufacturing and the remaining turnover from missiles and space.

Within aircraft manufacturing, the biggest share came from large civil aircrafts (around 22% of total EU aerospace industry turnover) and military aircrafts (around 17%). Aircraft engines represented 9% whereas aircraft maintenance represented above 19% [4].

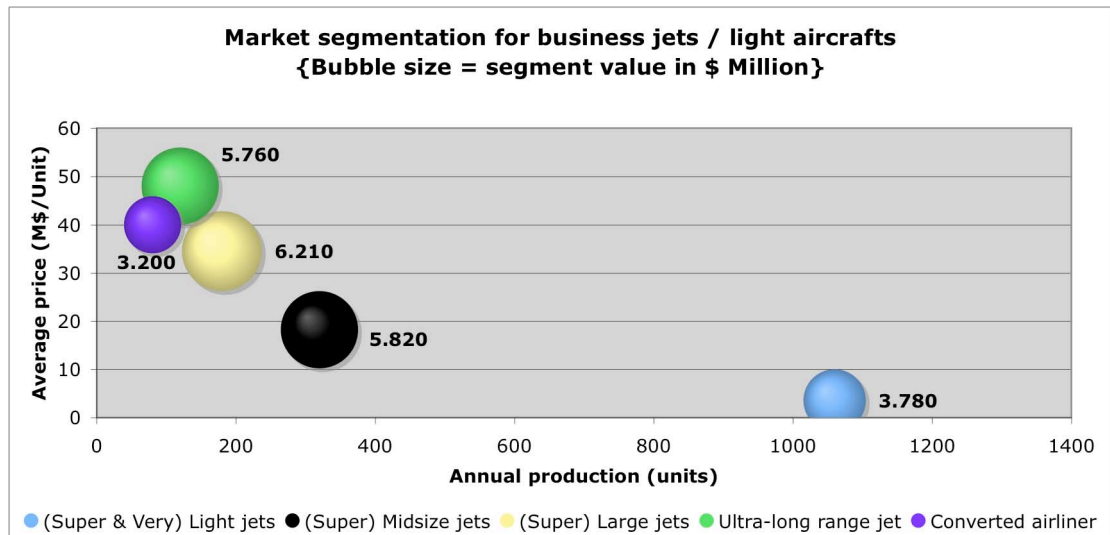
Civil Aircrafts sales are both driven by public procurement (much more centralised in the US than in the EU) and airlines' purchases (highly cyclical and very much dependent on demand from emerging markets for growth) [2]. World passenger traffic was expected to increase by 4.9% per annum and the number of frequencies offered on passenger routes will more than double. By 2026 the world's airlines will take delivery of 24,262 new passenger and freighter aircraft, worth US\$2.8 trillion at current list prices [8]. Over the next 20 years the commercial aircraft market is worth \$3,1 trillion [6]. Most of this business will be generated from single-aisle deliveries, while 1,698 large passenger and freighter aircraft will account for 19% of total aircraft delivery value. The following picture shows an indicate market breakdown for 2007 based on different aircraft classes from both Airbus and Boeing.



**Figure 2-1: Market segmentation for commercial air transport**

(Source: Own elaboration based on Airbus and Boeing Market forecasts)

During the last 50 years, some 22,000 western-built commercial jet aircraft have been produced. Some 5,900 of these had been definitely withdrawn from use by the end of 2006, 1,100 were in storage and 15,000 are still in active service with airlines [8]. At the end of 2006, the worldwide fleet was estimated at approximately 12,000 aircraft for all segments excluding Very Light Jets. With a yearly retirement rate of 0.5% to 1.0% of the fleet and expected deliveries as mentioned above, the business jet fleet should grow to approximately 20,600 aircraft in 10 years [9]. The world market for light business jets was estimated at around \$ 10 billion in 2007 [18]. The following picture shows an indicate market breakdown for 2007 based on different jet classes.



**Figure 2-2: Market segmentation for business jets**

(Source: Bombardier market forecast)

Though both aircrafts and engine manufacturers had forecasted an annual growth in air traffic around 5% for the forthcoming 20 years, the present financial turmoil together with variable oil prices (from above \$ 140 a barrel in summer 2008 to around \$ 40 in 2009) have turned all previous projections upside-down. As of February 2009, projections are that passenger traffic will fall by 3% and cargo by 5% with revenues falling down by 6%. Accordingly, US airlines (that may be followed by EU and Asian ones) have already announced plans to cut transport capacity in order to increase the load factor of their airplanes (and thus reduce operating costs) [10]. Remarkably, the combined value of the orders for Airbus and Boeing planes exceeds \$500 billion at list prices; so large-scale cancellations and deferrals could easily amount to tens of billions of dollars and affect suppliers of engines and other parts in addition to the jet makers [25].

In order of market share, General Electric, Rolls-Royce plc and Pratt & Whitney dominate the turbofan engine market. GE and SNECMA of France have a joint venture, CFM International that, as the 3<sup>rd</sup> largest manufacturer in terms of market share, fits between Rolls Royce and Pratt & Whitney. Rolls Royce and Pratt & Whitney also have a joint venture, International Aero Engines, specializing in engines for the Airbus A320 family, whilst Pratt & Whitney and General Electric have a joint venture, Engine Alliance marketing a range of engines for aircraft such as the Airbus A380. Williams International is the world leader in smaller business jet turbofans.

#### Business & technology development strategies

The European industry is going through a consolidation process that has reduced the number of large players from 30 in the 90s to 11 in 2003. This process has enabled key European players (e.g. Rolls-Royce, EADS-Airbus, SNECMA/SAFRAN or Dassault) to have net sales and R&D investments in line with their major US competitors [2]. As a result of this process, the aerospace industry is now characterised by numerous cross-holdings. In spite of this, it has been reported that EADS is still managing around 3.900 suppliers while Boeing is managing some 1.500. Thus, further consolidation is expected [18].

Besides, the aeronautical sector is continuing its globalisation driven by different factors whose influence varies over time. The Euro's strength over the US dollar experienced over the last years and the industry concerns about further losses in their competitiveness in

favour of low-cost countries are expected to lead to significant outsourcing of production to non-EU low-cost countries such as China or Russia. As production of low-complexity and labour intensive components (e.g. doors, interiors, wiring harnesses) continues and sets the basis for these countries to become leading suppliers of medium complexity components (e.g. aluminum fuselage sections), western companies are expected to focus on higher added-value activities such as the development of the next clean-propulsion technology and moving from assembling aluminum intensive to those made out mainly from composites.

Examples of existing international aircrafts development programmes include, but are not limited to, the Russia's regional Sukhoi superjet SSJ100 program (Finmeccanica, SAFRAN) or the agreement of Bombardiers has already an agreement to support the development of the Chinese regional jet (ARJ21) in exchange for a share of the revenue. Many of these joint development programmes may lead to increased competition in the business jet segment in the first place followed by the single aisle aircrafts. In the case of engines the situation does not differ much. Honeywell, GE Aircraft engines and Pratt & Whitney have been building plants and engineering centres in these countries as well.

An important change in the business model of the aircraft industry is the fact that aircraft manufacturers are increasingly taking over the responsibility for aircraft maintenance (usually held by aircraft owners). This change is basically driven by the fact that aircraft maintenance costs are much higher than the acquisition costs and airlines want to have a better control over aircraft ownership costs. For instance, Rolls-Royce operates by the power-by-the-hour concept, whereby users pay for the hours they fly a plane and receive a specified level of maintenance service [2].

Despite most of the aircraft industry growth should come from Asian markets, these should not be seen as a lead market for environmentally friendly aircraft unless these have a clear impact on fuel consumption or increased payload. These markets priority is transporting more people and not reducing the environmental impact of airborne transport [2].

In terms of engines, aircraft manufacturers generally start to set up the requirements for engines and select an engine's design at the concept stage of aircrafts' design. Then, engine manufacturers can try modifying the engine design to make it fit with other aircraft requirements. This enables the possibility of economies of scale and compensate for the large development costs of new engines.

For instance, GE invested around \$ 2 Billion on the GE90 engine development and then an additional \$ 600 million in the GE90-115B. Engines are often sold at breakeven or at loss because they are not where engine manufacturers make money. In 2002, parts and service revenues accounted for 40% of GE's \$ 10'6billion in sales and close to 2/3 of its \$ 2 billion operating profit. [26]. Rolls-Royce forecasted engines' sales totaling \$ 700 billion over the period 2007-2026 plus an aftermarket (in the U.S. and Europe) of \$ 550 billion.

The European Aeronautical sector spent around € 11.7 Billion in R&D in 2007, a 12,4% of the industry turnover. On the civil side, representing 8.8% of the total industry turnover worth € 8,3 Billion, 85% of the investment came from industry [4].

To face the environmental consequences of an increased airborne traffic a Joint Technology Initiative called Clean Sky has been launched by the AeroSpace and Defence Industries Association of Europe (ASD) together with the EU with the goal to lower CO2 and noise emissions (even to the level that would enable night-flights in Europe) and have greener aircrafts [2].

Besides, the Advisory Council for Aeronautics Research in Europe (ACARE), bringing together 40 stakeholders from the aeronautics industry has set up a joint Vision for the industry in 2020 and a related Strategic Research Agenda (SRA) to ensure that the industry moves towards realising this vision. This SRA has set different High Level Target Concepts in different areas and has broken them down to manageable goals such as 50% CO<sub>2</sub> emissions reduction per passenger-kilometer, a 80% of NO<sub>x</sub> emissions reduction or a five-fold reduction in accidents to name a few [11].

However, due to the long-term characteristics of this sector, the relative importance of each of these goals may change over time. ACARE has already developed 3 main global scenarios as to indicate the relative importance of its goals. Thus, shifting from the sustained growth scenario that drove industry's globalisation over the last years to a recession scenario that could lead to protectionism and bloc' isolation (e.g. China, Europe) could very much influence industry's priorities (from greener to ultra-secure air-transport).

Down to individual companies, companies like Airbus and Boeing are working in projects to use nanotechnology for a composite-based airframe philosophy. These projects are usually either run through long-term collaborations (e.g. Boeing alliance with Ford and Northwestern University) or project-specific partnerships (e.g. Airbus in collaborative EU projects). As compared to material suppliers, companies in the aircraft business are more likely to incorporate nanotechnology on an ad hoc basis and use a (sometimes limited) central coordination to ensure that independent developments can benefit from each other (and save development costs). Lockheed Martin is a reported example of the last case [21].

Nevertheless, nanotechnology won't be adopted *per se* and will have to demonstrate its value as compared to competing alternatives. For instance, it has been claimed that with existing technologies the aircraft industry will be able to reduce the fuel burnt per seat by 20% over the next decade [52].

In general, in the Aerospace industry, major inventions and new technologies are protected by secrecy rather than applying for patents (with mainly minor inventions being patented) while trademarks and design are hardly used [2]. The reasons behind are the critical importance of protecting IPR in areas such as aircraft engine design or avionics and the, sometimes, close relationship between civil and military technology [6].

### 2.1.2 Drivers and Barriers to Innovation

The main drivers for the aeronautics industry are derived from globalization (e.g. expected increase in airborne transport), environmental (e.g. CO<sub>2</sub> emissions and noise reduction) and security (e.g. terrorist attacks) [2]. ACARE's JTI Clean Sky has set a target of 50% CO<sub>2</sub> emission reduction to be achieved by 2020 breaking them down into improvements in several areas: About 20 to 25% should come from airframes (e.g. weight reduction and aerodynamics), about 15 to 20% from engines and 5-10% from air traffic management [11].

The environmental impact of aircraft and engine manufacturing are negligible as compared to the energy consumed during use. Airbus reported that energy consumption during use is more than 99% of the total energy consumption over the complete aircraft lifecycle [7]. The A380 in service today, consumes less than three litres per 100 seat kilometres. In just the last 40 years, technological advances have reduced fuel consumption and CO<sub>2</sub> emissions by 70%, noise by 75% and unburned hydrocarbons by 90%, while increasing the number of people moved per take-off or landing slot and setting unprecedented levels of comfort [8].

During flight aircraft engines emit CO<sub>2</sub>, NO<sub>x</sub>, SO<sub>x</sub>, water vapour, hydrocarbons and particles

(with particles basically consisting of sulphate from sulphur oxides and soot) [7]. Besides, the introduction of legislation to restrict the use of certain substances (e.g. CrVI, Lead or Cadmium) has led the aerospace sector to develop alternative (and environmentally friendly) materials.

Beyond purely environmental drivers for reducing CO<sub>2</sub> emissions, the fact that fuel is the largest cost for all airlines (30 up to 50% of direct operating cost) is probably the strongest driver for lighter aircrafts and cleaner propulsion systems. As compared to the economical value of 1.5 to 3 US\$ for pound saved in the automotive sector, the value of weight saving in the airborne commercial transport has been estimated at around US\$ 300 per pound saved (getting to as much as US\$ 3.000 for fighter aircrafts) [6].

Probably as important as the fuel economy, aircraft designs aim at maximising the payload in relation to cost. As an indication, the weight of a fully loaded aircraft taking off could be broken down as follows: 20% is payload, 40% is structural weight and 40% is fuel [19].

In conclusion, lighter aircrafts can increase the payload, reduce fuel consumption and lead to secondary weight reductions by downsizing aircraft engines due to the reduced thrust needed to propel the aircraft. Decreasing components weight while keeping the required performance can be achieved by increasing the specific stiffness ( $E/\rho$ ) and specific strength ( $\sigma/\rho$ ) of materials being used [19].

Besides airlines' demand for aircrafts with better payload-range performance, airlines demand more flexibility to take-off from short runways, and improved climb rates. Upgrades in business jet designs (fuelled by a strong increase on demand) will lead to a strong demand for new and derivative engines offering next generation of environmental, cost and reliability improvements [6].

From a safety and security point of view, the aeronautics business remains extremely conservative and risk averse, making it difficult for nanotechnology applications to be integrated into new products. This is even more prominent for civil aircraft makers. Carrying passengers puts extreme demands on the qualification process of new technologies. The material has not only to prove its supremacy, but also its durability, whereby the physical properties are maintained under extreme conditions and on a long-term basis. In addition, a production process suitable for an industrial scale and a reasonable price/performance ratio is mandatory [22a].

Finally, cost reduction is always an issue in such a cost-competitive industry. Maintenance, Repair and Operation (MRO) represent a huge cost. According to the TATEM project, maintenance activities can account for as much as 20% of an operator's direct operating costs and have remained at this level for many years. For example, it has been estimated that line mechanics spend 30% of their time trying to access information to diagnose and rectify failures, and errors can impact aircraft safety [20]. Yet another example, a standard de-icing procedure of a large aircraft could cost US\$ 10.000 [23].

In terms of barriers, one of the principal obstacles to the application of new materials noted by the aerospace industry are the long timeframes needed to test and validate their reliability. Given its stringent regulatory, quality and safety requirements [5], there are very detailed certification procedures to meet airworthiness standards for aircraft and components. In Europe, EASA can act as a single entity and take binding decisions. Given the importance of this issue for Europe's major aerospace companies, industry has been closely involved in setting up the new EASA structures. The certification process typically lasts 18 to 24 months [56].

Long development times required for the design and development of new aircrafts (approximately 10 years) and their production (10 years as well) lead to a significant delay between the development of conceptually new technologies and such a developments entering the market [7]. For new developments, the long-term orientation of R&D and the risk involved makes it hard for SMEs to compete with large firms (despite having more flexibility and, probably, creativity) [2]. The fact that aircrafts lifetime in western countries is of around 30 years (with many of them then being sold to airlines in developing countries) also hinders the penetration of new technologies into the market [7].

Regarding nanotechnology-related applications, the lack of availability of nanomaterials for mass industrialisation (e.g. cost-effective, reliable, reproducible, etc.) may hinder their market penetration even if their added value is demonstrated in real components. Thus, industrialised production processes need to be developed thereby reducing overall costs through the increase of volume produced.

Another barrier identified concerns the still unknown effects of many nanomaterials on the environment. This covers workers health and safety, environmental impacts resulting from accidental damage, and recycling of materials containing nanomaterials.

### 2.1.3 Nanotechnology Impact

"It's as big as going from the propeller to the jet, maybe more," said Boeing Chief Technology Officer David Swain about nanotechnology.

When industrial players at the end of the business value chain make such a statement it is difficult to deny that nanotechnology is a potentially disruptive technology for the aeronautics sector. However, there is a considerable delay between the development of conceptual new technologies and such developments becoming available for use [7]. Actually, it may take 20 to 50 years to realize the full benefits of nanotechnology in the aeronautic industry [32].

In the aeronautics industry, there is a great need for new or improved materials that can contribute reducing aircraft ownership and operating costs (as well as their environmental impact) either through weight and/or fuel consumption reduction or reduced Maintenance, Repair and Operation (MRO). Nanotechnology can have an impact on virtually all aircraft components and systems, from airframes to propulsion systems, from electrical and electronic systems to windows or interiors.

Nanotechnology can provide materials with improved (or tailored) properties that improve their functional performance (e.g. mechanical or electrical properties) or that deliver multi-functional properties (e.g. lightweight conductive nanocomposites). These (new) materials can be roughly grouped into nanostructured (bulk) metals and nanocomposites and nanostructured coatings and can be applied in aircraft components (e.g. landing gears, air filters) and/or in production equipment (e.g. tooling for composites or cutting tools for metals) [21; 38].

In terms of nanostructured (bulk) materials, they include virtually all materials used in aircraft components. From aluminium and composites used in airframes to nickel superalloys used in turbines. Materials with improved, new or tailored properties could be obtained either through innovative production processes (e.g. Severe Plastic Deformation) or through mastering existing processes by improved modelling, simulation and characterisation tools.

Nanocomposites include both polymer matrix composites but also metal matrix ceramics

(MMC). These materials consist of a matrix material (not necessarily nanostructured) plus a nanomaterial such as nanoparticles (e.g. for flame retardancy), nanotubes (e.g. for mechanical reinforcement or electrical conductivity) and the like. Ultimately, it could enable the full integration of electronic devices (e.g. sensors) in aircraft materials (e.g. moving from diagnostics to prognostics and self-healing).

As aircrafts operate in (harsh) environments (e.g. corrosion, oxidation, wear/friction) that limit materials' performance, nanostructured (multi-layer) coatings can provide suitable protection. This would enable these materials' operating under higher temperatures (e.g. turbines), reducing ice formation or extending their lifetime (e.g. preventing UV degradation of aircraft paint or reducing wear in landing gears or brakes).

Beyond aircraft components, nanostructured coatings or materials can find applications in production equipment (e.g. tooling for composites production with longer lifespan and durability), be they used in nanomaterials production or not.

Besides improving materials performance, nanotechnology can also provide alternative solutions (e.g. aluminium nanostructured coatings) to well-established (not environmentally friendly) coatings such as Chromium VI used for corrosion protection.

Finally, nanotechnology provides the tools for better characterisation of material properties and a better understanding of the impact of process parameters in the achieved properties. This is a key enabler for tailoring material properties according to the required functionalities and for reproducible and controllable processes' results. Ultimately, nanotechnology can provide enhanced modelling and simulation capabilities by extending macro and micro-scale models to incorporate the phenomena occurring at the nano-scale (e.g. ab-initio modelling). This will not only impact new production processes for nanomaterials but all kinds of production processes used across all industrial sectors.

#### 2.1.4 Relevant product segments and applications

Several application areas have been identified: (1) airframe and components; (2) engines and components; (3) landing gears; (4) coatings and paints and (5) interior equipment and furnishing [22b] and (6) avionics and other electrical/electronic systems (incl. wiring). The first two application areas are further analysed later on this report.

Future airframes<sup>1</sup> will need lighter, high-performance, robust and cost-efficient, multi-functional materials [31]. Accordingly, lightweight structural materials are the main focus for applications of nanomaterials in civil aviation [12]. Cost-efficiency is another focus area, with lower loading levels of nanoclays providing the same reinforcing properties as conventional reinforcements. Beyond optimising performance, airframes would be able to interact with and respond to changes in the environment, would they be a damage in its own structure or changes in the airflow through its wings (e.g. shape memory alloys or multifunctional composite materials). For instance, Boeing is following the "integrated vehicle health-management" approach and uses nano and other technologies to embed sensors throughout aircrafts to monitor electronic, pneumatic, hydraulic and even structural components [32].

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<sup>1</sup> Further information is available in section 1.4 of this report

In aircraft engines<sup>2</sup>, nanostructured coatings and bulk materials enable higher operating temperatures [21] leading to more energy efficient and less polluting engines [2] or coatings that lengthen components' lifetime by improving protection against corrosion, oxidation, wear/friction or impacts.

Regarding landing gears, they are heavy components working under extreme stress during landing and take-off and are exposed to harsh environmental conditions (e.g. oxidation, corrosion) [33]. The development of lightweight materials together with suitable nanostructured (environmentally-friendly) coatings is one application area receiving substantial attention (also in the defence sector) [33; 23]. The company Heroux Devtek was already using nanotechnology in 2005 to coat landing gears for jet fighters [21] and Raymor Industries Inc. claimed aircraft manufacturers were introducing HVOF coatings as an alternative for hard-chrome coatings in landing gears [43].

Coatings and/or paints are one of the key application areas in the aeronautics sector. Aircraft materials are usually coated to achieve the desired functionalities. Transferring some of these properties to the surface is the approach to improve materials' functionalities in an economical way. These coatings do provide functionalities such as corrosion and thermal protection but can also prevent or reduce wear, ice formation or sliding (important for safety reasons). For instance, Air Canada explored replacing paints by nanocoatings and expected a weight reduction of about 350 pounds resulting in fuel saving costs of more than \$25,000 per year [33]. Regarding the prevention of ice formation (with each de-icing procedure costing around \$ 10.000), nanostructured coatings have been reported (though not marketed) that can repel water and prevent corrosion and reduce ice formation on optical elements and aircrafts [24]. Other advantages that can be brought by nanotechnology are the use of (ceramic) pigments that do not degrade due to UV radiation (thus avoiding the need for aircraft re-painting) [22b].

In terms of windows (or glass), they are used in a variety of sectors and research is going on to provide them with functionalities such as anti-scratch, anti-reflection, anti-glare, low-weight or impact resistance. These functionalities can be achieved by depositing nanopowder based thin layers onto glass [22b]. The aeronautics sector is expected to benefit (or lead) these developments but will also put stringer requirements (which may justify cost increases not acceptable in other sectors). Moreover, developments in this area could benefit from developments in windows protecting infrared sensors in missiles [53].

Last but not least, nanotechnology can have an impact on aircraft electric and electronic systems (e.g. lighter wires). For instance, reductions in wirings' weight from 1,600 kg to around 450 kg have been claimed possible in the old Boeing 747 by replacing copper by carbon nanofibres [23]. The aeronautics' sector will also benefit from advances on a.o. computing power, sensors or display technology.

Besides, many aircraft components or elements can be (drastically) improved. These include, but may not be limited to, filtration systems for higher air quality use nanoscale silver particles to eliminate undesirable odours and kill airborne health threats, low weight interior components (e.g. seats, carriages), self-cleaning textiles or other applications such as low-wear resistance brakes, or additives for propellants [21; 23].

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<sup>2</sup> Further information is available in section 1.5 of this report

## 2.2 Application: Airframe

### 2.2.1 Short application description

Airframes consist of components such as the wing upper and lower, the fuselage, spars, frames, ribs, landing gears and control surface. Modern aircraft structures are designed using a semi-monocoque concept consisting of a load-carrying shell (reinforced by frames and longerons in the bodies) and a skin-stringer construction supported by spars and ribs in the surfaces [15].

Airframes development is split between serving two market views. One view expects an increase of direct flight between local airports, thus requiring a large number of smaller (and safer) aircraft. This is the so-called “fragmentation” approach. The other view (so-called “consolidation”) is based on further development of “hub” airports thus requiring large high-capacity aircrafts [2].

From business jets to civil aircrafts, airframes come in a large variety of shapes and sizes with material selection depending on the required performance and cost boundary conditions. From (very) light aircrafts costing less than \$ 500.000 and with an empty weight of around 1.000 kg to Large Civil Aircrafts costing more than \$ 100 million and an empty weight of more than 150 tonnes.

A very general estimate of the ratio of empty weight to gross weight of most airplanes is about 50%, though there is a modest tendency to increase the structural weight fraction with size. As the aircraft size increases there are components more strongly affected by the stress increases due to structural weight increases (e.g. lifting surfaces) and those that are little affected (e.g. fuselage) [15].

Fail-safe design is achieved through material selection, proper stress levels and multiple load paths structural arrangements that maintain high strength even in the presence of a crack or damage. Typically, the primary structure for civil aircrafts is designed based on average expected operational conditions and average fatigue test results for 120.000 hours that, after applying scatter factors between 2 and 4, leads to crack-free structural life ranges from 30.000 to 60.000 hours [15].

#### Materials used in airframes

Materials that best match the requirements of airframe components are aluminium, titanium, steel and composites. Over the last decades composite materials have gained importance in airframe construction leading to less use of aluminium and much less use of steel (nowadays around 10% in weight). Titanium use in civil aircraft has basically remained flat and represents around 10-12% of the overall airframe weight though it is expected to increase in new large aircrafts [35].

What is probably more important than the present mix of materials is the trend to keep developing multi-material airframes in the future. As stated by a senior structural engineer at Airbus, aircraft manufacturers keep their options open and, “as far as they can see it, it will always be a mixture of materials” [17].

Aluminium alloys have a low density (approximately  $2.7 \text{ g/m}^3$ ) are the most widely used material in civil transport. However, their low melting temperature (approximately  $660^\circ\text{C}$ ) impedes their application in areas near the engine or as skin materials for supersonic aircrafts. The 2XXX and 7XXX age hardening alloys are the most commonly used in airframes.

Age hardening (or precipitation hardening) increases the strength of the alloy by distorting the lattice and creating resistance to dislocation motion.

On the one hand, 2XXX (alloyed with Copper) have lower crack growth rates (thus better withstanding fatigue than 7XXX) are used in the lower wing and the fuselage. To avoid overaging (leading to degradation of mechanical properties), the skin temperature must be kept below 150°C. Creep may also occur at high temperatures (e.g. supersonic aircrafts) and special alloys are required. On the other hand, 7XXX (alloyed with Zn) are the aluminium alloys offering the greatest potential for age hardening, though copper is usually added to improve stress corrosion cracking (with the drawback of difficult weldability). The resistance Stress Corrosion Cracking (SCC) has been the main limiting factor for these alloys and decreases with increasing Zn:Mn ratio.

Composites have been used at floor beams, doors, and aerodynamic fairings and for control surfaces (e.g. rudders, elevators and ailerons). Due to the possibility to design composite materials to fulfil a specific set of properties (e.g. stiffness, strength, density), carbon-fibre composite materials are gaining importance. This is thanks to the high specific strength and stiffness, tailored directional properties, non-corroding in salt environments, excellent fatigue performance, dimensional stability and the possibility to integrate different functions into a single part (reducing the parts' count). On the negative side, composites are susceptible to impact damage and lightning strikes, moisture pick-up and relatively high cost. Besides, they do not yield plastically in regions of high stress concentrations and are subject to random variation of properties due to manufacturing techniques (namely RTM).

For instance, while the Boeing 777 contains 50% aluminium and 12% composites, the numbers for the new 787 Dreamliner are 15% aluminium, 50% composite (mostly carbon fiber reinforced plastic) and 12% titanium. The majority of its primary structure –including the tail, wing and fuselage– is made of advanced composite materials. The function integration benefit of composites is highly visible in the new 787 airliner where each fuselage barrel will be manufactured in one piece and the barrel sections joined end to end to form the fuselage thus eliminating the need for about 50,000 fasteners used in conventional airplane building and replacing 1.500 aluminium sheets. The Airbus 380 contains a 25% of composites but the planned A350 is claimed to contain up to 60% composites (using panelled fuselage skins made of CFRP offering much easier maintenance and reparability) [7]. Whereas the use of composite fuselage structure is becoming the standard in the General Aviation sector (small planes), the A380 is expected to be the first large aircraft in which partially non-metal skin materials will be applied [13].

Looking into the future, the ALCAS project (Advanced Low-Cost Aircraft Structures) aimed at fully applying carbon-fibre composites into aircrafts' primary structures resulting in 20% weight saving with a zero increase in recurring costs as compared to metallic structures for airliner platforms. For business jet platforms the objective was a 20-30% reduction in recurring cost with a 10% weight saving against the metallic structure [20].

Titanium alloys are stronger and stiffer than aluminium alloys. Besides, they are corrosion resistant and also have a low density (for pure Ti 4.5 g/m<sup>3</sup> as compared to 2.7 g/m<sup>3</sup> for Al). Thus, Ti components can be smaller in size than its aluminium counterparts and are used in components where volume is important (e.g. landing gears and attachment points) or in high temperature areas. Ti has a melting point around 1.100°C above that of aluminium and 200°C above that of steel though its maximum operating temperature is around 600°C above which creep (starting at 0.3-0.5 of the melting temperature) and rapid oxidation occur. The main limitation for Ti application is its high cost (approximately 7 times that of aluminium

and steel). Applications of titanium alloys in airframes include undercarriage components and flap tracks while it can be used as skin materials for supersonic aircrafts above **Mach 2.4**.

Steel is also stronger and stiffer than aluminium alloys and is used in components where volume is important (e.g. landing gears, attachment points, gears and bearings) whenever titanium alloys cannot provide the required tensile strength. However, their use has been declining as it suffers from a higher density (7-8 g/m<sup>3</sup>).

Finally, magnesium alloys are being developed but cannot be found in aircrafts airframes yet. For instance, the IDEA R&D project has been investigating magnesium application (including coatings) on non-structural, semi-structural and structural casting parts 30% lighter than present solutions. This project was expected to produce demonstrators that would undergo all the full-scale testing procedures carried out by aircraft manufacturers. Moreover, the AEROMAG project is focused on the development of new magnesium wrought products (extrusion and sheets) that could replace aluminium alloys in fuselage parts, systems and interior components and aimed at 35% weight reduction in selected parts [20].

### 2.2.2 Functional requirements

The airframe is required to resist applied loads (originated from different sources), provide an aerodynamic shape and protect passengers, payload and equipment from external environmental conditions. As different parts of the airframe are subject to different mechanical, chemical and thermal property requirements, each component/system is subject to different selection criteria. Typical constraints include weight, stiffness, strength, fatigue performance (high/low cycle), corrosion resistance and cost [19]. The following picture visualises the critical requirements for different airframe components.

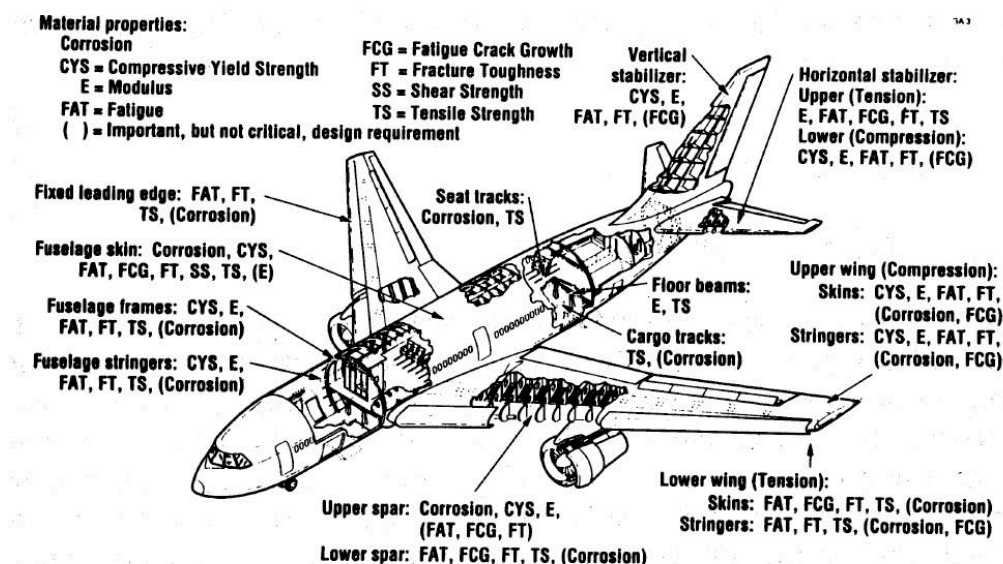


Figure 2-3: Critical requirements of airframe components [19]

From a more general perspective, an airframe structure needs to fulfil a wide set of requirements both in terms of performance (through design & engineering) and manufacturing. Depending on the design approach and the material mix selected for the airframe structure, it would be possible to fulfil them all through an integrated design or auxiliary solutions may be needed. The following picture visualises the requirements both

from a performance and manufacturing perspective.

Thus, the basic structure could provide the required stiffness, strength and stability while specific coatings would provide environmental protection (e.g. against corrosion). In terms of manufacturing, different parts may be produced and assembled or integrated into one bigger and more complex part.

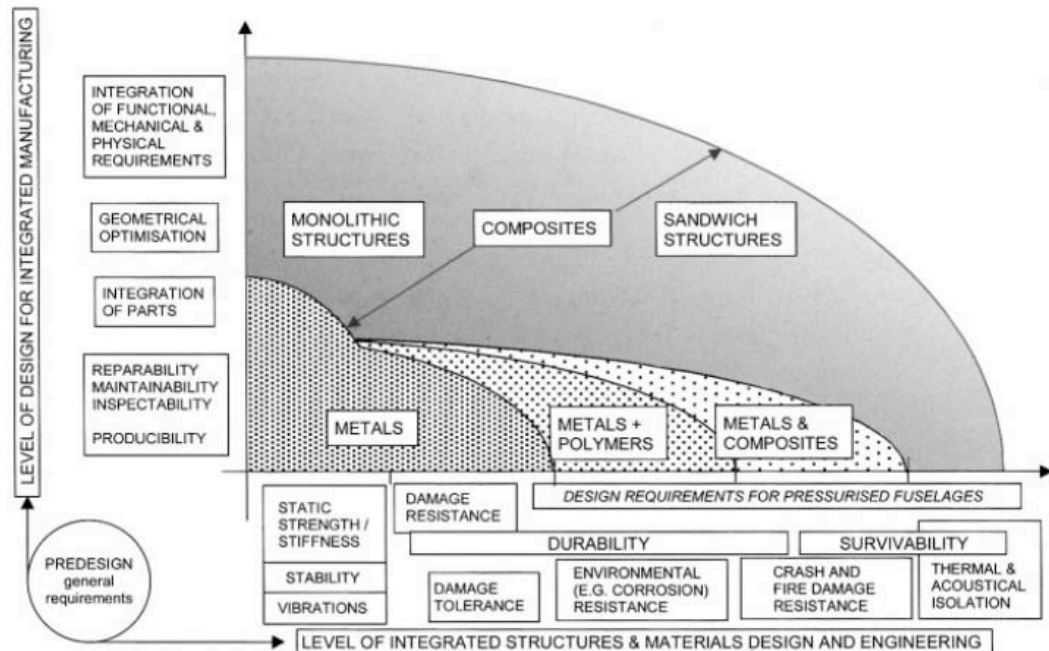


Figure 2-4: Design requirements for fuselage structures [13]

Large aircrafts' lifetime in western countries is of around 30 years (with many of them then being sold to airlines in developing countries and kept in operation beyond that). Given this timeframe, different modes of failure due to corrosion (e.g. stress and exfoliation corrosion) and fatigue damage are important drivers of maintenance cost for metal aircrafts.

Possible damage either from plane's crash or (accidental) impacts during operation, maintenance or while in the ground are also critical requirements. Either through multiple load path structures, no-growth concepts (e.g. crack does not propagate and the structure's integrity is not compromised) or fail-safe designs, airframes (and specially primary structural elements) must resist and tolerate damage and crashworthy. Beyond this, fire resistance must ensure to fulfil with the 90-seconds rule for evacuation in large aircrafts.

An important functional requirement for external parts is protection against lightning strikes. According to Boeing estimates, every commercial airplane is hit by lightning about twice a year. Moving from metallic parts to composites poses new challenges as they will not be able to conduct lightning away as metallic parts do (no airplane crash caused by lightning has been reported over the last 40 years). Most sensitive areas triggering lightning (e.g. while going through an electrically charged cloud) include the nose, the leading edges, the tail or the wings. Amongst them, wings pose special risks as they accommodate the main fuel tanks.

With regard to passengers' comfort, to avoid the need for using oxygen masks passengers' compartments are pressurized; however, the onboard air is equivalent to an altitude of

8.000 ft and results on passengers' tiredness. Using stronger materials could enable further pressure increases and increase passengers' comfort [23].

### 2.2.3 Boundary conditions

The aircraft industry is, by the very nature of this business (transporting human beings and a very high likelihood of passengers' death in case of an accident), risk averse. Though this does not mean it is a conservative industry, if the (potential) reward is good enough, any measure will be taken to ensure that risk is kept at the very minimum through extensive test programmes and evolutionary - rather than revolutionary - development programmes.

From an aircraft industry perspective there are 4 critical requirements to be considered when introducing a new material: (1) stable material and material supplier; (2) materials and design database; (3) stable process and (4) demonstrated technology [14].

Due to the globalisation process this industry has gone through, airframes' production is largely distributed in different sites and organisations [16]. Thus, realising the benefits of new materials and/or technologies often requires reconsidering the way airframes are built and lead to reorganisation of the suppliers' networks. Being capable of operating in such a complex global industry is a critical factor to introduce innovative solutions into the market.

Regarding the parts' sizes and production volumes, there are of course differences between business jets/small aircrafts and large civil aircrafts. While companies like Airbus and Boeing may produce around 400 - 500 aircrafts per year, business jet companies may produce two to three times this number.

In terms of sizes, different airframe components are much larger for large aircrafts but may not differ much in terms of thicknesses. On the other hand, they pose different challenges in terms of manufacturing and cost. For instance, tools accessibility may be more difficult for large aircrafts and these will also require much bigger equipment (e.g. for composites curing and consolidation) and, in the case of composites, ensure proper viscosity of the resin to be used in processing the larger parts.

Long development times required for the design and development of new large aircrafts (approximately 10 years) and their production (10 years as well) makes it critical to exploit windows of opportunities to avoid even further delays in commercialising nanotechnology developments (and revenues generation). Initiatives such as the EU VIVACE project (led by Airbus) aimed at creating a virtual environment to support the entire design process in a virtual extended enterprise may reduce development times by 30% but will pose new requirements in terms of being able to adopt new organisational approaches and IT tools.

The introduction of new materials in airframes (as for other aircraft components) is highly dependent on factors such as cost but also materials' manufacturability and availability. Regarding cost, it is critical to understand the entire manufacturing/assembling processes to reliably estimate the cost impact of introducing a new material. Regarding availability, when new materials (e.g. nanomaterials) are introduced into the market they are rarely available for mass-production as their full introduction into the market normally requires further technological development.

Besides, the introduction of new materials needs to undergo a long and expensive certification process by the US and European airworthiness authorities. The EU R&D project like MUSCA (Multi-scale analysis of large aerostructures; led by EADS Corporate Research) project started in 2005 aims at developing, testing and validating technologies for more cost

effective structural static analysis. The project aims also at providing recommendations to the relevant Airworthiness Authorities.

One important boundary condition is to ensure proper and economic maintenance, repair and operation throughout the airframe lifetime. Thus, difficult access for inspection and repair will set much stronger requirements on the part (e.g. through fail-safe approaches) and possibly limit the potential benefits of introducing new materials (e.g. the theoretical minimum thickness that would realize the required weight savings may not even be possible due to safety requirements).

For large aircrafts flying at high altitudes, fuselage pressurization poses more stringent requirements to the airframe structure so as to ensure passengers comfort (and safety) during flight.

Finally, the cyclic character of the aircraft business clearly affects the production capacity to match the requirements of the ups and downs. Therefore, managing the workload and level peaks and valleys is critical both for aircraft manufacturers and their suppliers. For instance, getting involved in the development of new aircraft when production of existing ones falls can be an approach to manage oscillations in workloads [15].

#### 2.2.4 Product examples

There have not been nanotechnology applications reported in present commercial aircraft airframes until recently. However, a first application in the General Aviation sector was already announced in 2008, when Avalon Aviation's Giles G-200 (single engine fully acrobatic) flew with Unidym's carbon nanotubes incorporated into its carbon fiber composite engine cowling [59]. This material provided for increased strength and flexibility to combat the effects of aerodynamic stress and engine vibration.

Early in 2009, PPG Industries also introduced a chromate-free repaint/repaint process that includes a new exterior epoxy primer based on nanotechnology and an adhesion promoter PPG manufactures under license from Boeing [60].

#### 2.2.5 Economic evaluation

This chapter provides an overview of possible market sizes that could be targeted by nanomaterials and the materials systems they are part of.

The fact that fuel is the largest cost for all airlines (30 up to 50% of direct operating cost) is probably the strongest driver for lighter aircrafts and cleaner propulsion systems. As important as the fuel economy, aircraft designs aim at maximising the payload in relation to cost. As an indication, the weight of a fully loaded aircraft taking off could be broken down as follows: 20% is payload, 40% is structural weight and 40% is fuel [19]. Airport landing fees are partially dependant on aircraft weight.

The value of weight saving in the airborne commercial transport has been estimated at around US\$ 300 per pound saved (getting to as much as US\$ 3.000 for fighter aircrafts) [6]. This comes from the cost savings realised throughout the complete life cycle of the vehicle or its components that justify higher investments. However, the realization of all potential benefits will depend on several factors (many of which uncertain) such as the evolution of oil prices (e.g. from 140\$/barrel to 40 in few months), the actual use (e.g. varying projections for air traffic growth) or lifetime of the vehicles.

In terms of the airframes, the economic impact of nanotechnology can be roughly calculated

based on the expected and potential use of nanoenabled materials (both bulk materials and coatings) in the production and the repair of airframe components. Nowadays, materials represent about 50% of the costs for manufacturing an aircraft structure in high-cost countries. The remaining costs are 35% labour and 15% overheads [5].

Airframes consist of a material mix that has changed its composition over time. Without nanotechnology being used at all, composites have gained importance in airframes designs and this trend is expected to continue. However, it must be taken into account that airframes are systems and not stand-alone components. Parts/components are produced and assembled to deliver the required overall performance. Thus, calculating the economic impact by assuming direct material replacement can be at least misleading and, at the same time, hide some of the potential benefits of new or improved materials (e.g. reduction of parts' count and assembly costs by using composites).

Considering the growing importance of composites in airframes design (more than 50% of the weight of the Boeing 787), nanocomposites will be one of the key areas for nanotechnology applications as long as oil prices are high and production costs similar to metallic counterparts [36]. Conductive composites (required for electric charges dissipation) are one of the lead markets [37]. Despite carbon-fibre composites only contributed to 3% of the 20% decrease in fuel consumption of the Boeing 787, the company has the conviction that it is the technology for the future [42].

The Green Regional Aircraft ITD (part of the JTI Clean Sky / Composite materials) is specifically looking at demonstrating the applicability of nano-filled resin systems to produce composite panels with improved impact resistance and thermomechanical properties such as electrical conductivity and fire resistance. However, the generic planning of the Clean Sky initiative does not foresee flight test before 2013 [55]. According to a material supplier, 90% of the outer structure of the new Boeing 787 consists of lightweight polymer-based composites and Boeing was looking towards adding carbon-nanotubes to improve structural integrity and provide lightning protection [57].

About 2.400 metric tonnes of composite aerostructures were produced in 2007 and it was estimated that about 70.000 metric tonnes of engineered composites would be produced over the next decade. About 13% would be used in regional aircraft whereas the success of the Boeing and Airbus twin-aisle aircraft will be responsible for most of the new demand for composites [36].

By 2020 more than 163 million kg of nanomaterials, valued at \$ 2 billion, would be used to produce nanocomposites, with demands for nanotubes alone exceeding \$ 1 billion. Aircraft is a key market for nanoclay and nanotube polymer composites and will remain so accounting for 40% of demand by 2020 [34].

What is important to realize is that nanofillers may not fully replace established fillers (e.g. carbon or glass fibres) but reduce the load of these materials and make them more effective [21]. The overall demand for structural carbon materials in the aerospace and defence segment was estimated at around \$ 1 billion in 2008 and expected to increase up to \$ 1.4 billion in 2013 [45]. The use of carbon fibre reinforced plastics (CFRP) is expected to grow at around 17% annually by replacing aluminium. The market for CFRP is expected to reach \$ 3.5 billion in 2019 [46].

Despite most of the present demand is for thermoplastics, thermosets are expected to increase their share and reach around 20% of the nanocomposite market (not aeronautics specific) in 2020 [23]. In terms of value, the US nanocomposites industry in 2006 reached

\$ 860 million and was expected to grow 21 percent annually through 2011. The global nanocomposite market has been estimated at \$ 1.5 billion in 2008 [47]. Higher-priced resins, such as engineering plastics used in less cost-sensitive applications, will lead gains [34].

Regarding nanostructured metal parts such as titanium, steel or aluminium, research results promise further weight reduction yet to be realized. For instance, the company Metallicum Inc. (using Severe Plastic Deformation production processes) claims its nanostructured titanium could reduce by 5% the titanium weight in a Boeing 747 (estimated at 100.000 pounds) [44]. The Airbus A320 and the Boeing 737 are expected to have a buy-in weight of titanium of 12 and 18 tonnes respectively (including engines' components) and reaching up to 90 tonnes for the Airbus A350 and Boeing 787 [35]. The development of metal matrixes (e.g. aluminium) reinforced with nanotubes could reduce the weight of polymer composites by 68% in dry weight [58].

The replacement of aluminium parts by CFRP is also expected to increase the use of titanium, which is used instead of aluminium for fasteners and joints [46]. The standard Boeing 747 jumbo jet contains about 75,000 kg of aluminium. Because the metal resists corrosion, some airlines don't paint their planes, saving several hundred kgs of weight [48].

In terms of airframe coatings, they do influence aircraft drag and weight of all kinds of aircrafts. As an example, the weight of exterior coatings of the new A380 accounts for around 725 kg (as compared to the 480 kg in the Boeing 747). A reduction of about 12% in dry weight (80 kg) in a large aircraft would lead to savings of around 20.000 litres of fuel (or 4.400 gallons) and about 50 tonnes of CO<sub>2</sub> emissions. This does not include interior structural coatings that would sum up another 725 kg. The market for aeronautics' coating could be less affected by the economic recession and aircraft production slowdown because existing aircrafts need to be periodically repainted (e.g. decorative coatings usually last between 5 to 6 years) [39].

The total coating market for the aerospace sector had been estimated at about \$ 150 million in 1999 [40], \$ 215 million in 2001 and expected to increase by 50% until 2010 [41]. Other sources claim the paint market alone for commercial aircraft is around \$ 300 million per year [49]. In the U.S., commercial aviation accounted for more than 70% (including general aviation) of the market. OEMs accounted for 65% and refurbishers for the remaining 35% in the commercial aviation sector [41].

Considering the characteristics of the aeronautics' business in general and the airframes in particular, this application is expected to stay a niche market for nanomaterials. Beyond this, the penetration of nanomaterials into this sector is expected to be slow especially due to the long lifetime of airframes and related components.

## 2.2.6 Selected key companies

- Airbus / EADS
- Boeing
- Alenia Aeronautica S.p.a (Italy)
- Embraer (Brazil)
- NASA
- Integran Technologies Inc. (Canada).
- Héroux-devtek Inc (Canada).
- Metallicum Inc. (owned by Manhattan Scientific)
- MetaMateria Inc. (subsidiary of NanoDynamics Inc.)
- PPG Aerospace (United States)
- AkzoNobel Aerospace Coatings (The Netherlands)

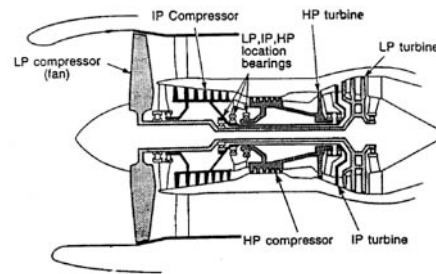
## 2.3 Application: Propulsion systems

### 2.3.1 Short application description

There is a wide range of propulsion systems for civil aircrafts depending on the performance requirements and available budgets. The main difference between a propeller and jet propulsion is that the propeller moves a large mass of air at low velocities whereas the jet moves small masses of gas at high velocities.

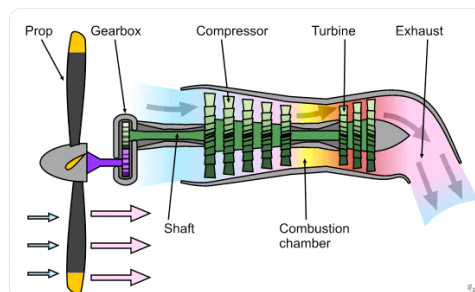
Turbine engines are used in all kinds of aircrafts while light aircrafts sometimes use air-cooled piston engines. For turbine engines a distinction can be made depending on the mechanism used to propel the aircraft. The turboprop (turbo-propeller) consists of a gas turbine that drives the propeller whereas in the turbojet it is the exhaust from the rear engine what propels the aircraft.

In simple turbojet engines, the air is taken into the compressor stage, mixed with fuel and ignited. The turbine drives the compressor. The fan is composed of a series of blades (up to 1,5 to 2 meters in diameter), operates at less than 150°C, is driven by the low-pressure turbine and can reach 5.000 rpm. Next (multi-stage) compressors lead to around forty times increase in pressure and above 650°C. This hot pressurized air leaving the compressor is mixed with fuel and ignited. At above 1000°C the air inside the combustor expands rapidly towards the rear part of the engine through a multitude of turbines (which rotational kinetic energy is transmitted to the compressors at the front of the engine) and exits the engine providing provides the thrust to propel the aircraft [27].



The turbofans is a modified turbojet where more than 90% of the propulsion comes from a multi-blade fan located inside the engine and the remaining 10% comes from the jet thrust. In turbofans, the purpose of the fan is to dramatically increase the amount of air moving through the engine, most of it by-passing the jet turbine, thus increasing the engine's thrust. Nowadays by-pass ratios are above 10:1.

A turboprop engine is similar to a turbofan, but instead of a fan there is a conventional propeller at the front of the engine. The output shaft connects to a gearbox to reduce the speed, and the output of the gearbox turns the propeller. A speed reduction gearbox is inserted between the power turbine and propeller shafts to prevent supersonic speeds at the propellers tips. The gearbox is part of the engine, whereas in a turboshaft the (helicopter) rotor reduction gearbox is remote from the engine. The engine's exhaust gases contain little energy compared to a jet engine and play a minor role in the propulsion of



the aircraft. In general, turboprops are used are used on small subsonic aircraft (though high speed can be achieved) but can also be found in large civil and freight transport aircrafts (e.g. Lockheed C-130).

## Materials used in propulsion systems

The material selection for turbines is highly dependent on the different operating temperatures of engine areas. If temperatures are low to medium (e.g. in the front area) titanium is normally used while for high temperature areas (e.g. rear combustion areas) nickel superalloys and/or ceramic materials are used. The use of materials like composites and aluminium is limited to outer parts subject to lower temperatures.

The main advantages of nickel superalloys are their high strength, toughness and corrosion resistance at elevated temperatures and their creep resistance up to 1000°C. Other materials such as aluminium, steel and titanium suffer from huge losses on their specific strength as they approach their melting temperatures. Besides using Ni superalloys, several complementarily approaches are implemented to satisfy these stringent requirements: blades are cast as single crystals (thus avoiding internal grain boundaries and minimising creep), cooled down through internal channels across the blades and coated with a metallic coat (e.g.  $\text{Al}_2\text{O}_3$  or  $\text{Cr}_2\text{O}_3$ ) to increase oxidation resistance and with a ceramic coat for thermal insulation (the so-called thermal barrier coating or TBC).

For High-Pressure Turbines (HPT), the development of new alloys offering increases in metal surfaces temperature of as much of 150°C over the presently used Ni-based, single crystal superalloys is considered of strategic importance and research has been done on such as Mo- and Nb-based Silicide multiphase alloys that have enhanced high temperature capabilities of up to 1300°C [20; ULTMAT project]. Alternative materials being researched are based on intermetallics or ceramic matrix composites [27].

The rise in the turbine inlet temperature leads hotter environments that worsen corrosion and oxidation of jet engine components. Thus, thermal barrier coatings (TBC) are critical to ensure the durability of components such as turbine blades and vanes and can provide an additional 150°C temperature tolerance. The TBC's topcoat of turbine blades and vanes consists of a low thermal conductivity material such NiAl-based materials, (Ni/Co)CrAlY or ceramics (e.g. YSZ) [27].

### 2.3.2 Functional requirements

In addition to the general requirements for the airframe such as high specific strength and stiffness, good fabricability and acceptable cost, main requirements for aircraft engines include lightweight, power (or thrust), reliability and reparability. New engines are also expected to reduce both pollutants' emissions and noise.

Beyond these, aircrafts have very long service lifetime (above 30 years) and are subject to a very different environmental conditions (e.g. humidity, ice, rain, salt spray, below zero temperatures, etc.) and have very critical requirements in order to protect the aircraft from multiple types of corrosion mechanisms. For engine components, high temperature oxidation is the most important mechanism due to the high operating temperatures. These lead to specific requirements regarding creep resistance, microstructural stability, thermomechanical fatigue at high temperatures and oxidation and (hot) corrosion resistance.

On top of this, the Carnot cycle determines the maximum thermodynamic efficiency of jet engines, with higher efficiency being achieved by a larger maximum-to-minimum temperature ratio within the engine system (between the turbine inlet and the fan inlet temperature) [27].

Thus, it is important to consider the temperature and pressure profiles along the turbine engine. The temperature profile goes from around 200°C in the front, up to 1000°C at the exit of the compressor, reaching a maximum temperature of 1400°C in the combustor and getting down to around 1000°C at the turbine exit. Besides, the pressure profile varies from almost zero atmospheres at the inlet of the turbine and rises up to close to 40 at the end of the High-Pressure Turbine (HPT) and progressively dropping to almost zero atmospheres at the outlet.

Blades in gas turbines operate at 1400°C and are required to have a service lifetime between 10.000 to 20.000 hours. High-pressure turbine (HPT) is a particularly sensitive component in aircraft engines. The current trends are to continue increasing the turbine inlet temperature and the turbine stage load. This tends to reduce the engine's weight but may have a negative impact on components durability, very often determined by the lifetime of the blades [20; TATEF-2 project].

It is very common for the peak metal temperature of a blade to be located in the suction surface trailing edge region. Therefore, the trailing edge is one of the life limiting areas of the blade. Advanced cooling concepts are required to ensure the turbine blades durability. At the same time, trailing edges need to be as thin as possible due to the pronounced effect of trailing edge thickness on aerodynamic loss. This gives rise to an inherent conflict between structural integrity, manufacturing constraints, and induced aerodynamic losses of the blades and vanes leading to a strong demand for highly efficient cooling technology in the trailing edge region.

Moreover, the weight and cost requirements lead to (ultra-)high lift blade concepts for the decreasing number of parts and to unshrouded blade concepts for reducing the weight while keeping high efficiency levels [20; AITEB II project].

### 2.3.3 Boundary conditions

In commercial aviation, the size of the fan (or propeller) limits the places where engines can be mounted. As it is the objective to maximize passenger cabin space, many aircraft manufacturers design their aircraft mounting the engines below the aircraft's wings or in the rear fuselage [28].

An important aspect is machinability (e.g. such as tool life, machining speed and tool cost). As reported by the MACHERENA project [20], presently used materials such as Fe-Ni alloys or Ni-based materials are very difficult to machine due to their high Ni content and heat resistance. Intermetallic materials such as TiAl (a good candidate for replacing existing materials due to its low weight and good resistance at high temperatures) have an even lower machinability (10% of that of Ni alloys) and lead to production costs that are very high for many applications.

Another important requirement is that of inspection and reparability. Engines regularly undergo visual inspections and, at regular intervals, they are overhauled (completely dismantled for a piece-by-piece inspection). The maintenance, repair and overhaul of aero-engine components consist of a chain of different processes such as inspection, welding, milling and polishing. Today most of these processes are carried out manually though the industry is developing improved machining equipment to automate the individual process steps [20; AROSATEC project].

On this regard, non-destructive testing is a critical requirement for the aeronautic industry in general and engines in particular. As visual inspection is the standard procedure, the need

for more sophisticated inspection mechanisms will probably raise MRO costs. Remarkably, engine manufacturers have been offering a 5-year maintenance holiday [30]. This is the main driver behind the development of materials with self-diagnose and/or self-healing properties.

Finally, there are indications that aircraft manufacturers are interested in being able to quickly switch from an engine to another to facilitate taking advantage of technological developments or to facilitate maintenance. It has been reported that Boeing's goal is to make changing engine types as simple as a standard same-manufacturer replacement. Boeing's goal is to be able to change engine in just 24h; other sources claim that swapping engines produced by different manufacturers could take as long as 15 days and make it economically unfeasible.

### 2.3.4 Product examples

No products have been reported.

### 2.3.5 Economic evaluation

This chapter provides an overview of possible markets (including sizes) that could be targeted by nanomaterials and, whenever possible, it indicates the possible share of the market captured by specific nanomaterials.

The market for aircraft engines can be divided into engines sales and after-sales, the last including maintenance, repair and operation services.

In terms of engines' sales, around 40.000 engines were in operation in 2005 and were expected to grow (in line with the increase of aircraft sales) to 57.000 units in 2015 [30]. From 2007 to 2016, the demand for jet engines was expected to total between 60.000 and 70.000 units (with an annual production between 5.000 and 7.000 units) with a market value between 180 and 300 billion dollars [28; 30]. Of these 60.000, around 85% would be installed in commercial or business (jet) aircrafts with the remaining finding use in military aircrafts [29]. It has been estimated that 90% of all jet engines to be delivered over the next decade will be turbofans [28]. Crucially, demand for aircraft engines depends on the aircraft production levels: the consumption of aircraft engines is a function (or a multiple) of aircraft production.

It is usual that aircraft manufacturers developing a new aircraft set the engine's requirements and design at the concept stage of the new aircraft. Once the engine is finalised, engine manufacturers usually try to adapt the design to other aircraft requirements, thus achieving economies of scale that allow them covering R&D efforts [54].

Engines' price is very much related to the engine's thrust (and size). According to list prices, engines' prices can range from less than a million dollars for very small thrust (< 3.000 lb) to \$ 10-20million for larger engines (from 45.000 lb to more than 100.000 lb).

The jet engine industry is dominated by the United States, accounting for approximately 60% of the global market. If world civil air traffic doubles in the next 20 years, the demand for engine and spare parts will reach US\$ 400 billion [27].

The MRO market for commercial air transport for 2005 was estimated at around \$ 40 billion, of which around \$ 14 billion (approximately 38%) corresponded to engines' overhaul MRO. This neither includes the Business and General Aviation sector (small aircrafts) nor military engines. Including all these segments, the engine MRO market in 2005 was estimated at

\$ 25 billion, with Business and General Aviation accounting for around \$ 4 billion and the military sector accounting for around \$ 7 billion. Despite GE and Rolls-Royce have the largest market share, the MRO market is more fragmented than the engine market. In terms of prognostics and health management, GE alone monitors 9.000 engines in flight. Rolls-Royce has a subsidiary providing monitoring services and generating annual revenues around \$ 130 million.

The engine overhaul cost structure has been estimated as follows: 62% in materials, 22% in labour, 13% in outside parts repair and 3% in fees. The outside part repair market has been estimated as follows: High Pressure Turbine (HPT) and compressor airfoils account for 19% each, LPT for 12%, Stators and Cases 7% each and other parts accounting for the remaining 36%.

Regarding the potential market for composites, it has been reported that demand for composite engine structures during 2007 totalled more than 675 metric tonnes including carbon fibre, glass fibre, kevlar, epoxy and high-temperature matrix systems and core materials. This represents a market value of more than \$ 400 million dollars and could exceed \$ 7 billion over the next 10 years. However, these estimates were made before the crisis started to hit the aeronautic industry [28].

The reasoning behind these calculations is that the search for bigger by-pass ratios in turbofans leads to larger (and heavier) fan sections. For instance, the CF6-80C2 engine in service for decades (e.g. Boeing 747-400 or Airbus A330-200) has a by-pass ratio of 5:1 and its fan section accounted for about 20% of engine's total weight. In the newly introduced GEnx engine the by-pass ratio reached 10:1 but increased the fan section weight to 30% of the engine's total weight. It has been reported that this figure could reach up to 35% of an engine total weight of around 2700 kg [28]. Increasing the weight of the fan and its containment case requires an increase on the weight of the rotor and engine structures and finally on the structures where the engine is mounted on.

The titanium (buy-in weight) demand for civil aerospace engines during the period 2005-2014 was estimated at around 12.000 tonnes per year (of which 9.000 for commercial jets) for a total of around 4.600 engines per year [34].

Nanoceramics is also an important research area for improving turbines. The research focuses on reducing the ceramic brittleness while keeping the temperature resistance. Pyrolysis could provide ceramic materials that retain their nanostructure up to 1400°C. For instance, in 2007, GE Global Research announced what it claims is a promising breakthrough in making nanoceramic materials from polymeric precursors.

Regarding the bulk materials used in turbines blades and vanes, usually nickel superalloys (though other materials such as MoS are being researched), the fact that they are produced as single crystals to avoid diffusion across grain boundaries and related phenomena such as oxidation makes the benefits of nanostructuring unclear. Nevertheless, the bulk material is covered thermal barrier coating (TBC) consisting of a metallic bondcoat providing oxidation / corrosion protection and a ceramic topcoat providing thermal insulation.

Projects such as TOPCOAT are developing TBC coatings for turbine blades and vanes that provide high strain tolerance, and a greater lifetime and reliability than coatings produced by Atmospheric Plasma Spraying [20]. Amongst other alternatives, nano-phase suspension plasma spraying are being explored and expected to lead to a 1.5% reduction in engine costs, 20% of maintenance cost (due to doubled life-time) and an increase in the operating temperature of 20 to 30 K as compared to components coated with APS (leading to a 1%

reduction in fuel consumption) [20].

Estimated global sales of thermally sprayed coatings are in the US\$ 5 billion range per year, 50% of which are achieved by atmospheric plasma spraying. The development of suitable deposition equipment, sophisticated on-line process control, ease of application to complex surfaces, availability of a broad range of tailored feedstock materials, and sensitive characterization and quality assurance methods make novel surface coatings and their improved deposition techniques increasingly attractive [51]. It has been reported that nanomaterials such as zirconium oxide in combination of Yttrium oxide are used in coatings for gas turbines and jet engine skirts [22b].

As it happens in the automotive sector, the aeronautics sector can also benefit from nanotechnology in terms of tooling and equipment improvements. Several R&D projects in Europe (e.g. TITALUM and MACHERENA) have aimed or are aiming at improving alloys' machinability and reduce tooling costs.

### 2.3.6 Selected key companies

- Rolls-Royce
- General Electric
- SNECMA Group
- Pratt & Whitney
- Inframat Advanced Materials LLC
- Nanogate
- Sulzer Metco AG
- Raymor Industries Inc.
- Unidym, Inc, a majority-owned subsidiary of Arrowhead Research Corporation



### 3.1. General market description

The turnover of the world automotive industry approached the €2 trillion in 2004, which was **equivalent to the 6th largest economy in the world**. (OICA International Organisation of Motor Vehicles Manufacturers). Also in the European level, the automotive industry is without any doubt a powerful major contributor to the economy, generating **turnover of 551 billion EUR in 2008**, which represented around 5% of the Europe's gross domestic product (GDP).

The European automotive industry produced **17,1 million passenger cars in 2008**, which is 32% of the worldwide vehicle manufacturing (ACEA). Compared with the total number of vehicles in use in Europe, estimated to be 260 million (Lux Research, 2008), the simplified trend for vehicle renovation could be calculated as around 6%/year.

The growth of European automotive markets has been flat in recent years (with the exception of the new Member States). On top of that, since the first half of 2008, when a total of 8,5 million cars and light commercial vehicles were sold in Europe, the production and sales have dropped drastically. The **global financial economic crisis has had a dramatic effect** in the European automotive industry: European new passenger car registrations fell by 7.8% to 14,712,158 units in 2008, recording the sharpest decline since 1993, as can be seen in Figure 5.

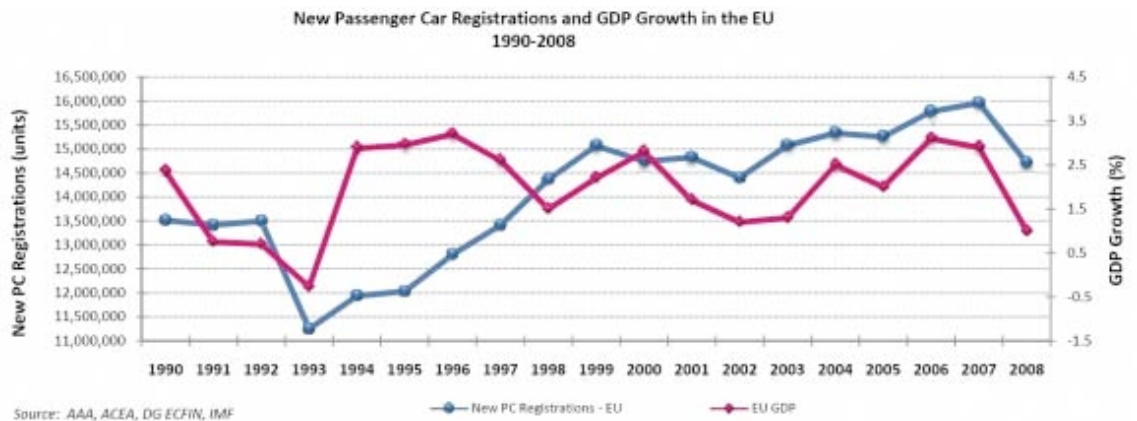


Figure 5: Car registrations and GDP growth in EU

Source: ACEA

The common opinion is not more optimistic and accepts that this declining situation will continue over at least 2009 and 2010.

"Toyota is worried about the future, and it is not just because the company expects a \$1.7 billion loss" New York Times, January 14th 2009

"The common opinion is this is the worst we have seen for the last 20 years." Lars Holmqvist, CEO of CLEPA in 2008

Regarding the markets for the cars produced in Europe, in January 2009 there was a shift: **China overpassed USA with 130.000 units and became the largest automotive market** for the first time in history (Goutai Junan Consulting, 2009). This Asian country has become not

only a location for low production costs but also the most important market, because even though the motorisation index is 10 times lower than in Occidental countries (e.g. in China 60 cars/1000 inh. while in USA 750/1000 inh.) its population is more than 1.300 millions.

The main products of the automotive industry, i.e. the vehicles, can be divided according to the differences in terms of prices and production volumes, as simplified in Figure 6.

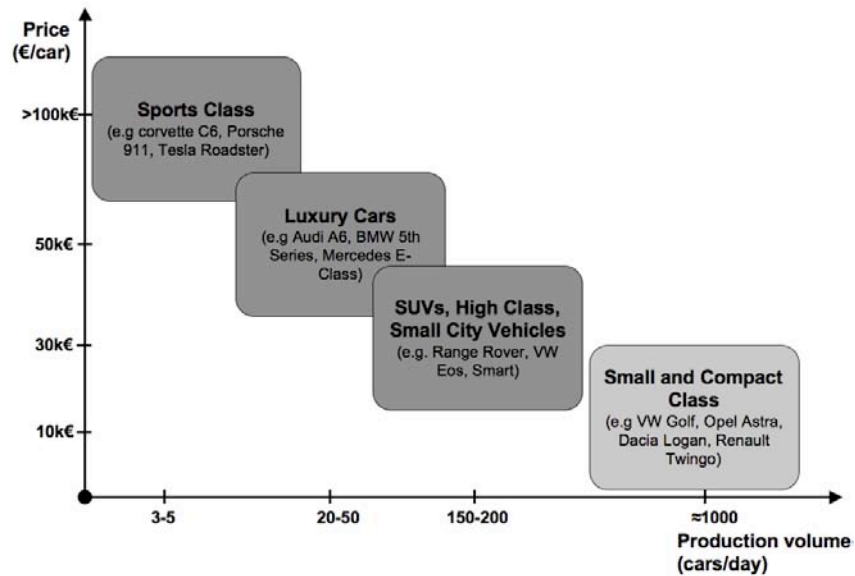


Figure 6: Simplified product volumes and market prices

Most of the vehicle parts are manufactured by specialised suppliers.

These suppliers are organised in multiple tiers, as in shown in Figure 7. While Tier-1 suppliers take responsibility for developing, producing and refining complete components or modules of the car (e.g. cooling, seating, tires), Tier-2 provide them with their parts to manufacture the components (e.g. cables, connectors) and Tier-3 provide with materials (e.g. aluminium sheets, steel profiles). The car manufacturers, usually known as OEMs, assemble the vehicles and produce some strategic parts.

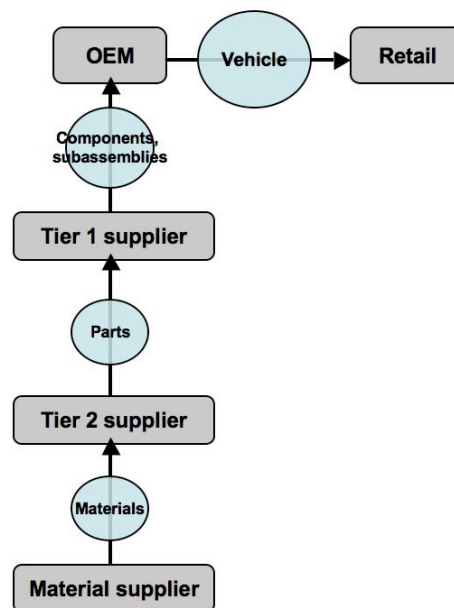


Figure 7: Simplified automotive industry value chain



### 3.2. Nanotechnology impact in the automotive industry

“In light of the broad scope of many nanotechnologies, and the billions of dollars being poured into nanoscale research by governments and industries worldwide, we expect that the impact of nanotechnology on our business could be quite significant” Mr. John Ginder, Acting Manager, Physical and Environmental Sciences Department for Research and Advanced Engineering at Ford Motor Company, 2005

The application of nanotechnology in cars can be present in almost all the systems and parts e.g advanced powertrain, using new energy, reducing car weight, enhancing material functions, increasing comfort degree & flexibility, raising cost efficiency. Figure 8 shows some examples of possible applications of nanotechnology in a car.

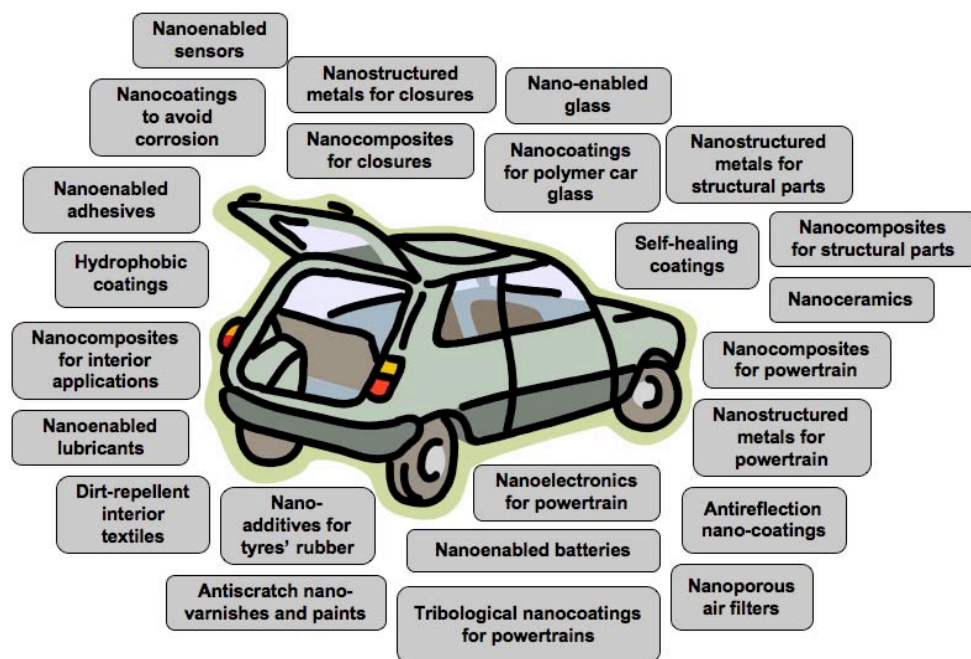


Figure 8: Examples of nanotechnology potential in automotive applications.

According to the Institute of Nanotechnology, 70% of all automotive applications are predicted to use nanotechnology in 2015.

One of the main contributions from nanotechnology to the automotive industry is expected to be nanostuctured metals, because they have proved to be stronger than their traditional counterparts. Therefore, they can **reduce the need of material** or even make possible the **substitution of a current material** (e.g. steel by composite) by lighter or cheaper metals (e.g. steel by magnesium). Apart from strength, nanostuctured metals have other qualities with important potential for the automotive industry, like improved corrosion resistance or magnetic properties.

As well, nanocomposites, like metal matrix composites (MMC), ceramics or polymers with nanofibres, could be the best way to customise the materials in order to get the optimal properties for each application. Strong nanocomposites could **substitute current steel or other metals**, thus making the car **lighter** and therefore reducing its oil consumption and CO<sub>2</sub> emissions. In fact they have been used since 2001, when Toyota started using nanocomposites in a bumper, making it 60% lighter and twice as resistant to denting and

scratching.

Nanoscaled filler materials for rubber, like carbon black or silica are nowadays included in modern car tyres. The result is higher **performance, durability and grip**.

As the automotive industry is tending to **multimaterial** vehicles, where some of the traditional joining technologies (e.g. welding) are not suitable to join different materials or make impossible a satisfying recycling rate. To solve that, a new generation of adhesives that can be more controllable, reliable and recycling-friendly is being developed with nanotechnology.

Nanocoatings can upgrade the surface properties of the parts, for example improving their **corrosion and wear resistance**. This has an impact on the durability of the parts, the reliability for example used in the transmissions can reduce the loss of energy.

To improve the efficiency of the engine, nanoenabled lubricants and fuel additives are being developed.

Another clear trend of the automotive industry is the **electrification**. Nanoelectronics (mainly in the engine management system and the electronic transmissions) and nano-enabled batteries can have a very important role in bringing reliable, well-performing systems to the market in a short and medium term.

Some suppliers are already offering to increase the **comfort and safety**, like antireflection coating for the surfaces, flame-retardant polymers, nanoporous air filters or dirt-repelling interior textiles.

Also in car glass nanotechnology can have impact, for example with electrochromic, antiglare coatings for mirrors, dash panels and glasses, hydrophobic (anti-fog) coatings for mirrors and glasses, solar heat control glass, switchable glasses (for sun roofs that can select the transparency of the glass) and self cleaning glass.

As an important driver in the transport sector is the weight reduction, nanotechnology is also contributing to make possible the **substitution of mineral glass by polymer glass**, especially polycarbonate, which could reduce a car's overall weight by up to 20 kg, depending on the car. The main barriers to overcome are to integrate other functionalities in the glass to add value (e.g. printed antennas) and to protect the surfaces from scratching, abrasion and climate influence (e.g. extremely hard aluminium oxide nanoparticles coating).

Nanotechnological expertise will become one of the main competences in automotive engineering, according to Volkswagen (2003 statement)

### 3.3. Drivers and Barriers to Innovation

The pollution generated by transport has become an important concern for the citizens and the governments. In Europe, road travel is the second biggest source of greenhouse gas emissions, after power generation. Passenger cars are responsible for releasing 12% of the EU's total CO<sub>2</sub> emissions into the atmosphere. Therefore, **reducing the environmental footprint of the vehicles** has become an important driver in the automotive industry.

Even with the significant improvements in fuel efficiency related technologies, the CO<sub>2</sub> emissions rose by 26% in the period 1990-2004, due to the traffic increase and the bigger car sizes. This is driving the automotive innovations mainly towards reducing vehicle weight and new powertrain systems, mainly Plug-in Hybrid Electric Vehicles and "pure" Electric Vehicles.

**Reducing fatalities and increasing comfort** is also an important driver for the automotive industry. The car users demand more and more safety control (even assisted to autonomous driving) and at the same time more comfort and commodities inside the vehicle, mainly based in electronic systems.

The automotive industry has always been very competitive. Suppliers fight to be able to produce a specific part, because due to the large production volumes, it can mean a big part of business for that company during several years. But since the end of 2008, **competitiveness** has become even more important: With the global financial and economical crisis, which is hitting the sector, the companies are pushed to innovate to ensure their position in the future market. New products, mainly electric cars or their systems, are being disputed by plants, companies and governments.

The following table summarises the above-mentioned drivers and directions:

Drivers	Directions
Reduce environmental footprint	Fuel efficiency technologies
	Weight reduction
	New powertrain systems
Safety and comfort	Electronic systems to control safety and comfort
Competitiveness	Innovativeness
	New products, like electric vehicles

On the other side, there are barriers for the new technologies to be introduced in the automotive industry that have to be taken into account, like stringent regulations, overcapacity in the production plants, and the lack of the communication between the high-end scientific community and the industry.

**The automotive industry is highly regulated** (over 90 European directives), particularly in the fields of safety and environment, and the stringency of such regulation is becoming a driver for technological change in the sector, although it also adds to the cost of production. Unlike for other markets, the cars to be sold in Europe have to pass stringent mechanical

and chemical tests, and this has positive repercussions in the quality of the products and their safety, but also implies that the minimum time to develop a car passing all the regulations and standards in around 5 years.

Another barrier is that the automotive production plants are normally designed to cover the maximum demand, which leads to an almost-always situation of **overcapacity**, which is since mid 2008 drastic because of the production reduction. As the overcapacity implies an important resistance to investments and product modifications, it affects the uptake of new technologies in the automotive industry.

As in any other industry susceptible to use high-end research products, there is sometimes a **lack of understanding between the industrial and the scientific communities**. This is because in the high-end research (e.g. biotechnology, nanotechnology), the research is often not intended to address any specific need, but driven by the researchers to find out "what is possible". This creates a big distance between the research and the market applications. This gap has normally to be overcome with specific programmes in the research centres.

The table below summarises the barriers explained:

Barriers	Effects
Stringent regulations	Long development times
Overcapacity	Resistance to equipment investments
Gap scientific-industrial communities	Delays in the adoption of high-end technologies

### 3.4. Relevant product segments and applications

The application of nanotechnology-enabled products can be segmented depending on the final parts of the car where they will be applied. The following segments have been identified: (1) Car body (Body in White and Closures), (2) Powertrain (incl. engine), (3) External paints and coating, (4) Suspension and braking systems, (5) Tyres and (6) Car glass. The first two application areas are further analysed later on this report.

The car body is the main structure of the car and most of its parts have to comply with safety conditions to protect the passengers and the fuel tank. The current trend in these parts is to reduce their weight, by substituting the traditional steel with new steels, lighter metals or even composite materials.

As well, nanotechnology can have a role in the materials that will optimise the engine and the joints performance. Two segments have been identified in this category due to the potential impact of nanotechnology: (7) Lubrication and (8) Adhesives.

Improved lubricants can improve the engine efficiency and the performance of other mobile parts as well as avoid maintenance operations, like oil changes. Also in the production phase, lubricants have an important role in the durability of the tools and the process costs (e.g. temperature necessary).

As well, in the new- and multi-material trend for tomorrow's car production, the adhesives can have an important role, due to their capacity to join different materials, combined with other properties, like for example corrosion protection. Adhesives that are more reliable and controllable during the joining process are necessary in the automotive industry.

Another promising field of application for the nano-enabled products is the production equipment, namely the segments (9) Cutting tools and (10) Moulds and dies.

Parts suppliers and OEMs have important investments in the above-mentioned production tools and their durability is often not as long as desired, involving also high costs in replacement and maintenance operations. Especially with the new materials used in the automotive industry, it is necessary to use improved production tools.

## 3.5. Application: Internal Combustion Engine and Powertrain

### 3.5.1 Short application description

**The powertrain refers to the group of components that generate power and deliver it to the road surface.**

The main elements of the powertrain are drive wheels, transfer case, driveshaft, differential, transmission, clutch, crankshaft (also called crank), flywheel, torsion damper and engine. In the internal combustion engine (ICE) (four-stroke engine), the key parts include the crankshaft, connecting rod, one or more camshafts and valves. All of these parts are assembled in the engine block.

Hybrid and electric powertrains are gaining more and more importance for the automotive industry, due to the environmental and competitiveness issues mentioned in the previous chapter. However, it is foreseen that IC Engines will be still leading in the next decades. According to PWC Automotive Institute, in 2014 a total of 770 million automobile engines will be produced, of which around 74% engines will be combustion gasoline, 24% combustion diesel and only 2% hybrid gasoline.

"Despite new hybrid and full electric powertrains being developed, many carmakers expect the combustion engine to remain the dominant powertrain concept over the next decades" Dr. Klaus Draeger BMW.

#### **Materials used in the engines and powertrains**

According to PWC, for an average upper medium car, the powertrain (including the engine) accounts for about one third of the vehicle weight. The greatest part is the engine, whose weight can vary from 70 to 180 kg.

Of all engine's components, the engine block is the heaviest one weighting more than 20 kg.

Therefore, an important trend in the engines and powertrains is weight reduction, and accordingly **heavy metals**, like the cast iron used in the engine blocks (density:  $7.9\text{g/cm}^3$ ) have been widely replaced by **lighter materials**. For instance, switching from a cast iron engine block to a magnesium alloy version can save **13kilograms**, a 40% weight reduction.

Figure 9 shows how aluminium has replaced cast iron in the production of cylinder heads.

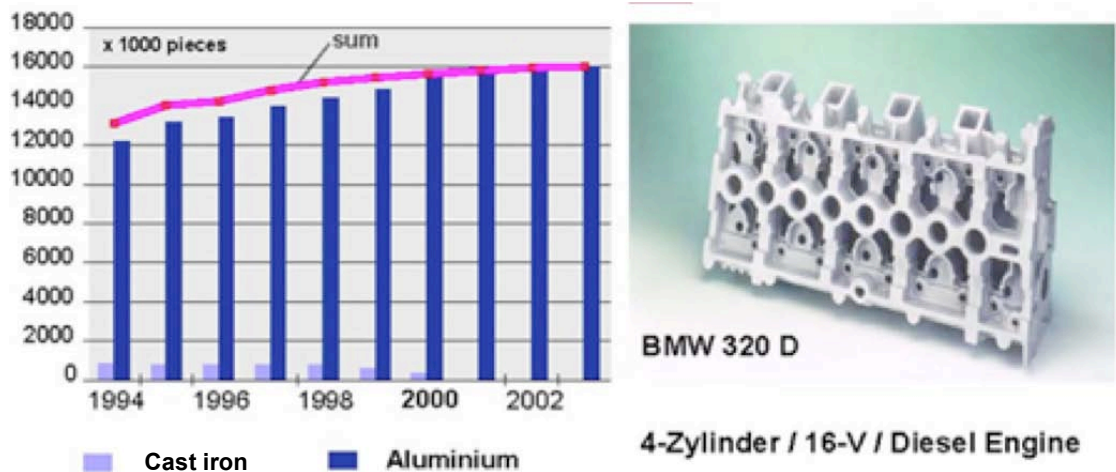


Figure 9: Production of cylinder heads in Europe

Source: Hydro Aluminium

On the other hand, every replacement normally implies some problems and changes and the appropriate balance always has to be found. For instance, replacing cast iron blocks in the engine by aluminium faces some problems due to the fact that engine lubricants' formulations have been tailored to cast iron properties. The current aluminium surface or coatings are not compatible with engine oil formulation. To overcome this, the aluminium bores require cast iron sleeves inside.

A material that has not been widely used much in powertrains and engines even though its proved thermal qualities are **ceramics**. Till now, the inherent brittleness of ceramics kept them out of the market for large parts, (e.g. engine blocks) and were used for smaller components (e.g. valve parts and bearings). The main reason is the tendency to form micro-cracks during manufacture, which results in high rates of product rejection and consequently higher production costs.

Related to the materials used in the powertrains, it has to be taken into account that the trend in modern engine design is **downsizing**, i.e. making the components smaller. The effect of the materials is that as smaller sizes of the components often lead to higher load and stresses on the component itself. The risk of component failure increases.

## Friction in the engine and powertrains

Reducing friction and wear in engine and drive train components is a vital issue for automotive manufactures, and it is estimated that could save the US economy as much as US \$120 billion per year.

As shown in Figure 10, only about 13% of the energy available in the fuel is available to drive the wheels. The losses are mainly due to engine inefficiencies and mechanical losses in the driveline.

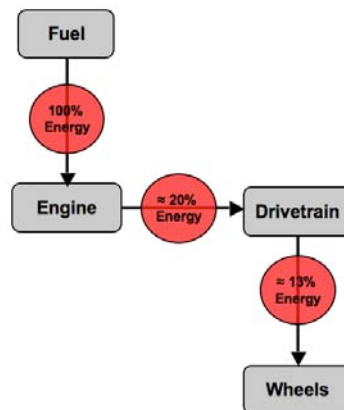


Figure 10: Energy losses along a powertrain

There are technologies, mainly **coatings**, which can reduce the friction and therefore the energy losses. One example would be carbide-based wear-resistance coatings for cylinder walls, pistons, bearings and other engine components (crankshaft, valve train, etc.).

The applicability of these specific coating in these complicated parts bears sometimes manufacturability problems. For example, in the pistons, it has to be taken into account that their different rings need different types of coating: while the top compression ring usually has a wear resistance coating such as flame-sprayed molybdenum, the second compression ring is not normally coated and the bottom ring used to have a chromium plating, to improve the oil retention. Another example in the powertrain is cylinder bores: most of them have inner radius of 70-110 mm and such dimensions call for special tooling for applying the coating.

### 3.5.2 Nanotechnology impact in the IC engine and powertrain

**Nanotechnology improvements in metals and composites** could contribute to reduce the powertrain weight and therefore to reduce the energy consumption of the vehicle. Nanocomposites, mainly metal matrix composites or polymer nanocomposites, could replace steel parts, offering an important weight reduction potential. Nanostructured metals, controlling the material in a nano-scale can provide customised characteristics in the different parts of the components. As an example of research, nanostructured Al casting alloys are being researched by Ford and the Northwestern University in collaboration to develop stronger and better performing parts.

**Tribological nanocoatings** can be applied in automotive powertrains to improve their mechanical efficiency, like advanced PVD and CVD coating. Novel hard and / or low friction coatings made of nanocomposites with SiC, SiO<sub>2</sub>, TiO<sub>2</sub>, BN<sub>3</sub>, C, diamond, even Teflon with matrix material such as Ni, Al, Fe and alloys offer an improved mechanical stability, which mean less wear, better gliding, thinner coating and less lubricant, longer service interval and reduced fuel consumption. The wider application of tribological nano-coatings could reduce significantly the energy losses in the engine and the driveline.

To complement all the above-mentioned, **nano-enabled lubrication** can improve the efficiency and reduce the maintenance in powertrains. As well, **nanoceramic materials** offer an opportunity to rethink the internal structure of the internal combustion engine and its component coatings.

### 3.5.3 Functional requirements

**Corrosion resistance** is a vital issue for engines and powertrains.

A critical part is the cylinder: In addition to wear (due to mechanical interactions), corrosive wear may occur in the upper part of the cylinder region during short-trip service in a winter climate.

As well, parts that are inside or close to the engine have to be **heat resistant**. The materials have to be thermally stable and also able to dissipate the heat.

Failure in the engine or in the powertrain can imply high risks for the passengers. Therefore, their parts have to comply with stringent **reliability and durability** standards.

Besides, the engine and powertrain parts have to be accurate enough in their functioning to produce the **minimum vibrations (and noise)** possible and some parts also have to absorb them.

Last but not least, as parts of the vehicle, the powertrain parts also have to be assessed regarding their life cycle and have to comply with all the relevant recycling standards.

### 3.5.4 Product examples

- **NanoLub™ (ApNano Materials Inc):** Solid lubricants with nano-spheres of inorganic compounds have been developed by the company ApNano Materials Inc (Israel) together with Volkswagen Group. These solid lubricants would avoid the oil changes.
- **Carbon NanoSphere Chain™ (CleanTechnology International Corp):** Nanocarbon material that can be used for composite applications in automotive industry and as additive to the fuel for improving lubricity.
- **Catalytic converter (Nissan Motors):** Nissan Motors has introduced a catalytic converter for gasoline engines that uses only half the catalyst as conventional catalysts. It has been developed as part of a joint collaboration between Renault and Nissan. Using nanotechnology, Nissan has succeeded in keeping the particles separated under high temperature. With the clustering reduced, the amount of catalyst required is also reduced. This is achieved with no degradation of performance in cleaning up the exhaust. In turn this will reduce the cost to the auto manufacturer and the consumer.
- **Toyota timing belt cover (Toyota):** Nylon timing belt of nylon-nanoclay composite. Its main characteristics are its toughness and heat resistance.

### 3.5.5 Some key companies

#### Engine & powertrain suppliers

- Robert-Bosch GmbH
- Magna International
- Electrovac
- Aveka Group
- GE Plastics
- Synkera
- Emil Bröll GmbH
- ZF Friedrichshafen AG

#### Adhesives, rubber and lubricants

- Fuchs Petrolub
- ARC Seibersdorf research GmbH
- ApNano Materials Inc.
- Hatco Corp.
- IAVF Antriebstechnik AG
- Trelleborg

## 3.6. Application: Car body

### 3.6.1 Short application description

The car body parts considered in this chapter are those called the **Body-in-White and the closures**.

The Body-in-White is the basic structure of a car. In case of crash this structure has to absorb as maximum energy as possible and protect the passenger space at the same time. It is also the heaviest part of a conventional car with a share between 25 and 30% of the complete car weight. Being the vehicle's largest structure, it might seem ideal for weight reduction, but normally reducing body weight involves a trade-off with body stiffness, a key characteristic which influences vehicle dynamics, durability and crash worthiness.

To complement the Body-in-White, the closures are assembled. The main automotive closures are the doors, the hood and the deck lid (hatchback or tailgate). The closures account normally for around 6% of the car's mass.

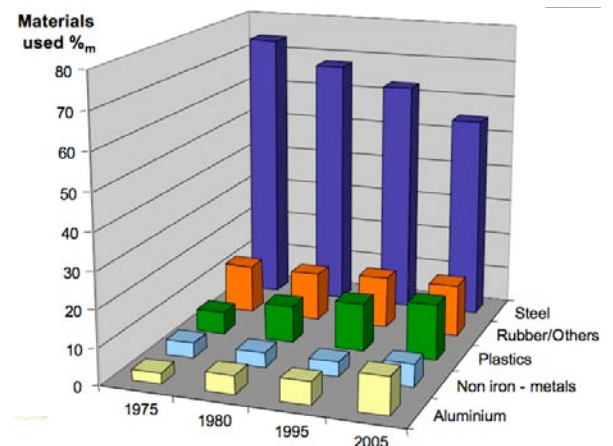
As closures are not part of the primary crash-energy management system, many automakers have started with them in the weight reduction, mainly switching from steel to aluminium and composites.

#### Materials used in the car body

Steel has been dominating the market for car body parts in the past decades.

However, more and more other materials are gaining market shares, as can be seen in figure 11. The main reason for material substitutions has been weight reduction.

Figure 11: Materials used in car bodies since 1975  
Source: SuperLIGHT-CAR project



Also important associations like EUCAR are betting on multimaterial concepts, as graphically explained in

Figure 12.

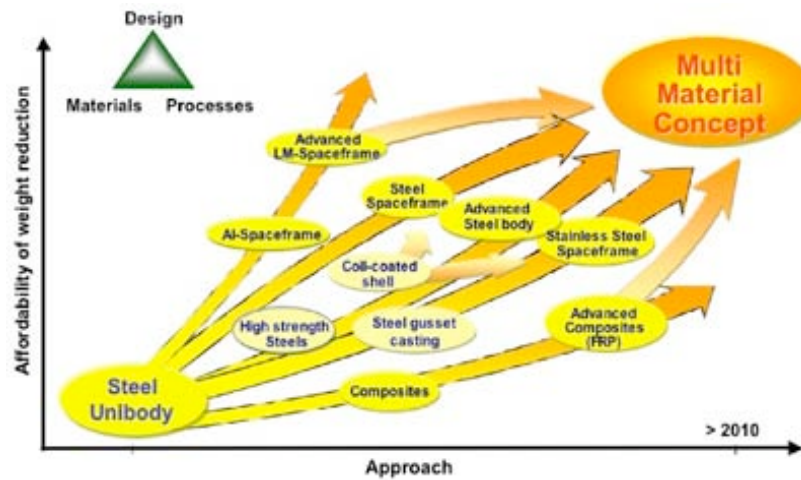


Figure 12: Trend to multimaterial vehicle structures for weight reduction  
Source: SuperLIGHT-CAR project (originally EUCAR figure)

The average **aluminium** content in car body is 26 kg, basically in bonnets and doors, front structure and bumper beams.

Aluminium has been used in car bodies since 1993, as a light substitute for steel. One of the typical cases are the hoods, which are typically made out of steel, but aluminium is rapidly getting more popular with auto companies. It is foreseen that the use of aluminium in the automotive industry will increase up to more than 200 kg per vehicle, according to the European Association of Aluminium. As example, Ford is working more and more with aluminium, such as in Jaguar vehicles, the Ford GT and the Shelby GR-1 concept car.

The gross yearly sales of Al sheet to OEMs for closures in 2003 was \$600.000.000.

Another material in the lightweight substitution race is **Magnesium**. And density-wise, it has a big advantage: a steel cube with the dimension 10x10x10 cm weighs 8,6 kilograms, whereas an aluminium cube with the same measurements only weighs 2,7 kilos and if it was made of magnesium, it would weight 1,8 kg. Besides, magnesium has high strength and stiffness to weight ratios, and provides good vibration damping. Automotive manufacturers have believed in magnesium potential and Ford and VW even invested in primary production in Australia and Israel. Regarding its price, in recent years the abundance of magnesium in China has had the effect of lowering the raw material costs, at times even lower than aluminium cost.

The most widely used wrought Mg-alloy is the AZ31 (Mg-3Al-1Zn), which is available for extrusions, plates and sheets. Magnesium sheets are especially suitable for large parts like the hood or the roof. However, the application of magnesium sheets in the car body has not yet been spread. VW stopped production of the Lupo magnesium tailgate: the main reason was the cost of the corrosion protection. It's not that magnesium is not at all used in the automotive industry, but it is being mainly used in parts that are not exposed to corrosive environments, which is clearly not the case for the body-in-white or the closures. Another limitation for magnesium sheets is they have to be stamped at high temperature (200-

300°C), preheating the die as well.

To solve the corrosion problem there are diverse possible solutions: coatings at different stages of production and thin films or thin layers, as in the promising proposal of the researchers in the University of Berlin to use aluminium foil to cover the magnesium alloy.

The steel industry is not letting the other materials overpass it for car body applications and continuously introduces new materials with improved properties. Steel is being very competitive for automotive structural parts with its **Advanced High Strength Steel (AHSS)**. AHSS such as Dual-Phase, Transformation Induced Plasticity (TRIP) and martensitic steels provide interesting characteristics because they have very high strength, and yet can be easily formed to make complex automotive parts.

Last but not least, **composite materials** have been in used in structural parts in the vehicles since the 1950s, when the Corvette was launched with the body made of fiberglass. However, almost 60 years later, this material has not been generally adopted in mass production. The main reasons are that the cycle times are in general still too long, raw materials (resin, fibres, etc.) are relatively expensive and it is difficult to achieve high quality surfaces. Composite materials are often used by aftermarket manufacturers, for example to construct hoods out of fiberglass, carbon fiber, or dry carbon.

### 3.6.2 Nanotechnology impact

Nano-enabled products are not used in the automotive structural parts yet. The products currently in the market are mainly with aesthetic purposes (waxes, paints, etc.) in the high-class or luxury vehicles. Still, nanostuctured metals and polymer nanocomposites have an important potential to contribute to further weight reduction in the car bodies. Lighter bodies without compromises to the stiffness and crash resistance means less material and indirectly less fuel consumption.

**Nanostuctured metals** are stronger than their traditional counterparts. For this reason, they can have an important role in reducing the weight of the vehicles. Moreover, they have improved properties in corrosion resistance and can even be tailored with different characteristics depending on the requirements of the zone. When the technology is able to produce large parts (bigger than a screw) with a competitive price, nanostuctured aluminium and magnesium will be suitable to be widely used in structural parts, replacing steel. Also for nanostuctured steel, as the properties would have improved, the material could be reduced, and thus the weight.

The same functionality is applicable for **polymer nanocomposites**. Polymer nanocomposites could introduce tailored, light materials to the car body applications. Carbon nanotubes and inorganic nanoparticles can be added to conventional materials for special properties. Applied in the automotive industry, the matrix polymeric composite makes possible that the composite parts can be painted together with the rest of the auto body and treated in the same process as the metallic material.

As an example of applied research in this area, Ford researchers are working at Northwestern University with nanotechnology to develop stronger and lighter structural materials, such as metals and plastic composites. These metals and plastics use nanoparticles as fillers that reduce weight and increase strength.

Apart from lighter structural parts, there are more applications for nanoenabled products in the automotive industry. As introduced in the top of this chapter, the driver that is currently opening doors for nanotechnology is aesthetics. This will be the main selling point for **antiscratch, self-healing and dirt-repellent nanocoatings, paints and varnishes.**

### 3.6.3 Functional requirements and boundary conditions

As the car body is the main structure of the vehicle, its functional requirements regarding **crash resistance, fatigue and static performance** are very stringent and if the vehicle does not comply with the European standards, the car cannot be commercialised. All these standards and regulations respond to passenger protection measures, aimed at reducing the number of fatalities in the European roads.

In case of crash, the Body in White has to absorb as much energy as possible, but with a controlled deformation, so as to cause as few damages as possible in the driver and passengers space. The most known tests are Euro NCAP front crash, side impact, rear impact, natural frequencies and static stiffness, in which accelerations, intrusions, intrusion velocities, torsions and bending are measured in specific parts of the car body.

For hoods, **pedestrian safety** is as well an important boundary condition for design. In Japan and Europe, regulations have come into effect in recent years that place a limit on the severity of pedestrian head injury when struck by a motor vehicle. This is leading to more advanced hood designs.

As well, the external car body parts have to have **high quality surfaces (Class A), corrosion resistant** and be **UV-light resistant**.

Like the rest of the vehicle, car body parts also have to be assessed according to their compliance with stringent regulations for **recycling**. This is specially an issue when several materials are mixed in the car body, since the recovery is more complicated.

### 3.6.4 Product examples

- **AEROSIL(Degussa):** Nanoparticles used in the body shell for pigment stabilisation, rheology control and corrosion resistance. It is present in car varnishes as well, for improvement of the scratch resistance.
- **Nanopaints used in Mercedes Benz models (Daimler AG)**
- **Mercedes-Benz** also makes a major contribution to exemplary long-term quality and value retention with a scratch-resistant clearcoat based on nanotechnology. This innovative paint system, which celebrated its world debut at Mercedes-Benz at the end of 2003, is a standard feature of the new C-Class and is used for both metallic and non-metallic finishes.
- **General Motors** introduced their nanocomposite thermoplastic olefin (TPO) **step-assist** for the 2002 Chevrolet Astro and GMC Safari minivans.
- **Renault Clio and Megane** are also using a nanotube filled polyamide / polyphenylene ether (PA/PPE) blend for their **sport fenders**.

### 3.6.5 Some selected key companies

- Daimler
- Volkswagen
- Renault
- General Motors
- Degussa
- Faurecia
- ArcelorMittal
- Hydro Aluminium
- Fraunhofer Gesellschaft Institutes
- Fiat
- Magna International
- Electrovac
- Ford Motor Co.
- Aveka Group
- GE Plastics
- Synkera
- Emil Bröll GmbH
- Toyota
- Nanocor Inc.
- Blackhawk Automotive Plastics Incorporated
- Bayer AG
- NanoX

### 3.7. Economic evaluation of nanotechnology in the automotive industry

Nanotechnology enabled products have an enormous **potential** in the automotive market, often estimated as to be included in 70-80% of the total automotive applications by 2015. Regarding **market forecasts**, different estimations have been published in the recent years, some of which are listed in Table 1. Even though the broad range between the estimations, the lowest one (and probably the most accepted one) is the impressive amount of more than 6 billion US dollars for 2015.

Lux Research (2004)	8.500 million US\$ (2004)
Frost & Sullivan (2005)	1.276 million US\$ (2008)
	1.526 million US\$ (2010)
	6.460 million US\$ (2015)
RNCOS (2006)	Close to 7 billion US\$ (2015)
Helmut Kaiser Consultancy (2007)	8.600 million US\$ (2007)
	54.200 million US\$ (2015)
	137.400 million US\$ (2020)
Institute of Nanotechnology (2007)	1.110 million US\$ (2007)
	6.460 million US\$ (2015)

**Table 1: Different nanotechnology market forecasts in the automotive market**

However, nowadays only **very few applications are present in the current or planned cars.** While nanotechnology enabled products promise to reduce significantly weight and increase efficiency of our automobiles, at the moment **only products with relatively low market impact, mostly used in parts that don't compromise neither safety nor the vehicle performance, have accessed the market.** In fact, only paints and coatings accounted in 2008 for about 43 per cent of the entire nanotechnology market in the automotive industry. Moreover, other existing applications, like carbon black, have been used since long before the nanotechnology boom. For example, Toyota introduced the first commercial nanocomposite in the automotive industry in the 1990s, developing a nylon-nanoclay composite for tough, heat-resistant, nylon timing belt covers.

Nanotechnology research has to be focused on providing complete solutions and understand the reasons for which the industry (mainly the OEMs) and the final customers are willing to pay more, or to invest. One of the most important drivers for nanotechnology in automotive is expected to be weight reduction. It is estimated that around 25% of the market of nanotechnology in automotive is and will be derived from the need for lightweight

structures. This is linked to the commonly accepted feature that European OEMs are willing to pay around 5 € for each kg saved.

Regarding the different car segments, it is expected that nanotechnology-enabled products will be mostly introduced in niche applications and high-class or luxury cars at the beginning. The reason for this is the volumes and cost constraints in the most popular car segments. For example, a material that pretends to be used in the compact class (C-class) cars to reach a very large market, will have to be very competitive in price (e.g. similar cost as the current alternative) and have a cycle time short enough to be able to supply parts for a volume of 1000 cars/day or higher. This implies that most of the nanotechnology enabled products cannot be yet used in C-Class segment cars, due to their high volumes (e.g. 437 505 units of Peugeot 207 were sold in 2007, making it the best selling car in Europe).

The main products that are already in the market or are expected to be launched in brief for the automotive industry are the nanoadditives for tyres rubber, antireflection nanocoatings for mirrors and control panels, nanoenabled lubricants and antiscratch nano-varnishes and paints.

After them, the research is already driving to promising solutions to launch more nanotechnologyenabled products to the market in medium term (3-7 years), like hydrophobic coatings, dirt-repellent interior textiles, nanoporous air filter, nanoenabled glass, self-healing coatings, nanoenabled adhesives, polymer nanocomposites for interior applications, nanocoatings to avoid corrosion, nanoenabled sensors for car driver, car-car and car-infrastructure communication and tribological nanocoatings to improve the efficiency of the powertrains.

“We have used nanomaterials in exhaust catalysts and as polymer fillers for decades. But, we don’t necessarily know where the ‘killer applications’ for the new generation of nanotechnologies will be”  
Mr. John Ginder, Ford Motor Company (2005)

It is foreseen that the promised '**killer applications**', like nanotechnology-enabled batteries or transparent structural parts, will take longer to penetrate the market but will have an important impact for the industry and the final costumer. Other fields of research that will probably introduce important nanoenabled products in the long term (10-15 years) are nanoceramics to be used in engines and nanocomposites or nanostructured metals for lighter car body parts and powertrains.

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## Annex: Expert Engagement

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This report has been partially based on the interview done with the following experts:

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