Auto – Aero:
Technology Transfer Assessment
for
Light Weighting

Deliverable 3.2.1: Benchmark and Mapping of Sweet Spots for Auto-Aero Technology Transferability

Deliverable 3.2.2: Database of Success Cases on Knowledge Transfer in Lightweight (chapter 7)

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Executive summary

The strive for emissions reduction has propelled the urge for lightweight transportation. With an emphasis on road and air transport, this report assesses the impact of weight reduction on emissions-lowering of aircraft and automobiles. A weight reduction of 100 [kg] implies a saving of 19000 liters of kerosene for a fully operated A320 over a single year (CO_{2e} reduction = 57000 [kg]). For cars, this number is 52.7 liters, or 130 [kg] of CO_{2e}.

The incorporation of novel, lightweight materials and related production processes is able to realize significant weight savings. However, while the aerospace sector is prepared to accept materials costing 800 € per kilogram, this limit is significantly lower for cars: 7 to 8 €. Affordable, glass fiber-based composites do not provide worthwhile gains in terms of specific stiffness but do certainly show potential for weight reduction in strength-dominated, primary structures. Moreover, for secondary structures, they still offer significant weight-saving potential, regardless the eventual maximization of stiffness or strength. The more expensive carbon and polymeric fiber-based composites can realize impressive weight knockdown numbers in almost every application (structural and secondary). The problematic recycling of thermoset composites can be mitigated by thermoplastic ones, thereby offering significantly shorter cycle times.

There is plethora of technology transfer possibilities between auto and aero, particularly in terms of automotive OEMs adapting aerospace technologies. The main auto-to-aero transfer openings reflect on supply chains, logistics, and lean manufacturing.

In the recent past, the application of composites in the automotive sector has grown significantly but has mainly be applied in the top-notch sector of high-end sports cars. With the BMW i3 as initiator, advanced lightweight materials are slowly entering the commodity sector. However, the reduced structural efficiency of affordable glass fibers, as opposed to the significant pricing of polymeric and carbon fiberbased composites, does still form a high threshold for further applications; to ensure profits for the automotive industry, additional material pricing should not exceed 7 to 8 € (as mentioned earlier).

Despite a number of success stories, the main inhibitors for further light weighting are, as previously mentioned, pricing but also more complex mechanics, new processing methods, uncertainties for longterm behavior, and limited supply chains. Additional wish list items are short cycle times, full recyclability, electrogalvanic compliance of joined materials and reliable, quick joining. As legislation and markets put more pressure for economic and sustainable transportation, it is expected that the aerospace and automotive sector will gradually develop synergetic solutions towards these goals.

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1 Introduction

The increasing need for transportation over land, sea and air has propelled the competition between European, American, and Asian manufacturers and operators. The automotive market has evolved into a global competition game in which the share of Asian OEMs is increasing. On the other hand, European manufacturers tend to consolidate into bigger market players; recent examples are the expansion of the Volkswagen Group (VAG) and the fusion of Fiat-Chrysler with the PSA group. The aerospace manufacturing market is traditionally dominated by Boeing and Airbus with smaller parties like Bombardier, ATR and Embraer. However, it is expected that the Chinese-Russian cooperation for COMAC passenger airplanes will result into increased competition. In addition, the growing market share of Bombardier and Embraer should not be overlooked.

With an exception for the last two years (COVID19 pandemic), one can observe increasing environmental footprints for both land transportation and aviation. New regulations and penalty schemes aim to motivate manufacturers and operators to particularly reduce CO_{2e} emissions. Recently, the emissions of Nitrogen Oxides and Ammonia have been placed in the agenda of regulatory entities as well, as these pollutants do also form a threat for future generations.

To accommodate the need for reduced emissions, the automotive and aerospace sector have set significant steps. The efficiency of engines and drivetrains did almost double as compared to aircraft and automobiles of the 70s and 80s. In addition, the reduction of aerodynamic drag and rolling resistance, in conjunction with the use of advanced, tailored lightweight materials, did undoubtedly reduce the environmental footprint of transportation. However, the improvement of aerodynamic and thermodynamic efficiency is currently approaching the limits set by physics laws. Therefore, the research, development and utilization of lighter moving structures has nowadays gained a prominent place in the agendas of regulatory organizations and funding institutes/ programs.

With a focus on North-West Europe, the European Regional Development Fund authorities (ERDF) have launched a funding scheme to support high-TRL level research aiming at weight reduction for aircraft and automobiles. This program, Interreg RighWeight, [70] is particularly focusing on technologic challenges as provided by OEMs, to be resolved by SMEs that are then to be supported by knowledge institutes and field labs.

In the framework of this program, the current study focusses on state-of -the-art lightweight solutions in respectively the automotive and aerospace sectors in Europe. The main part of this report is attributed to the assessment of the interchangeability between automotive and aerospace weight reduction practices in terms of design principles, employed materials, associated production processes, cost management issues, MRO (Maintenance, Repair, and Overhaul) and logistics. The goal hereby is to pinpoint which technologies can be transferred from one sector to other, thereby aiding light weighting.

After a short breakdown of emissions caused by transportation, complemented by a generic outline of related legislation (chapter 2), the industrial landscapes of respectively the automotive and aerospace sectors are shortly presented (chapter 3). Next, in chapter 4, emphasis is attributed to the role of weight reduction as a key player for lower emissions. A generic assessment of the interaction 'design-materialsproduction' is then launched in chapter 5 to demonstrate the potential of nontraditional materials and techniques for light weighting. IN chapter 6 (main chapter),suitable cross-cutting areas are determined and analyzed on possible gains for each sector, with additional emphasis on electric and hydrogen vehicles, complemented by a short outline of multifunctional composites. These sweet spots of transferability are then demonstrated in chapter 7 by recent success cases where the main idea is to highlight the underlying ideas, rather than providing an extensive database. The last section, conclusions and recommendations, attempts to provide a short overview of opportunities and threats associated with the researched technology transfer possibilities.

2 Emissions by Road and Air Transportation

2.1 General Picture

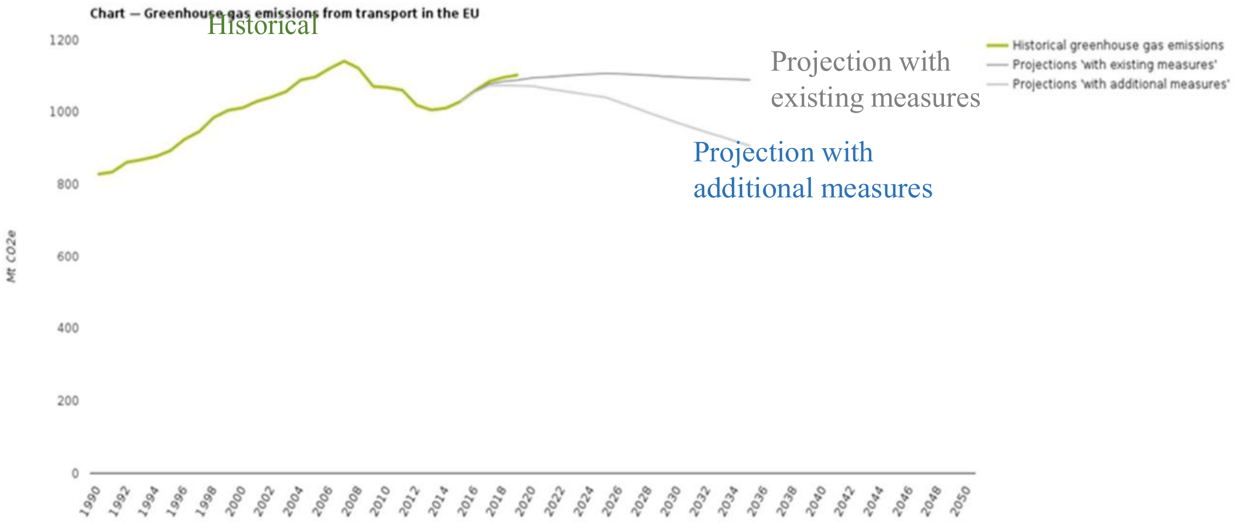

Fig. 2-1: Greenhouse gas emissions from transport in the EU [22]

The historical greenhouse gasses (GHG) emissions curve by transportation in CO_{2e} (CO_2 equivalents) did practically follow a constant growth rate over the period 1990 – 2018 (Fig. 2-1). After that year, a slight reduction was realized over 2008 – 2015. The current grow rate is less dramatic but the urge to reduce transportation emissions is undeniable. When the current measures (until 2020) are projected over the interval 2021 – 2027, a stabilization will set in. However, the preferable scenario is to realize a reduction from app. 1100 Mega Ton CO_{2e} to 800 – 900 Mega Ton CO_{2e} over that period [24].

For the previously stated green scenario, the share of land transportation and aviation in emissions should comply with Fig. 2-2. Still, the biggest share of pollution is generated by aviation and medium to heavy trucks. The declining contribution of passenger cars for 2020 and later can be largely attributed to specific measures like phasing out internal combustion engines and promoting hybrid/ fully electric drivetrains. In addition, aerodynamics has improved by 20 to 30% over the last two decades. Paradoxically, weight has increased due to stringent safety requirements, on-board systems, and HVAC (Heating, Ventilation and Air Conditioning) add-ons. For trucks and commercial vehicles, the transition to electric drivetrains is expected to set-in at a later stage. The engine efficiency for commercial aviation has increased by 40% since the 1950's. The contribution of improved aerodynamics in aviation is roughly 15%.

2.2 Automotive Emission Requirements

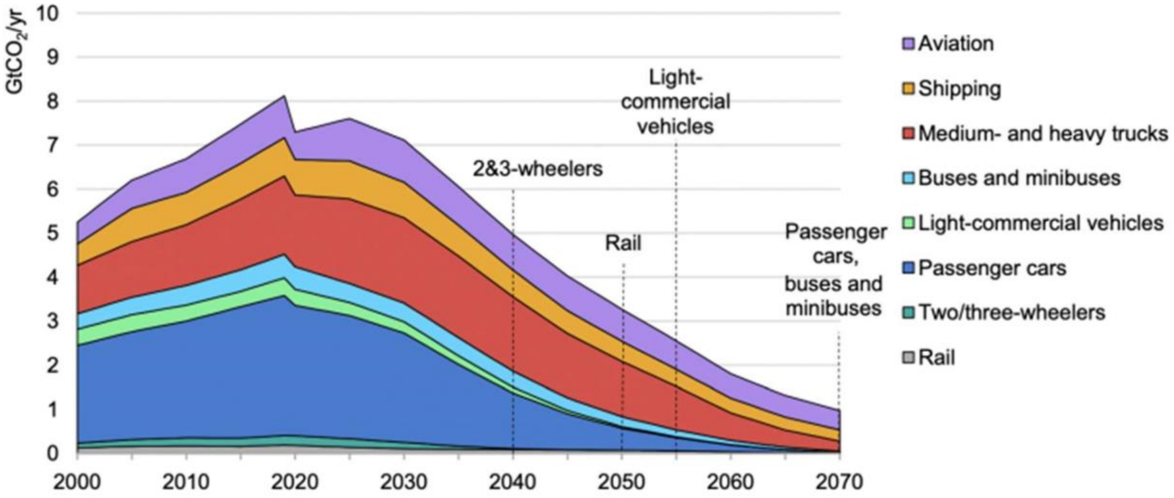

Fig. 2-2: Global CO_{2e} emissions in transport my mode according to the sustainable development scenario [71]

Since 1991, the European Union has launched several regulations for automotive emissions reduction. For passenger cars, the average emission rate for the entire fleet produced by a particular manufacturer in a single year is set to 95 [grams/km] of CO_{2e} with a 95% compliance in 2020 and 100% in 2021. This requirement translates in an averaged fuel consumption of app. 4 liters/100 [km]. The standard for light commercial vehicles is set to 147 [grams/km] (5.6 liters/100 [km]). The regulations foresee corrections for the average fleet weight and the extent in which innovative technologies are applied, while rewarding or penalizing deviations from the pollution targets accordingly. A more comprehensive overview can be found in [22-23, 34].

Contrary to aviation, the creation of sustainable road transportation by electrification and alternative fuels is a feasible option. In particular the combination of H_2 and fuel cells is very promising when long driving ranges a requirement. It should be noted however, that this transition is rather challenging for heavy trucks at this moment.

2.3 Aviation Emission Requirements

For aviation, the European Union did establish directives from 2008 and onwards [23]. In these documents, global targets for emissions are set in combination with measuring methods and legal issues. A resolution adopted by the International Civil Aviation Organization (ICAO) , the Carbon Offsetting and Reduction Scheme for International Aviation, or CORSIA, aims to stabilize CO_{2e} emissions at 2020 levels by requiring airlines to offset the growth of their emissions after 2020. The resolution demands emissions monitoring and reporting. In addition, an eligible emission credit points system is introduced to compensate flight-induced pollution by emission-reducing projects in other sectors. However, the exact formulation of these requirements in a quantitative way is still in progression.

One vital remark should be made here: the main driver for more efficient engines, systems and aerodynamics in aerospace relies in the reduction of costs per passenger kilometer. Additional applied measures are optimized flight planning, improved cargo logistics, and weight reduction. Alternative propulsion systems are not yet a viable option as they typically pose significant added weight (batteries) and safety issues (compressed or liquified hydrogen).

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3 Industrial Landscapes

With the emission requirements in view, a short description of markets, production rates and forecasts for respectively the automotive and aerospace industry is here provided. For the establishment of suitable technology transfer possibilities, the framework in which these industries operate must be established as it forms important boundary conditions.

3.1 Automotive

3.1.1 Production Figures

The worldwide automotive market is mainly propelled in its growth by upcoming markets, in particular the Asian one. An overview of production numbers is provided in the figure below:

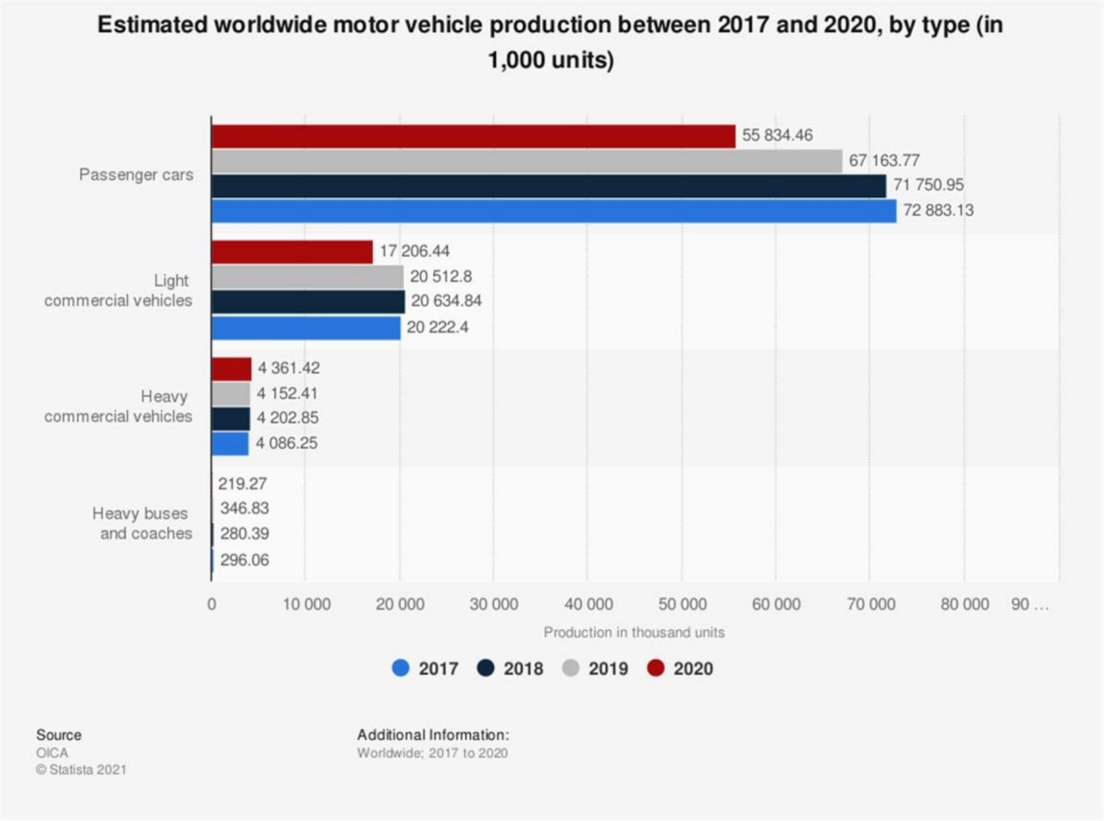


Fig. 3-1: Worldwide vehicle production over the period 2017 – 2020 [79]

The chart regarding vehicle production volume per country shows that the Chinese one (app. 25.000.000 units) is almost a triple of the American output (app. 8.800.000 units per year). The Japanese and European production rates are comparable to the American one. In Europe, the biggest productivity can be attributed to Germany, Spain and France. Italy, traditionally a big player in the European market, shows however lower numbers.

The presented charts do only refer to motor vehicles. In global terms, the percentage of hybrid and electrical cars sold in Europe over 2020 is app. 11% of the total automobile sales. In 2020, app. 620.000 plug-in hybrids were registered, in conjunction with app. 750.000 all-electric cars. These numbers are expected to increase significantly due to government support programs and lower selling prices.

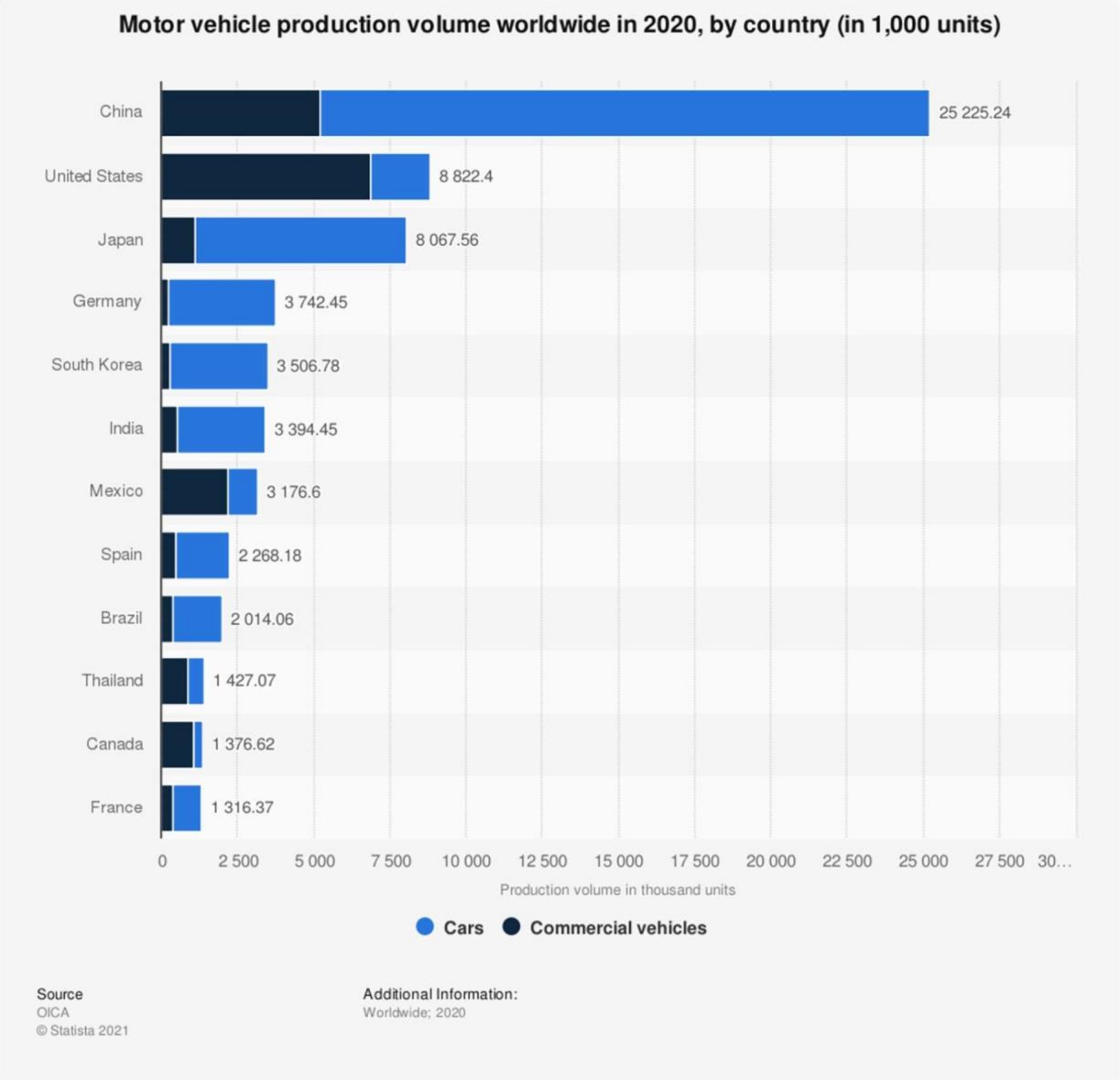


Fig. 3-2: Motor vehicle production in2020 by country [78]

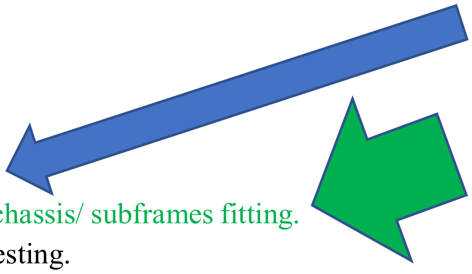
In most cases, the profit margins on new car sales are extremely low. After-sales in the form of maintenance, repair, overhaul, financing, leasing and insurance are currently more profitable than the end-product itself.

3.1.2 Development and Manufacturing

Due to increased competition, digitalization and changing customer demands, the development time for new vehicles (from concept to manufacturing) has decreased dramatically over the last two decades (from almost 10 to 2-3 years). A typical scenario for a new vehicle program is [83]:

- Concept creation & selection.
- Go / no-go decision.
- Specifications & detailed design.
- Development and tooling.
- Manufacturing line commissioning.
- Preproduction and launch.
- Ramp up and mass production.
- Anticipation and development of face lift versions.
- Product retirement. □ Recycling.

The biggest challenge in the development cycle of new automobiles is the minimization of the total costs through (often shared with other OEMs) platform creation for a big range of models, a high degree of automation, production chain optimization, extensive infrastructure, lean manufacturing with "just on time" availability of parts / subassemblies. Typical manufacturing phases, mostly for metallic components, are:



- Sheet metal stamping.
Electronics and HVAC.
- Closure subassembly. Dashboard & interior.
- Body-in-white assembly. Engine (casting, forging, machining).
- Powertrain and chassis/ subframes fitting. Inspection and testing.
Paint shop. Driveline (casting, forging, machining).
- Body assembly. Subframes assembly (welding, bolting).
- Peripherals (forming, welding).

□

With the introduction of novel, polymer-based materials, additional processes have emerged like Injection Molding, Press Molding, Resin Transfer & Infusion, Adhesive Bonding etc. These novel techniques however are not yet widely applied as the percentage of polymeric materials in weight is rather low in automobiles. This percentage becomes even lower for advanced, lightweight reinforced polymers, with an exception for supercars, hyper cars and special, limited editions.

3.1.3 Utilized Materials

Depending on the application area in e.g., a car, various material groups are utilized. For the sake of clarity, the distinction is here made between powertrain, chassis, exterior, and interior parts/ subassemblies [55].

Powertrain

- Currently o Steel (moving parts).
  - Iron (practically entirely replaced by aluminum for housings).
  - Aluminum (not for axes, gears, bearings or heavily loaded mechanisms).
- Future trends o High Strength Steel (HSS). o Advanced High Strength Steel (AHSS).
  - Composites (at first instance: housings. Later: connecting rods). o Magnesium (housings).

Chassis (including body in white)

- Currently o Steel.
  - High Strength Steel (HSS).
  - Advanced High Strength Steel (AHSS).
  - Specialized aluminum.
- Future trends o High Strength Steel (HSS).
  - Advanced High Strength Steel (AHSS).
  - Specialized aluminum.
  - Advanced polymers (like Liquid Crystal Polymers, LCP). o Composites. o Multi-material combinations (sandwich panels etc.).

Exterior

- Currently o Steel.
  - Aluminum. o Plastics.
  - Composites (limited to roofing).
- Future trends o High Strength Steel. o Aluminum.
  - Advanced polymers.
  - Composites. o Multi-material combinations (sandwich panels etc.).

Interior

- Currently o Steel. o Aluminum. o Plastics.
  - Composites.
- Future trends o Bio-based plastics.

  - Natural fiber-reinforced composites. o Sandwich structures (paper, aluminum or NOMEX core).

The weight of a typical automobile can be distributed among the above indicated groups as follows:

- Powertrain = 22% o Engine.
  - Transmission.
  - Suspension and steering.
  - Brake system. o Exhaust system.

- Chassis (including body in white) = 30% o Monocoque.
  - Reinforcing Subframes.

- Exterior = 23% o Doors.
  - Hood (bonnet).
  - Trunk. o Glass parts. o Bumpers.

- Interior = 11% o Dashboard.
  - Seats. o Upholstery. o Flooring / Sealing.
  - Panels.

- Heating, Ventilation and Air Conditioning (HVAC), on-board systems, electronics = 14% o Modules. o Lights.
  - Wiring, CAN busses. o Relays, switches, sensors, actuators.

3.2 Aerospace

3.2.1 Production Figures

The worldwide aircraft fleet was traditionally dominated by North America and Europe. However, the last 20 years, the Asian market realized giant leaps [76]. As of 2019, Figure below, the Asian market has overtaken the European and North American ones. The presented chart does not reflect the influence of the COVID19 pandemic but provides useful estimations regarding fleet sizes in 2039. In most cases, it is estimated that fleets will double.

Next to the expected fleet growth, it is estimated that the traditional Airbus-Boeing market will encounter increased competition from emerging builders like Comac (C919, China) and Irkut MC-21 (Russia). Existing builders with a lower market share are Embraer, ATR and Bombardier. In particular Embraer was able to realize a reasonable share in the market of small commercial aircraft.

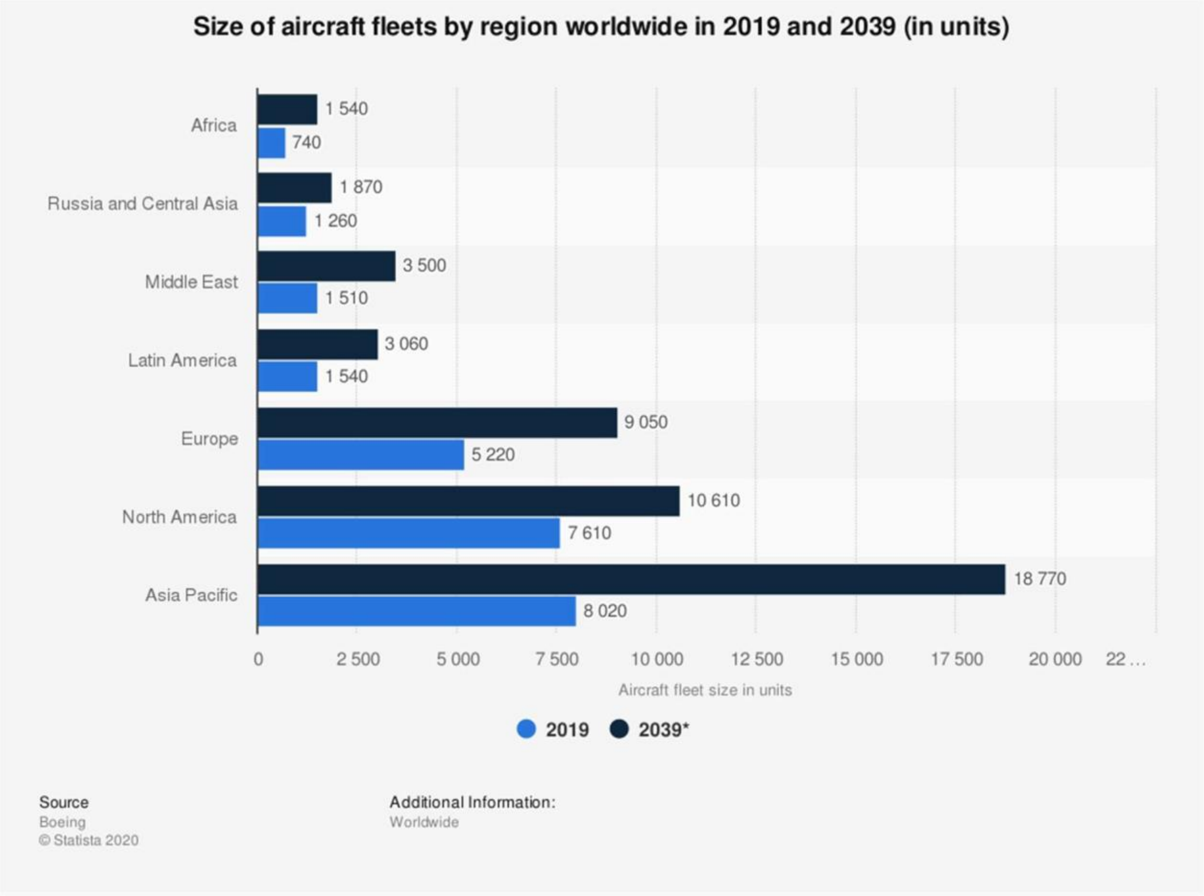


Fig. 3-3: Worldwide aircraft fleet, 2019 – 2039 (estimated) [53]

Particularly in Europe, the focus of aerospace research has increasingly shifted towards own aircraft manufacturers, in particular Airbus. The harsh competition between the latter and Boeing is a well-known phenomenon. Airbus was, before the COVID19 pandemic kicked in, able to surpass Boeing ins sales and become the bigger manufacturer worldwide.

Despite the limited commercial success of the A380, Airbus was able to launch the A350 successfully, in conjunction with new generations of the A320 (and related derivatives) with options for more efficient engines. On the other hand, Boing did suffer great losses due to the 737 MAX design flaws and the consequently generated lack of trust in this series, both by airline operators and customers.

In the graph below, depicting worldwide deliveries of Airbus, one can clearly observe the effect of the COVIC19 pandemic in 2020.

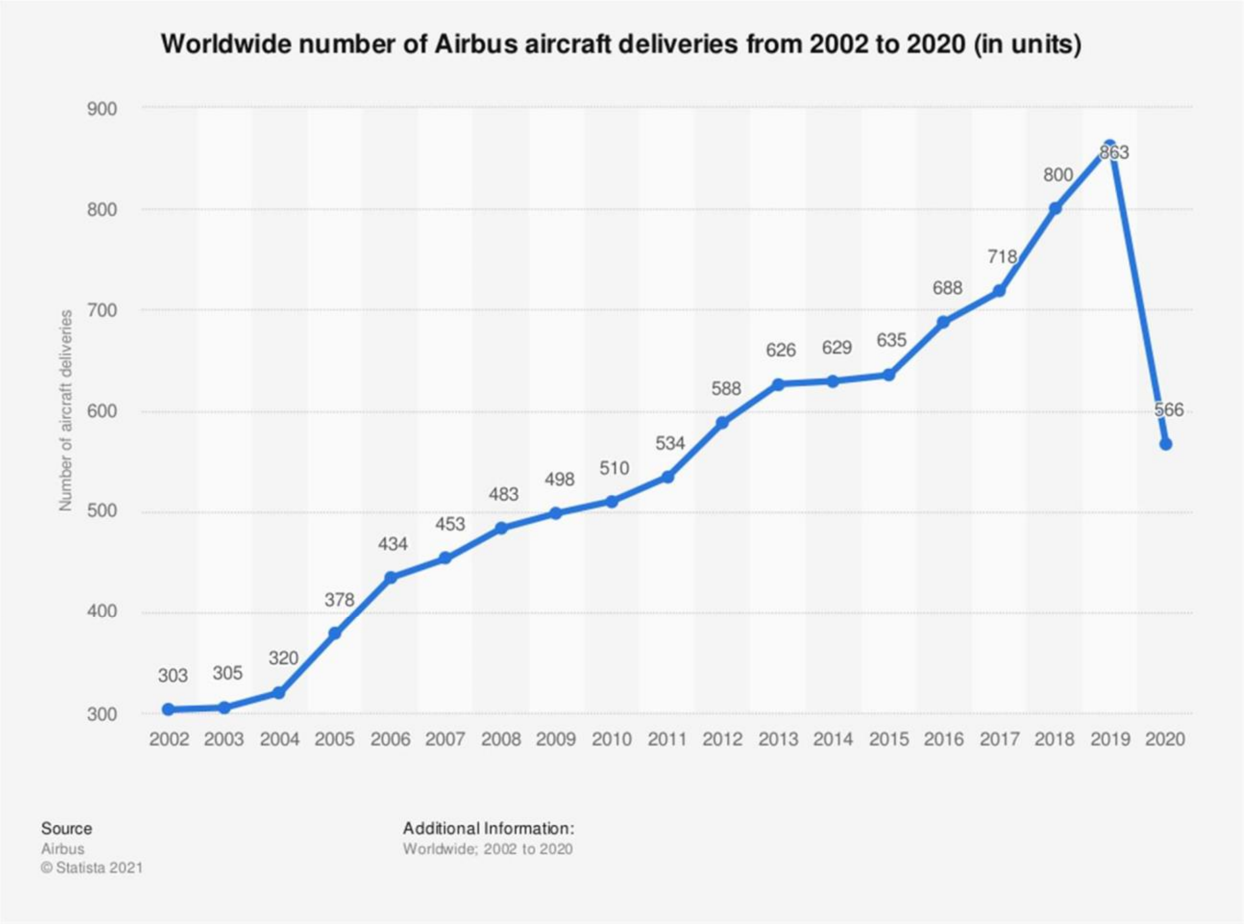


Fig. 3-4: Worldwide Airbus deliveries, 2002 – 2020 [54]

Table 3-1: Airbus deliveries forecast for 100+ seaters [2].

Passenger aircraft				
Region	Start Fleet 2019	End Fleet 2038	20-year new deliveries	Remaining
Africa	607	1,547	1,249	299
Asia-Pacific	7,104	19,223	16,324	2,899
CIS	935	1,765	1,498	267
Europe	4,871	8,887	7,434	1,452
Latin America	1,373	2,896	2,684	212

Middle East	1,287	3,397	3,200	197
North America	4,692	7,147	5,968	1,179
World	20,870	44,862	38,358	6,503

The anticipated deliveries of Airbus, up to 2038, are provided in the table above[1]. These numbers correspond well with the anticipated worldwide fleet growth as indicated in Fig. 3-3.

3.2.2 Development and Manufacturing

The design and development phases for a new aircraft type might take more than 20 years in extreme cases. Main reasons for this phenomenon rely in harsh competition, design at the edge of materials' allowables, and stringent requirements for airworthiness certification. A typical design and development sequence is:

- Definition of requirements based on market forecasts and customer wish list.
- Initial global design generation.
- Global design selection, iteration on performance criteria. □ Simulations: performance, stability, control (wind tunnel).
- Detailed design & simulations (wind tunnel, experimental campaign: mechanics, electronics, lightning strike, impact, cabin (de-)compression, landing gear etc.).
- Preproduction assessment, jig and tooling design.
- Preproduction of prototype series.
- Extensive testing & evaluation campaign (certification).
- Launching customer deliveries.
- Production ramp-up.
- Anticipation and development of improved versions.
- Product retirement. □ Recycling.

The development of new aircraft is very costly and challenging. In principle, any design changes must be certified. This is the reason why aircraft manufacturers tend to use the same airframe for years while continuously upgrading engines, avionics, on-board systems etc. Unfortunately, in some cases, this can result in potential flaws as experienced by the 737MAX, complemented with issues in another model's airframe.

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[1] CIS = Commonwealth of Independent States: Former Soviet Union & Eurasia.

In order to build a typical midrange passenger airplane (Boing 737 or Airbus 320), several days are needed. Although the number of days can vary significantly as a function of incoming orders/stock, production planning and eventual obstacles with for example part deliveries or machine/ tooling defects, one can assume an average of 14 days per aircraft. Striking fact: a reasonably successful midclass automobile in Europe, for example a Peugeot, is built in the rate of 300 to even 1000 per day. The typical aircraft building sequence is as follows [47]:

Day 1 to 3:

- Fuselage assembly (by assuming that panes, frames and stringers have been delivered).
- Basic cabin artefacts: windows, flooring, cables, hydraulic lines, ventilation shafts etc.

Day 4:

- Attachment of wings and vertical tail fin.
- Installation of landing gear.

Day 5:

- Attachment of horizontal tail wings.
- Finishing of electronic, hydraulic, pneumatic etc. systems.
- Installation of galleys, bathrooms.

Day 6-10:

- Extensive testing campaigns (control surfaces, landing gear, cabin pressurization, hydraulics, electronics etc.

Day 11:

- Installation of flight systems, navigation systems etc.
- Power up of aircraft and extensive testing of all systems.

Day 12-13:

- Installation of engines and auxiliary systems.
- First standing on own landing gear.
- Finishing of aircraft interior .
- Testing of all systems.
- Extensive flight-testing campaign.

Day 14:

- Final tests by customer.
- Hand-over to customer.

The degree of automation is low as compared to the automotive industry. In addition, the margin for errors and imperfections is virtually nonexistent. Every production and assembly step has to registered, monitored, and confirmed by authorized personnel. To ensure airworthiness, everything has to be simulated and tested. For example, a stringer-panel assembly is evaluated on the building block approach: from specimen testing to substructure (for example the stringer itself, the panel, or the cohesion between those) and structure (the entire panel). At the end, during the development phase, the entire experimental aircraft is tested on huge benches for strength, stiffness, fatigue, impact, etc. The dominant processes used for manufacturing are:

- Plate forming.
- Plate rolling.
- Forging (landing gear).
- Profile extrusion.
- Machining .
- Riveting, bolting, adhesives.
- Molding (thermoset composites). Tape laying (composites).

It is quite typical to see that, while robots are predominantly applied in the automotive sector for transporting, positioning and holding subassemblies, in the aerospace sector they are often used in the shaping/ forming process itself (for example tape laying, riveting etc.).

3.2.3 Utilized Materials

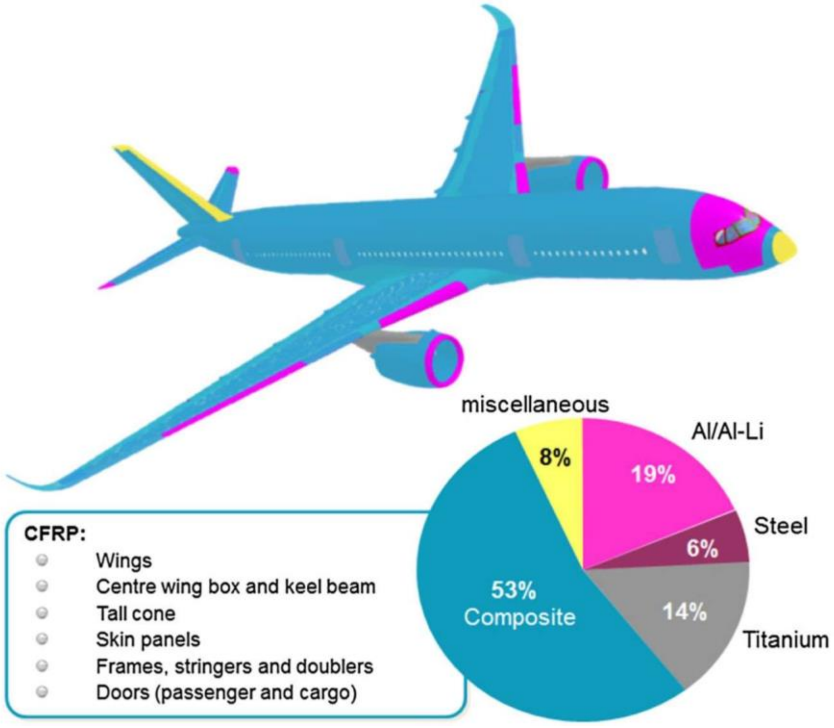

Fig. 3-5: Utilization of Carbon Fiber Reinforced Polymers and other materials in the A350 by weight [6]

Aluminum, typically the 2024 and 7075 series, forms the main material for past and recent aircraft. Steel and Titanium are mainly employed in engines, landing gears and mechanisms. Currently, Al-Li alloys and composites are increasing their share as building materials, Fig. 3-5.

According to [3], an 11% Compound Annual Growth Rate is to be expected for the years until 2025.The share of composites is currently above the 50% weight mark [32, 37]. Considering the fact that their density is about 3 to 4 times lower than that of aluminum, their volumetric portion of the aircraft is even larger. Novel technologies are shifting towards thermoplastic composites (re-meltable and re-usable polymer matrix), metal matrix composites (like GLARE, applied as part of the crown fuselage section for the A380) and ceramic matrix composites for high temperature applications [31, 57]. For interior parts, a number of (reinforced) plastics is applied where however, there is limited choice as these materials are subject to stringent FST cabin requirements (Fire, Smoke, Toxicity) [77].

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4 The Role of Weight Reduction in Emissions

The main goal of the Interreg Rightweight European Regional Development Funding scheme is, as stated earlier, to reduce the emissions of air and land transportation by weight lowering. The main question hereby is twofold:

1) Wat is de impact of weight reduction on emissions? 2)
Are the associated costs affordable?

The first question will be elaborated in a separate for the automotive and aerospace sector. The second question is to be assessed in chapter 5, in conjunction with general performance indicators like structural efficiency, and manufacturing performance.

4.1 Automotive

At the moment the European legislation on automotive emissions was created (1991), the efficiency of gasoline and Diesel engines was roughly 30 to 50% less than today. Therefore, it was estimated in that time that a 100 kg weight reduction could possibly lead to 11 grams of CO_{2e} per driven kilometer [44]. Obviously, this number represents a very coarse approximation for the average European car fleet. After that, the requirements on emissions have gradually been intensified (from Euro 1 to Euro 6 and 7). Taking the state of the art into account (Gasoline Direct Injection, variable valve timing and lift, common rail Diesels, combinations of induced and autoignition etc.), a 100 [kg] weight reduction will lead to roughly 8.5 grams less CO_{2e} per driven kilometer. Once again, this is based on the average fleet and the NEDC (standardized New European Driving Cycle)[2].

To illustrate the potential of weight reduction, a particular case here presented. It is assumed here that the seats in a Renault Clio are replaced by lighter ones, with an increased share of recycled materials.

Production figures (Table 4-1):

- Production rate: 150000 per year (410 units per day).
- Weight reduction per seat: 5 [kg] (20 [kg] in total).
- Assumed, initial scrap rate for seat frames (composites): 30%.
- New percentage of scrap reuse: 100%.
- CO_{2e} production emission per manufactured [kg] for a seat: 0.40 [kg].

Utilization figures (Table 4-2):

- Average driving distance per year: 150000 [km].
- Service life: 12 years.

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[2] The ENDC is currently being replaced by the WLTP (World Harmonized Light Vehicles Test Procedure).

- CO_{2e} driving-induced emission reduction per 100 [kg] less weight: 8.5 grams.

Table 4-1: Production-induced CO_{2e} reduction due to lighter seats (5 kg) and complete scrap re-use

Midclass automotive production Figs.	Units	Values
Original seat weight	kg	17.00
Total weight of lighter seat	kg	12.00
Delta material per seat	kg	5.00
CO_{2e}/kg of seat	kg/kg	0.40
CO_{2e} reduction per seat due less mat.	kg	2.00
Scrap rate for light seat	%	30.00
CO_{2e} reduction per seat due scrap re-use	kg	1.44
Total CO_{2e} reduction per seat	kg	3.44
Total CO_{2e} reduction for a Clio	kg	13.76
Production rate per year (averaged)	[-]	150000.00
DCO_{2e} for Clio fleet produced in one year	Metric Tons	2064.00

The emissions reduction by driving a Clio with 20 [kg] less weight is almost twice the manufacturing CO_{2e}, table below. In a very coarse approximation, one can linearly adapt these numbers to different weight reduction values. By extrapolating to the entire model range of a manufacturer, the CO_{2e} savings become considerable.

Table 4-2: Driving-induced CO_{2e} reduction due to lighter seats (total weight difference = 20 [kg])

Midclass automotive operation Figs. Renault Clio driving Figs.	Units	Values
Average number of seats per car	[-]	4.00
Delta weight per seat	kg	5.00
Total Delta weight per car	kg	20.00
Delta CO_{2e} per km for 100 kg reduction	gram/(100*km)	8.50
Delta CO_{2e} per km for lighter car	gram/km	1.70
Driving distance per year	km	15000.00
CO_{2e} reduction per driving car per year	Kg	25.50

Years of service	[-]	12.00
CO_{2e} reduction for one Clio over service life	kg	306.00
Production rate per year (averaged)	[-]	150000.00
DCO_{2e} for yearly produced Clio fleet/ driving year	Metric Tons	3825.00

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4.2 Aerospace

As previously explained, emissions-related legislation for aviation in hard numbers is currently under development. However, it is already clear that, despite an expected increase in fleet sizes, the aviation manufacturers and operators should counteract emission increase in terms of greener airplanes and alternative CO_{2e} reduction schemes in other sectors.

It may be regarded as a consensus that a weight reduction of 1% may result in a fuel consumption reduction of 0.75% for a mid-size airliner on a typical operations scheme. To demonstrate this, it is assumed here that an Airbus 320 is retrofitted with lighter seats that are made in such a way to enable full re-use of the scrapped material during production. Possible scrap reasons are non-conformities in material and production; however, the biggest part can be attributed to leftovers by cutting out a particular shape from a blank.

Weight and fuel figures (A320 from 2000)

- Maximum Take Off Weight (MTOW): 78000 [kg].
- Operational Empty Weight (OEW)[3]: 42600 [kg].
- Maximum fuel capacity: 22032 [kg].
- Maximum payload: 19900 [kg].
- Maximum range: 6112 [km].
- Fuel burn rate in cruise condition: 2.9 [kg/km].
- Fuel used for take-off: 4307 [kg].

Flight scenario 1: maximum take-off weight & maximum range (adapted payload, Table 4-3) □ Payload = 13368 [kg]

Flight scenario 2: maximum take-off weight & maximum payload (adapted range, Table 4-3)

- Range = 3860 [km]

Flight scenario 3: maximum payload & pre-defined range (adapted Take-off weight, Table 4-3)

- Take-off weight (TOW) = 72575 [kg]

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[3] Empty weight + engine oil, coolant, hydraulics, water, unusable fuel and crew.

Production figures

- Original seat weight (including all systems): 9 [kg].
- Optimized seat weight: 6.5 [kg].
- Number of seats: 190.
- Number of produced aircraft in one year: 500 (pre COVID19 number).
- Energy, needed to produce 1 [kg] of a seat: 5 [MJ].
- CO_{2e} per consumed MJ for production: 0.08 kg.
- Original production scrap rate reduced from 30% to 0%.

Table 4-3: Operation scenarios for the Airbus 320 (2000)

Airliner operation Figs. Aircraft type = A320, 2000	Units	App. manufacturer data Red = Input numbers
MTOW	kg	78000.00
OEW	kg	42600.00
Max fuel capacity	kg	22032.00
Max payload	kg	19900.00
Max range	km	6112.00
Fuel burn rate (cruising A320)	kg/km	2.90
Used fuel for MTOW take off	kg	4307.20
1: MTOW + max range -> adapted payload	Units	Values
Max fuel capacity	kg	22032.00
Res payload	kg	13368.00
Max range	km	6112.00
2: MTOW + max payload -> adapted range	Units	Values
Max fuel capacity	kg	15500.00
Max payload	kg	19900.00
Res range	km	3859.59
3: Max payload + Predefined range -> TOW	Units	Values
1% less weight -> 0.75% less fuel	Discount ratio [-]	0.75
Resulting TOW	kg	72574.72
Resulting fuel burn rate	kg	2.75
Used fuel for actual take off	kg	4082.51
Predefined range	km	2180.00

Resulting fuel taken on board	kg	10074.72
Max payload	kg	19900.00
Check calculation: TOW	kg	72574.72
Number of seats	[-]	190.00
Fuel burn per seat	kg	53.02
Burned fuel per passenger km (incl. take off)	gram / (passenger*km)	24.32
Kerosine heating value	MJ/kg	43.50
CO_{2e}/heating value	kg/MJ	0.07
CO_{2e}/kerosine weight	kg/kg	3.12
CO_{2e} per passenger km	gram / (passenger*km)	75.86

The effect of lighter seats for scenario 3 (flight from Amsterdam to Athens) is provided in the subsequent table:

Table 4-4: Co_{2e} emissions reduction for a fully loaded A320 flight from Amsterdam to Athens

Lighter seats	Units	Values
DWeight per seat	kg	2.50
Total Dweight	kg	475.00
DW %	%	0.65
Dfuell %	%	0.49
Dfuel per passenger km	gram	0.12
DCO_{2e} per passenger km	gram	0.37
Figures over service life	**Units**	**Values**
Flight distance	km	2180.00
Flights per day	[-]	4.00
Flight days /year	[-]	300.00
Years in service	[-]	25.00
Total flights	[-]	30000.00
DCO2 per flight	kg	154.24
DCO_{2e} for a single A320 over one year	Metric Tons	185.09
DCO_{2e} for a single A320 over its entire lifetime	Metric Tons	4627.35
DCO_{2e} for yearly produced A320 fleet/ flying year	Metric Tons	92546.92

The production related CO_{2e} reduction due to lighter seats and full recyclability of the related scrap is demonstrated below:

Table 4-5: CO_{2e} emission reduction for the yearly produced A320 fleet due to lighter seats and improved recyclability

Airliner Production figures	Units	Values
Original seat weight (economy)	kg	9.00
Lightweight seat	kg	6.50
Delta weight per seat	kg	2.50
Total Delta weight	kg	475.00
Production energy / kg	MJ/kg	5.00
CO_{2e}/MJ (average)	kg/MJ	0.08
CO_{2e}/kg of seat	kg/kg	0.40
DCO_{2e} per seat due less material	kg	1.00
Scrap rate for light seat	%	30.00
DCO_{2e} per seat due scrap re-use	kg	0.78
Total CO2e reduction per produced seat	kg	1.78
Total CO_{2e} red. per produced A320	kg	338.20
Produced A320 /year	[-]	500.00
DCO_{2e} for A320 fleet produced in one year	Metric Tons	169.10

It should be mentioned here that the productivity rate of 500 airplanes per year is rather high, and that the original weight of the seats is slightly exaggerated. However, the numbers do clearly demonstrate that, although the CO_{2e} reduction per passenger kilometer is not phenomenal, the numbers can quickly add-up to significant figures.

An important indicator for the fuel efficiency of aircraft, in a very coarse approximation, is the ratio of OEW/MTOW (operating empty weight as fraction of the maximum take-off weight). This number did actually increase in the past two decades from 0.5 to almost 0.6 due to additional cabin systems (entertainment, improved climate systems) and more stringent requirements. With a directed effort for weight reduction however, this number can possibly be brought back to, for example, 0.51. In a very averaged approach, one can assume that a reduction of 100 [kg] can knock-down the yearly fuel consumption of an Airbus 320 or Boeing 737 by 19000 liters [9].

5 Design, Materials and Production Process Interaction

From the previous analysis of the automotive and aerospace sectors in terms of markets, production rates, costs, and the effect of weight reduction on emissions, the interaction of design choices with the selected materials, associated production process and related costs is here shortly presented. For the selection of efficient materials, extensive use has been made of [4].

5.1 Requirements

The general requirements for auto/ aero are here divided into market, structural, costs, and recycling.

5.1.1 Market Requirements

The market requirements for aircraft are very different from the automotive ones. While the main driver for automobiles is costs minimization and fast production, airplane design is dominated by minimal costs for the operator.

Table 5-1: Short comparison of automotive and aircraft market goals

	Automotive (midclass model)	Aircraft (A320)
Market Size (items/ year)	100.000 to 1.000.000	100 to 1000
Development time & costs	2-3 years, high	10-15 years, very high
Competition	Extensive	2 to 5 major players[4]
Service life	10 to 15 years	25 to 30 years
Lifespan of design attractiveness	Short	Competition dependent
Selling point	Cheap, economic, gadgets	Minimal operator costs
Aesthetics	Very important	Not important

5.1.2 Structural requirements

The design philosophies of cars and aircraft are rather different. Structural car design is constrained by packaging (efficient use of the available space) road handling (torsional stiffness), crash and safety requirements, while the aircraft constraints are dominated by aerodynamics, aero-elasticity, vibrations, and fatigue. Major operational loadings for cars are typically obtained by quasi static analyses that result in an expected g-force envelope as a function of velocity.

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[4] Boeing, Airbus, Embraer, Bombardier, ATR, Comac (anticipated for near future)

A preliminary structural aircraft design procedure is governed by the so-called V-n diagram that outlines the operational flight envelope in terms of the allowable g-forces as a function of velocity (and implicitly of flying altitude) . During consequent iterations, refined aeroelastic and vibrations analyses become not only inevitable, but also very complex.

Table 5-2: Dominant factors for setting requirements in automotive/ aerospace

	Automotive (midclass model)	Aircraft (A320)
Stiffness	Torsion, crash requirements	Aeroelasticity, vibrations
Strength	Dominated by crash performance	Dominated by fatigue and V-n[5]
Weight	Dominated by CO_{2e} requirements	Dominated by competition
Durability	Mild requirements	Strict requirements
Maintenance	Profit generating	Strict regulations

5.1.3 Costs requirements

Development of novel aircraft is extremely costly, typically in the order of 8 to 15 billion dollars [7]. For cars, the costs might reach 6 billion dollars when a new engine and transmission is desired [16]. The development of a new platform (chassis, monocoque), typically to be used for different models and even different makers, adds 1 to 2 billion to these costs.

Table 5-3: Indicative costs and profit numbers for the automotive and aerospace industry

	Automotive (Toyota premium SUV or sedan)	Aircraft (A350)
Development costs + tooling	7.000 M€	12.000 M€
Costs per unit	18 K€	110 M€
List price	21 K€	300 M€
Profit per unit	3 K€	190 M€
Breakeven point	Theoretically 2.400.000 In practice: 200.000 to 500.000 due to platform sharing over averagely 5 models for 10 years.	64 In practice: >100 due to kinks, discounts (>50%), promotion, and upgrades

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[5] Diagram displaying the maximal g force loading factor as function of velocity; this results in a closed area that bounds the flight conditions.

Production lifetime until new model	10 years for platform 2 to 5 years for facelifts	5-10 years to minor upgrades 30 years for frame

5.1.4 Recycling

The recycling industry for the automotive sector in Europe is well-regulated. Currently, up to 95% of an EOL (End Of Life car) car can be recycled. While metallic parts can be reused properly, plastics are typically downsized to lower end applications (from semi-structural to interior parts or applications in other sectors). Aircraft need specialized locations for recycling and require much longer dismantling times (4 to 6 weeks). Typically, almost 90% can be recycled.

With current demands and regulations, both industries are required to incorporate recycling aspects into the design and development phase. In addition, the re-use of essential parts (like landing gears) should be enabled by proper certification procedures for re-entrance in the market as spare parts. Designing car parts for re-use by Original Equipment Manufacturers is not yet common. Typically, repair and overhaul of expensive car parts is governed by after-market parties. A comprehensive overview about recycling projects can be found in [21].

5.2 Structural Efficiency

Automotive/ aircraft parts, sub-assemblies and assemblies have in general complicated shapes, incorporate dissimilar materials, and contain (permanent or dismountable) joints. The approach presented below is undoubtedly a rigorous simplification of these artefacts but can conveniently serve as an indicator for the reasons why particular materials are not yet common, or why some materials may become attractive solutions provided that their costs will become affordable.

To determine the structural efficiency of a particular material, one needs a function (e.g., crash absorber beam), a number of constraints (for example minimally acceptable strength of costs threshold), and an objective (for instance minimal weight). The following table [4] provides a rough idea for selecting materials:

Table 5-4: Structural efficiency indices for basic load-bearing elements

Function	Objective	Constraint	Quantity to maximize
Tie	Minimum weight	Stiffness prescribed	$E \ \square \ \square^{-1}$
Beam	Minimum weight	Stiffness prescribed	$E_{(1/2)} \ \square \ \square_{-1}$
Beam	Minimum weight	Strength prescribed	$\sigma_{(2/3)} \ \square \ \square_{-1}$
Beam	Minimum cost	Stiffness prescribed	$E_{(1/2)} \ \square \ C_{m-1} \ \square \ \square_{-1}$
Beam	Minimum cost	Strength prescribed	$E_{(1/2)} \ \square \ C_{m-1} \ \square \ \square_{-1}$
Column	Minimum cost	Buckling load prescribed	$E_{(1/2)} \ \square \ C_{m-1} \ \square \ \square_{-1}$

Spring	Minimum weight	Stored energy prescribed	$\sigma_{(1/2)}$ □ E_{-1} □ □$_{-1}$
Panel bending	Minimum weight	Stiffness prescribed	$E_{(1/3)}$ □ □$_{-1}$
Panel buckling	Minimum weight	Stiffness prescribed	$E_{(1/3)}$ □ □$_{-1}$
Axle torsion	Minimum weight	Stiffness prescribed	$G_{(1/2)}$ □ □$_{-1}$

E = Young's modulus, G = Shear modulus, □ = density, σ = Yield strength, C_m = costs per unit weight

In this table, the prescribed quantities reflect on the performance of the element itself (not the material parameters). For example, a beam of certain dimensions with a constraint on the maximum allowable deflection would have the same performance for the average steel and aluminum; while the stiffness of steel is three times more than aluminum, the same applies on their density ratio.

For more complex cases like vibration eigenfrequencies, heat storage and dissipation etc. the determination of similar efficiency coefficients becomes very complicated and geometry dependent. Therefore, a number of simulations for different materials will then be required.

5.3 Materials Selection

For the graphical representation of material suitability for a particular goal, [20, 27-28] contain several convenient graphs. For the time being, only the pure material-related numbers are considered without any elaboration on their (recurring and non-recurring) production costs.

5.3.1 Maximum Stiffness per Weight Design

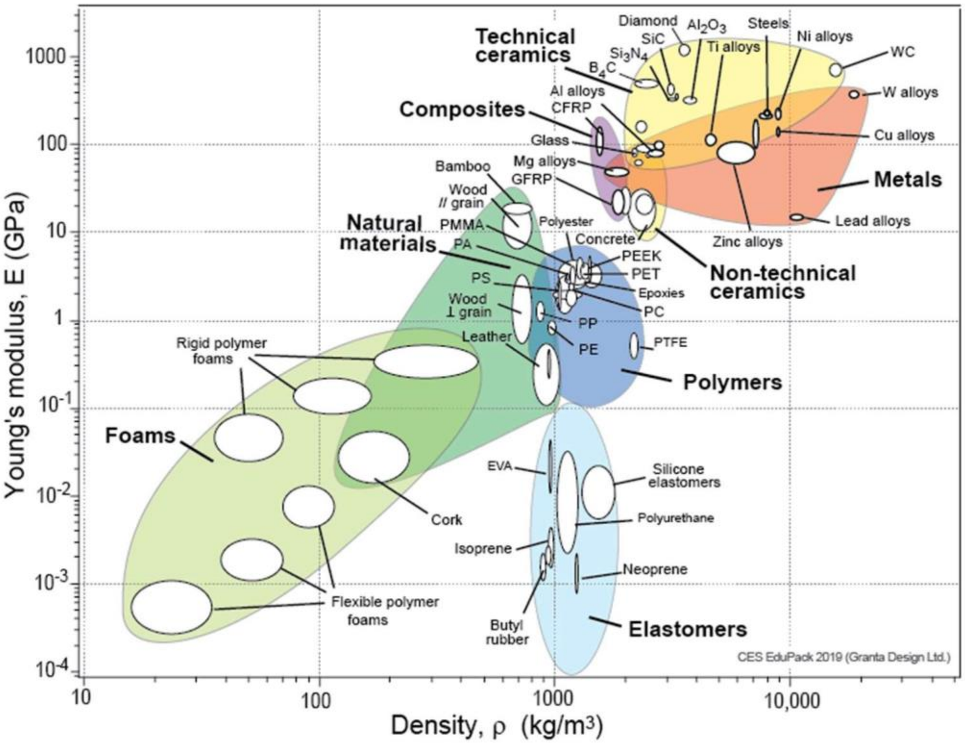

Fig. 5-1: Stiffness-density spectrum for engineering materials [27-28]

The stiffness versus weight graph has predominantly a diagonal character. Metals are very stiff but also heavy, polymers are, in most cases, insufficiently stiff for primary, even secondary structural applications. An acceptable compromise lies in composites which however have their own peculiarities like high costs and dedicated production process.

It is striking (but expectable) to observe that steel, aluminum and glass fiber composites have practically the same stiffness to weight ratio. This is the reason why aluminum car bodies-in-white did never become mainstream while glass fiber composites did only find applications in some body panels like hoods, fenders, roofing and interior parts. Fortunately, the combination of several steel types in cars like High Strength Steel (HSS) and Advanced High Strength Steel (AHSS) is able to release sufficient crash performance while keeping the weight at acceptable levels. It should be mentioned however that a modern car consists of more than 15 different steel alloys at specialized areas (sills, pillars, doublers); a combination that rises production costs (not to mention Electro-galvanic compatibility).

5.3.2 Maximum Strength per Weight

The same diagonal character applies on the strength versus density graph; strength comes at a cost. The numbers for aluminum are here slightly better than steel. However, when the strength threshold is high (for example more than 500 [MPa]), only specialized, and thus expensive aluminum alloys can comply.

Composites on the other hand are indeed able to realize weight savings but the most designs are stiffness dominated.

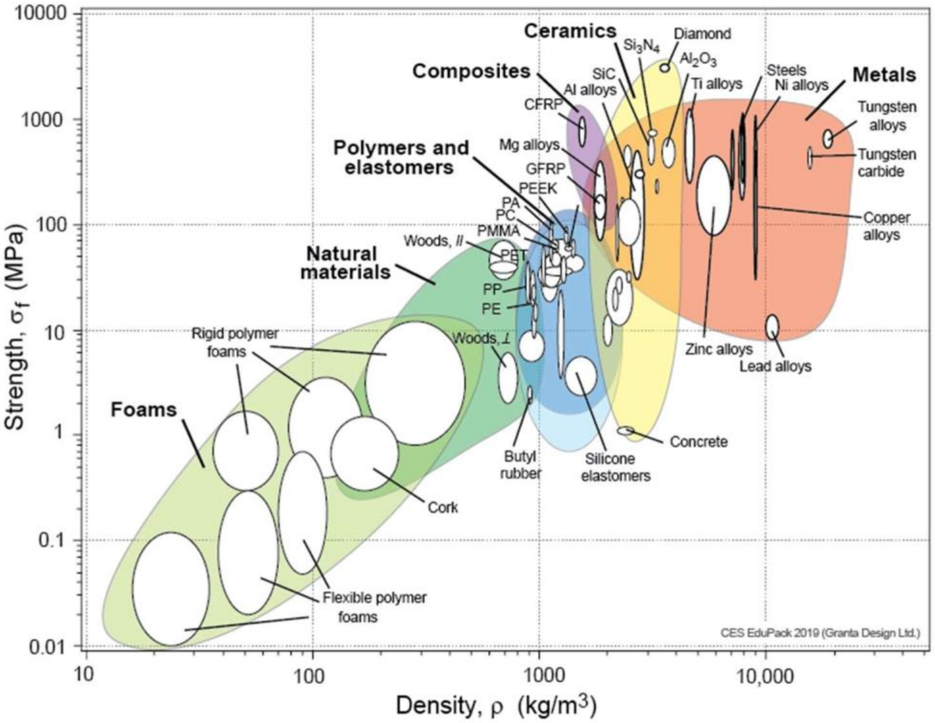

Fig. 5-2: Strength-density spectrum for engineering materials [27-28]

5.3.3 Stiffness to Strength Spectrum

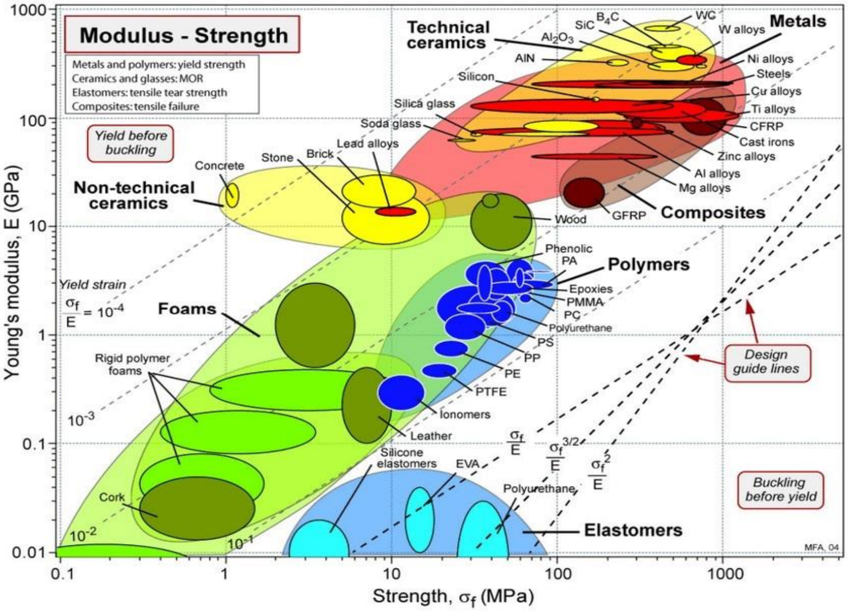

Fig. 5-3: Stiffness-strength spectrum for engineering materials [27-28]

The stiffness to strength graph is not very useful for weight minimization purposes, but it provides directions for cases when the maximum strength-stiffness combination is desired while the weight numbers are of secondary importance. When density is part of the design game, it is more convenient to compare materials on their specific properties (strength and stiffness divided by density):

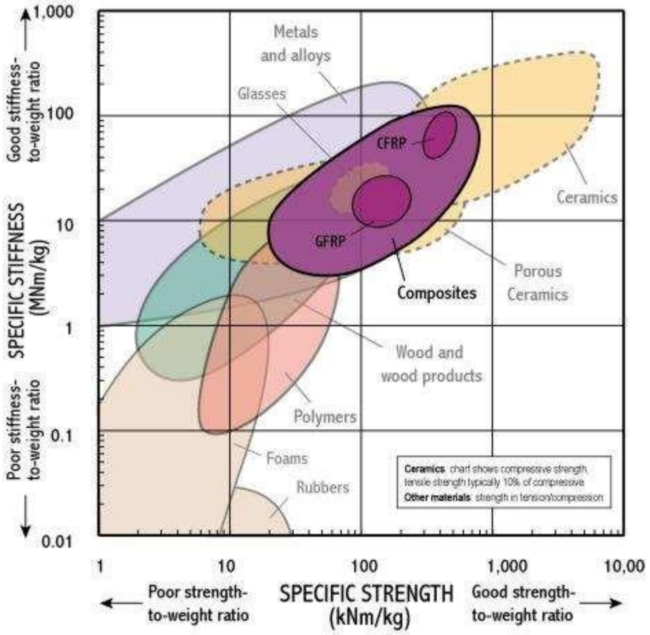

Fig. 5-4: Strength-stiffness spectrum (specific) for engineering materials [27-28]

The absolute stiffness to strength performance of steel and carbon-reinforced composites is very similar. However, as the density of carbon composites is 4 to 6 times lower than steel, they clearly show more potential. Nevertheless, as outlined in the next section, there are significant barriers to overcome.

5.4 Lightweight Affordability

5.4.1 Automotive

With the automotive CO_{2e} numbers presented in chapter 4, 1 [kg] of car weight reduction knocks the emission down by 0.085 grams per kilometer. Assuming that the original CO_{2e} emission is 95 grams per kilometer, the car is capable of driving 26 kilometers on one liter of gasoline. For 150.000 kilometers, the total fuel consumption will then be 5769 liters. With a kilogram less, the corresponding consumption becomes 5752 liters. Hence, the difference here is only 17 liters or 25.5 € (1 liter gasoline = 1.5 €). The figures become better for a reduction of 100 [kg] where the fuel saving attains the value of 527 liters or 790 €. From this figure, one may conclude that the price to pay for a kilogram less, should not exceed 7 €.

The main question to be answered here is: how much is an automobile manufacturer prepared to additionally pay for a kilogram reduction of weight per car? The obvious answer would be a fair share of the savings for the customer, but the automotive market relies mainly on other selling points: appearance, purchasing costs, performance etc. As the profit margins are around 10% of the total production costs, studies show that the preparedness for additional pricing is very low: about 5 to ultimately 7 € per [kg]. In the table below, some global additional price estimations are presented ([74] with adapted numbers):

Table 5-5: Price per weight comparison for materials of a premium sedan or SUV body structure

	Weight [kg]	Material price [€/kg]	Total price [€]	Light weighting costs [€/kg]
Steel	400	4	1600	Reference value
Aluminum	320	8	2560	12
Glass composites	360	5	1800	5
Carbon composites	150	40	6000	21.6

In terms of specific performance, the only affordable material family, close to steel, is glass fiber reinforced composites. However, as stated in the previous section, these materials do barely add any advantages in terms of stiffness per unit weight. Aluminum performs better but is more expensive. For specific strength however, glass fiber composites are preferred. Despite their excellent specific performance, carbon fiber reinforced composites are still too expensive [14, 15]. However, as automotive manufactures tend to increasingly form alliances with carbon fiber producers (BMW/SGL, Mitsubishi/ Grafil), prices are expected to drop significantly, even to levels close to 10 €/[kg] [21].

5.4.2 Aerospace

As previously mentioned, a weight reduction of 100 [kg] can have significant impact on the operating figures of aircraft. With the information provided in chapter 4 and the data in [9], on can deduce that 100 [kg] less Operational Empty Weight (OEW) can imply a saving of 19000 liters of kerosene for an Airbus 320 (average numbers). This results in 5700 liters less kerosene per kilogram weight reduction over 30 years (operating lifespan). In an extensive thesis[6], the authors mention a fuel consumption reduction of 5000 liters. Following their assumption that a liter of kerosene costs about 0.40 € per liter, the costs discount becomes 2000 to 2280 €. Hence, from an operating point of view, weight reduction does immediately pay off in significant numbers.

A Boeing 737 or Airbus 320 airliner is typically sold to an operator for 50 to 150 M€ as prices may fluctuate significantly as a function of promotion campaigns, stock, backlogs and delivery times. For an operating empty weight of 42.000 [kg] and a catalogue price of 126 M€, it can roughly be stated that an airplane attains the selling price of 3000 €/[kg]. With a safe margin, the production costs per kilogram are about 1500 €. In the table below, it assumed that composites come at a price of 2500 €/[kg]. This number is exaggerated because the relative share of engines in the production price is significant. An assumed

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[6] Kaufmann M. Cost/Weight Optimization of Aircraft Structures. Licentiate Thesis, KTH Stockholm, 2008.

averaged price per [kg] of composites would probably be closer to 1800 to 2000 €/[kg]. Nevertheless the “expensive scenario” has been adopted here for demonstration reasons.

Table 5-6: Demonstration of increased operator profits, even when OEW reduction comes at an additional price.

10% reduction for A320 by composites use	Units	Quantities
Original weight	kg	42.000
Weight knockdown factor by composites use	[-]	0.4
Increase share of composites	%	10
Weight reduction	kg	1.680
Production price original materials	€/kg	1.500
Production price composites	€/kg	2.500
Total original production price	€	63.000.000
Production price with original + composites	€	64.680.000
Production price increase	€	1.680.000
Selling price increase (50% margin)	€	3.360.000
Savings for operator per kg less over 30 years	€/kg	2.200
Total savings for operator over 30 years	€	3.696.000
Net operator profit (new selling price – savings)	€	336.000
Savings over a fleet of 50 units for 30 years	€	168.000.000

An annual saving of 11 k€ per airplane is here the worst-case scenario for the airliner. For a composites production price of 2000 €/[kg], these savings would become 56 k€, a significant number. Hence, while the production price per [kg] did not vary significantly in this case, the profits for the operator increased exponentially and so did the selling point for the manufacturer.

A 50% knockdown of the extra production costs per [kg] in composites (from an additional 1000 € to 500 €) results here in 5 time more savings for the operator. Affordable, high-end composites manufacturing is therefore the key technology to green/affordable air transportation (and automotive).

5.5 Material Costs

From the previous sections, the upper price limits for light weighting can be summarized as:

- Automotive: 7 € per kilogram reduction
- Aerospace: 800 € per kilogram reduction (1000 USD, a “classic”)

Albeit a very preliminary indication, the graphs form [4, 27-28] do provide a general idea in terms of globally expected material costs.

5.5.1 Costs per Stiffness

In the chart below, the relative costs are normalized to those of the "average" steel with a previously assumed price of 4 €/[kg]. The scales are both logarithmic. Aluminum alloys are roughly 2 times more expensive (magnesium is 3 to 4 but is typically limited to applications like high-end engines). Glass fiber reinforced composites do not provide any stiffness benefits per unit weight. Carbon composites do; however, they are 8 to 12 times more expensive.

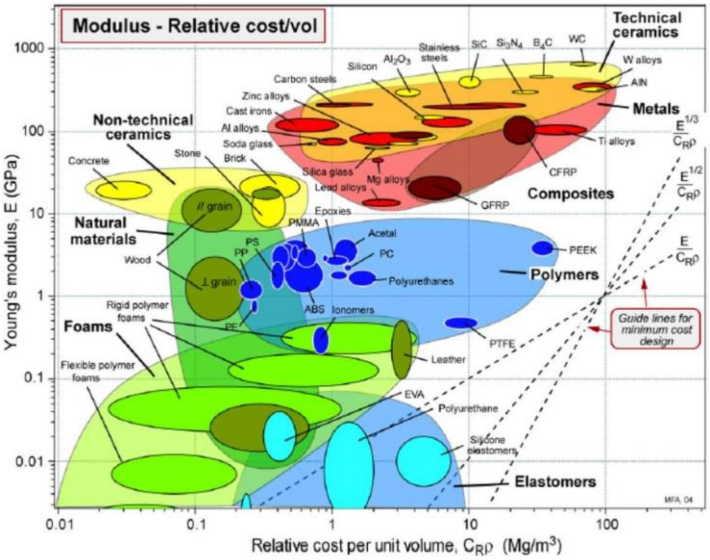

Fig. 5-5: Stiffness as a function of relative costs (normalized to steel) [27-28]

It should be mentioned here that the costs in the chart are per unit volume. Hence, the numbers have to be corrected for density.

- Steel: 7800 kg/m^3
- Aluminum: 2700 kg/m^3
- Magnesium: 1738 kg/m^3
- Engineering polymers: 1200 -1600 kg/m^3
- Glass fibers: 2400-2500 kg/m^3
- Carbon fibers: 1750-2000 kg/m^3
- Polymeric fibers: 900-1500 kg/m^3

For composites, the density of a fiber-polymer combination follows the simple rule of mixtures.

5.5.2 Costs per Strength

For the volumetric costs per strength, it should be noted here that glass fiber-based composites do show much better figures. With an average price of 5 €/[kg], a typical tensile strength of 1000-1500 [MPa] in the fiber direction (for a 50-50 epoxy-glass plate,) and a density just below 2000 [kg/m$^{3]}$, the price per specific strength (strength/ density) is quite attractive. Carbon composites have much better performance in specific stiffness and strength but are expensive. Polymeric fiber-based composites are typically used for armor protection and structures that have to sustain significant impact energy levels.

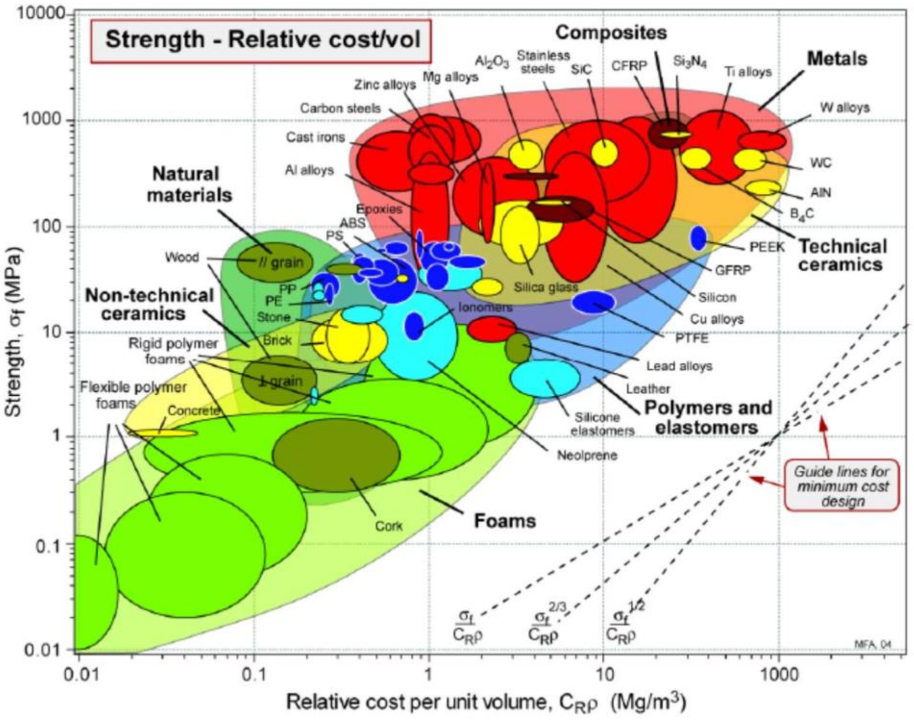

Fig. 5-6: Strength as a function of relative costs (normalized to steel) [27-28]

6 Cross-Cutting Areas: Transferability Auto-Aero

With the potential weight (and thus emission) reduction numbers and their additional costs for incorporation in auto-aero production established, the technology transferability between the automotive and aerospace industries will now be elaborated. From the previous material performance considerations, it is decided to provide special attention to composites for which a short outline regarding their production processes is here regarded as essential. Extensive textbooks in this topic, also regarding mechanics, are [29, 56, 60, 67].

6.1 Composites Production : a Short Overview

For a comprehensive market report, one may consider [88]. As compared to typical metal part fabrication processes, like rolling, stamping, machining and welding, the production of composite parts is rather different: lighter tooling, prolonged processing times and increased levels of manufacturing simulations and structural analysis. A major distinction here is the kind of polymer used; thermosets (TS) solidify by polymer cross-linking and thus rely on the combination of a resin with a hardener (sometimes, catalysts or accelerators are added). The reaction is not reversible, which is a property that makes their recyclability very challenging. On the other hand, thermoplastics are melt-processed and solidify by cooling. The reaction is reversible in terms of re-melting and re-shaping, but the quality of the polymer can generally not be preserved in its “new life”. A slight downgrading after re-use is to be expected.

6.1.1 Thermoset Composites

An extensive treatment of thermoset composites is out of the scope here. As general remarks however, one should note that high-quality products do often require extensive cycles in an autoclave. An autoclave is in essence a pressurized oven where the vacuum bagged product is placed in. A particular temperature and pressure cycle is then needed to solidify or “cure” the product. On some occasions, the thermoset might cure at room temperature with however, long processing time. Oven curing is quicker but also problematic for very large structures. The production processes for thermosets composites can roughly be divided in:

- Low end: Hand layup o Fabrics, pre- or post-impregnated with resin.
  - Spray gun layup: combination of resin with chopped fibers.
- Injection Molding o Resin transfer molding under positive pressure in mold with fabrics inside.
  - Vacuum-assisted resin transfer molding in mold with fabrics inside.
  - Reaction-injection molding (resin and hardener injected in mold under low viscosity, reaction takes place in mold).

- Molding compounds o Bulk molding compound: closed mold pressing of a resin-chopped fibers mixture. o Sheet molding compound: pressing of a pre-impregnated fabric into a closed mold.
- Prepreg molding o Pre-impregnated fabric lay-up, followed by curing.
- Tape laying o Broad pre-impregnated tapes, minimal in-plane steering.
  - Fiber placement: pre-impregnated tows, profound in-plane steering, typically applied for heavily optimized, variable stiffness laminates.
- Filament winding o Dry rovings with post-impregnation by injection techniques.
  - Pre-impregnated rovings.
  - Rovings through resin bath.
- Braiding o Over braiding (sometimes referred to as radial braiding). Typically, dry rovings, to be impregnated and cured on a later stage.
  - 3D braiding: from a 2D spool arrangement, several pass-through strategies for the spools will create 3D preforms for rods and beams where branching is possible.
- Pultrusion o Complete line with pre-impregnations units.
  - Pre-impregnated rovings, curing activated by elevated temperature.

- Novel techniques o Preform stitching (dry rovings). o 3D printing with continuous, wet fibers (extrusion).

6.1.2 Thermoplastic Composites

Compared to thermosets, thermoplastic polymer-based composites can offer significant advantages:

- Recyclability due to re-melting and re-shaping of the polymer.
- Improved fracture toughness.
- Short cycle times, no extensive curing needed.
- Pre-impregnated fabrics, tapes and rovings do not require low-temperature storage.
- Shelf life (best before) of materials is significantly longer.
- An extensive range in price, temperature limits, processing windows, chemical resistance and mechanical properties is available.
- Joining can be realized by fusion techniques (melt, induction welding, ultrasonic welding, conduction welding, resistance welding etc.) [8].
- For press-molding, lightly modified existing infrastructure can be used.
- Processing does typically not result in emission of toxic substances.
- Maintaining a cleaner production plant is easier.

The most significant disadvantage of thermoplastics is their high viscosity when melted; this renders inline impregnation as a nearly impossible task. Therefore, most raw materials used are pre-impregnated. Half products are typically delivered as rovings, tapes and fabrics with prices significantly higher than those of thermosets, especially when considering thermoset in-line impregnation on the basis of fibers and resin only. High-end thermoplastic half-products can reach 100 € per kilogram. As a comparison, a kilogram of Epoxy is epoxy at 2 to 5 €, a kilogram of glass roving is in the same range. The manufacturing processes for thermoplastics can be classified in a fashion as previously done for thermosets:

- Injection Molding o Combinations of polymers with short fibers (compound).
    - Overmoulding.
- Compression molding o Stamping (very short cycles).
    - Solidification in mold (longer cycle times). o Rubber block compression, single mold.
    - Diaphragm forming. o GMT: Glass Mat Thermoplastic forming.
    - LFT: Long Fiber Thermoplastic (long = couple of millimeters). o BMC: Bulk Molding Compound: process similar to thermosets.
    - Reaction molding: polymerization in mold.
- Rotation molding o Same as for pure polymers but now with short fiber compound.
- Tape laying (on-the run heating required: infra-red, torch, laser) o Broad pre-impregnated tapes, minimal in-plane steering.
    - Fiber placement: pre-impregnated tows, profound in-plane steering, typically applied for heavily optimized, variable stiffness laminates.
- Filament winding (on-the-run heating required) o Pre-impregnated rovings.

    - o Rovings through resin bath (e.g., dispersion impregnation).
- Pultrusion o Complete line with pre-impregnations units.
    - o Pre-impregnated rovings, curing activated by elevated temperature.
- Novel techniques o 3D printing with continuous, polymer-coated fibers (extrusion).

Research progress in thermoplastic composites has resulted in a wide range of affordable half-products, specialized polymers for short cycles and improved high-temperature performance. In addition, the speed of tape laying and 3D printing has started to reach competitive levels. Mid-class engineering polymer prices, in combination with glass, are almost at the level of epoxy/ glass fiber combinations. For automotive applications, thereby providing sufficient reliability and good performance. For the aerospace sector however, the strict certification requirements do not yet allow for the use of cheaper material combinations, particularly in primary structures. Nevertheless, secondary elements, based on recycled thermoplastics are gradually gaining more importance [13, 35, 63].

6.2 Aerospace to Automotive

Historically, the transfer of aerospace technologies to the automotive sector has been significant [17]. The other way around is mainly concentrated on automation, logistics, production planning and costs management. The transferability from aero to auto is presented on the basis of the main parts that form a passenger car:

- Power train:
    - o Engine o Clutch o Transmission o Driveshafts o Systems (fuel, intake, exhaust)
    - □ Suspension & steering:
    - o Subframes o Springs o Dampers o Suspension arms o Bushes
    - o Ball joints o Linkages o Steering house o Rims o Tires
- Braking system:
    - o Main brake cylinder o Calipers o Discs o Drums o Tubing o Control systems □ Body in white:
    - o Crash absorbers o Sills o Floor panels, A-B-C pillars □ Exterior:

  - Hood
  - Trunk
  - Doors
  - Roof
  - Bumpers

- Interior:
  - Panels
  - Seats
  - Dashboard
  - Safety systems
  - Control systems
  - Harnesses
  - Ducting
- Hydrogen containment:
  - Comparison to batteries
  - Structural efficiency
  - Alternative vessels
- Multi-functional structures

6.3 Power train

6.3.1 Engine

For almost 4 decades, practically all automobile manufacturers have switched to full aluminum castings for both the engine blocks and cylinders heads (these started much earlier to be made out of light alloys). In several attempts to lower the density of the used aluminum however, some manufacturers did face significant problems with valve seat drop-out or smashing into the housing due to the increased softness of these alternative materials, particularly in the case of non-hydraulic valve tappets. For nigh-end engines, several applications of magnesium are known. However, magnesium is more expensive and prone to corrosion when not properly protected.

The current state of the art focusses on organically designed, fully optimized connecting rods, able to significantly reduce forces due to minimized mass inertia. However, these are still in the experimental phase and only related to hope cars in development.

The introduction of short fiber reinforced molded plastics for water pump, thermostat, intake manifold, valve cover, blow-off valve housing among with engine covers, intake air ducting and engine supports did result in significant weight savings. However, for some high-temperature areas as post-turbo ducting and blow-off valve housings, polyamide-based compounds proved to quickly become brittle due to elevate temperatures. Solutions have been sought in more expensive materials like PEEK and PEKK with higher costs as a result.

The number of polymeric auxiliary parts is currently at its maximum, and mainly limited by the high temperatures in the engine bay area. Novel polymers like LCP (Liquid Crystal Polymers) are currently under investigation as an alternative.

6.3.2 Clutch and Gearbox

With the introduction of advanced automatic transmissions (like the DSG of Volkswagen) with double clutches and extensive lining and control systems, weight reduction has gained more importance. The use of polymeric compounds is however limited to peripheral systems as the main housings need sufficient heat conductance while exposed to high temperatures. For manual transmissions, most secondary system housings (for example the clutch master and slave cylinders) have already been replaced by plastic ones.

6.3.3 Drive and Propeller Shafts

The Introduction of filament-wound, glass and carbon fiber-based propeller shafts did already take place in the seventies for in particular American manufacturers. Most European rear axle-drive cars do already fully incorporate this solution. The challenge here is to streamline, standardize and optimize the production process for lowers costs. In addition, sufficiently attention must be directed towards joining techniques (attachment of splines and driving plates to the shaft) as these areas do often prove to be problematic.

Homokinetic joints are typically delivered as a complete driving axle, see Fig. below. Despite the complex machining and hardening procedure, they are relatively cheap (after market: 40 to 120 €). However, they are quite heavy (8 to 12 [kg]). With the shaft itself replaced by composites, its weight can be reduced from 2 [kg] to 0.5 [kg]. The gearbox side and hub CV (constant velocity) joints are the heaviest parts. They can possibly be replaced by reinforced, flexible but torsion-stiff shells with tailored fiber directions. Another way could rely on the specially designed involute shaft endings on which prestressed rovings can roll, unroll and slightly twist by preserving their non-contact length [43].

Fig. 6-1: A typical front-wheel drive CV axle

6.3.4 Fuel and Exhaust systems

Tanks

Most fuel tanks are already made by polymeric, short fiber compounds. Next to non-existent corrosion chances, they offer low weight, economic production and acceptable impact/ rupture resistance. However, for impact critical applications (racing, military) one can think about filament wound tanks with Aramid® or Dyneema® fibers. These fibers are known for the ballistics and impact resistance. Recent research in near net shape filament wound aramid helmets, proved to realize 50% weight reduction, zero scrap, and an overall ballistic performance improved by 30%. An alternative production method might rely on fusion bonding of thermoplastic, continuous fiber-reinforced shells with additional strips over the welded areas.

Lines

Fuel lines have to be chemical stable, impact tolerant and non-flammable. When incorporating a reinforced polymer tube from the aerospace industry that complies with the FST regulations, (Fire, Smoke Toxicity), the economic production of flexible, high-pressure resistant tubing becomes a fact. A suitable production process is the braiding of thermoplastic prepregs, followed by curing in a closed mold under internal pressure. Depending on the polymer choice, one can even realize fully flexible, high pressure tubing. Several publications have demonstrated that these artefacts are nearly insensitive to impact [42, 50]. The elaboration on high-pressured fuel containment forms a separate section in this report.

Inlet/ Exhaust tubing and mufflers

High-pressure pre- and after intercooler, flexible tubes are currently being replaced by fully automated produced filament wound artefacts, based on high-temperature elastomers [10]. Plastic inlet manifolds do not only provide less flow resistance but are also significantly lighter and cheaper than their aluminum counterparts.

A recent research effort in composite exhaust systems did result in some surprising conclusions [44, 68]. With proper measures like dedicated inner thermal insulation layers, layer covering meshes against abrasion and high temperature, and continuous fiber reinforcer outer shells, a thoroughly tested combination has been achieved, capable of:

- Weight reduction of 70%.
- Average sound attenuation form -10 [dB] to -50 [dB].
- Maximum outer shell temperature of 150 [^{o}C].
- Reduce heat radiation.
- Back pressure comparable with steel.

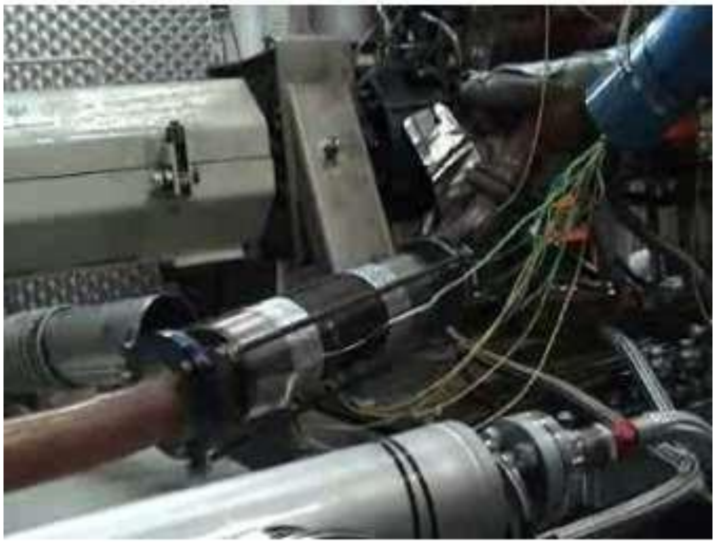

Fig. 6-2: On-engine testing of composite exhaust section at max. power (steel = glowing red, composites < 150^{o}C)

Identified drawbacks for this design are uncertainties about the insulation layers' durability, effect on desired exhaust sound spectrum, higher costs, and lack of research and development momentum in the industry due to discouragement of internal combustion engines.

6.3.5 Suspension and Steering

Subframes

Subframes are still made of steel (pressed plates, joint into a rigid frame) or aluminum (particularly for the support of the rear axle). Through bulk Molding Compound Techniques or assemblies of press-formed thermoplastic plates and beams that are welded together, composite subframes could be feasible [18]. However, one of the biggest issues can be found in joining them to the main body structures. Pin loaded composites exhibit much higher stress concentrations than isotropic ones when not properly designed. In addition, they are more prone to wear-out by vibrations while posing CTE (Coefficient of Thermal Expansion) compatibility issues for metals. The biggest issue however is the electrogalvanic compatibility. Glass fiber composites do not form any danger but, from a stiffness point of view, do not represent any improvement in terms of weight reduction. On the other hand, the structurally more efficient carbon fibers are nearly incompatible with most metals when in contact due to galvanic corrosion issues. Possible remedies are:

- Substitution of metallic parts by high-corrosion resistance alloys (best option = titanium, however, very expensive as a bolt).
- Placement of insulating interfaces.
- Use of epoxy resins without hydrolysable linkage to prevent moisture ingression.
- Use of proper sizing agents for the filaments, acting as sealants.
- Proper combination of anodization and coatings for metals.

With regard to highly loaded pin connections like bolts holding the subframe on the main body, typical solution s for wear-out, CTE =(coefficient of thermal expansion) differences and stress concentrations rely on insert placement. While metals tend to have significant CTE values, polymers expand less by increasing temperatures. Moreover, most carbon reinforced composites do barely show any CTE; in some cases, this might even become negative. An additional factor to account is crimpling of polymers (both thermosets and thermoplastics) after consolidation (typically 1% crimping).

With novel technologies like fiber steering, fiber stitching and overmoulding, an arrangement of dedicated, eventually concentric layers of carefully tailored materials can be placed around the loaded bolt in order to achieve radial orthotropy[7] [48, 73] and favorable stress distributions, Fig. below:

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[7] This fiber orientation distribution provides a minimized stress distribution for radial (bearing) and tangential loadings.

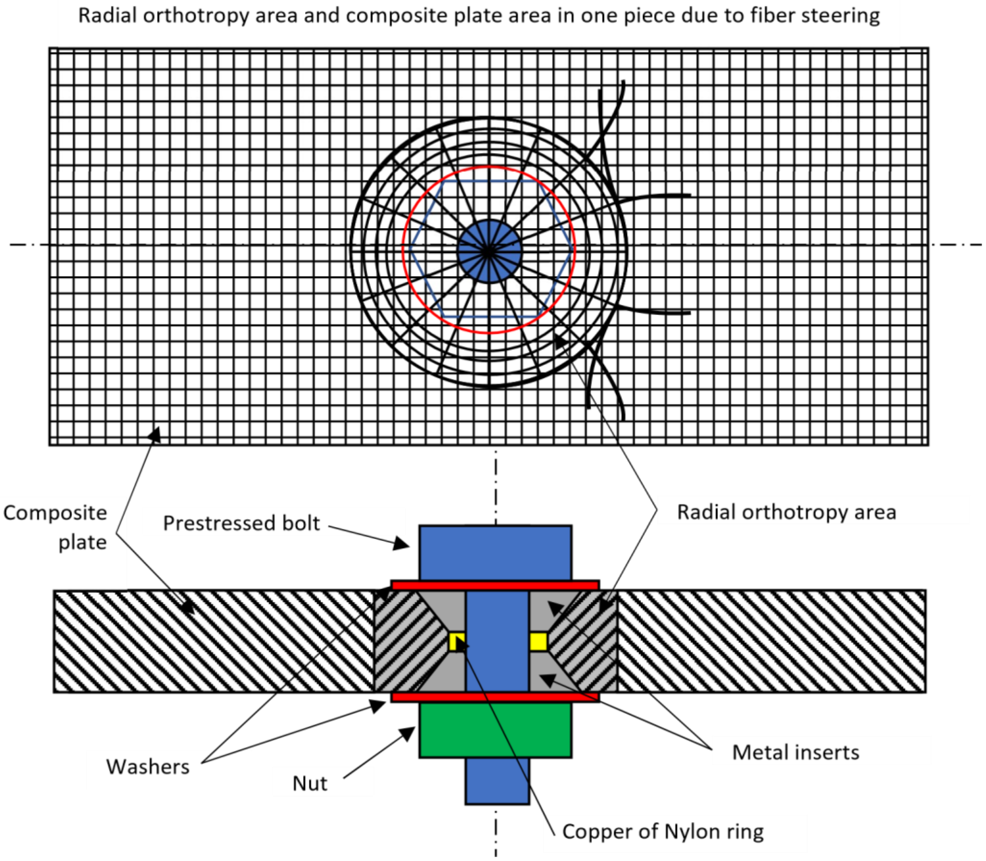

Fig. 6-3: Schematic of an arrangement combining inserts with radial orthotropy for a bolted joint in composites.

Springs and dampers

Several car makers do apply transversely mounted composite leaf springs to rear suspension systems thereby reducing the weight from 15 to only 5 kilograms[8]. In addition, attempts have been undertaken to replace steel coil springs by composite ones. For this, an inflatable tube was inserted in a braided sock, followed by resin infusion in a closed mold [66]. Whether this application has found its way to OEMs (Original Equipment Manufacturers) for mass production is yet unknown.

For reducing the weight of dampers, a possible solution would be to replace the outer cylinder by composite tubes of lighter metals. However, within a MacPherson suspension strut, the lateral loads and the requirement of a smooth inner sliding surface render this option very challenging, especially when considering the demand for very low costs.

Suspension components

Advanced suspension arm components like carbon fiber wishbones, composite flex plates and even knuckels are already incorporated in Formula 1 racing cars. Commodity cars are mostly quipped with forged

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[8] https://www.compositesworld.com/news/sgl-carbon-delivers-millionth-composite-leaf-spring-to-volvo

or pressed suspension arms, combined with rubber bushings and steel ball joints in cups with a polymer interface. The main reason for this classical approach relies in costs and ride quality.

Several projects have launched in the past to turn high-end solutions for composite wishbone arms into affordable, mass-production items. However, the inevitable usage of expensive fibers and highperformance connecting rods do still form a problem. The incorporation of rubber bushings and cushioned ball joints is co-dictated be NVH requirements (Ride, Vibrations, Harshness).

To propose a possible solution, when the wishbone is integrated with flex plates for attachment to the subframe, attractive possibilities emerge, Fig. below. The NVH requirements can then be satisfied by sandwiching the flex plates between two rubber layers.

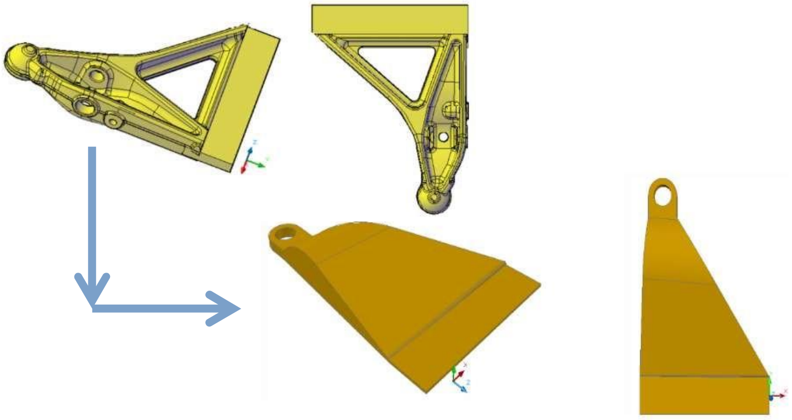

Fig. 6-4: Hybrid metal/ flex plate wishbone and its full composite variant: no fatigue at all

Bushings and Ball joints

These heavily loaded components are prone to wear-out and slack (clearance increase). Except hardened steel, there are barely any options for alternative designs unless the working principle can be changed.

As an addition to pressed rubber and metal parts, a network of fibers running from the inner cylinder to the housing in an overwound fashion, can add rigidity and tangential play limitation, Fig. below. This reinforcement principle does not only provide adjustable harshness by design, but also mitigates the risk of entirely losing the connection between moving and static parts.

The same principle can be applied to ball joints for securing total separation. For ball joints, the fibers are to be placed in special grooves, a-priori machined in the spherical part of the extending bolt. With heavily prestressed fibers, one can even crate a mechanism with however limited damping capabilities.

Steering house

Steering houses are currently made by LFTs (Long Fiber Reinforced Thermoplastics) where the optimization of local thicknesses for attachments, lines, and heavily loaded areas is critical. With the combination of 3D printing with continuous fibers in the mold, followed by over-injecting or coconsolidation, strategic, high performance reinforcements can be realized.

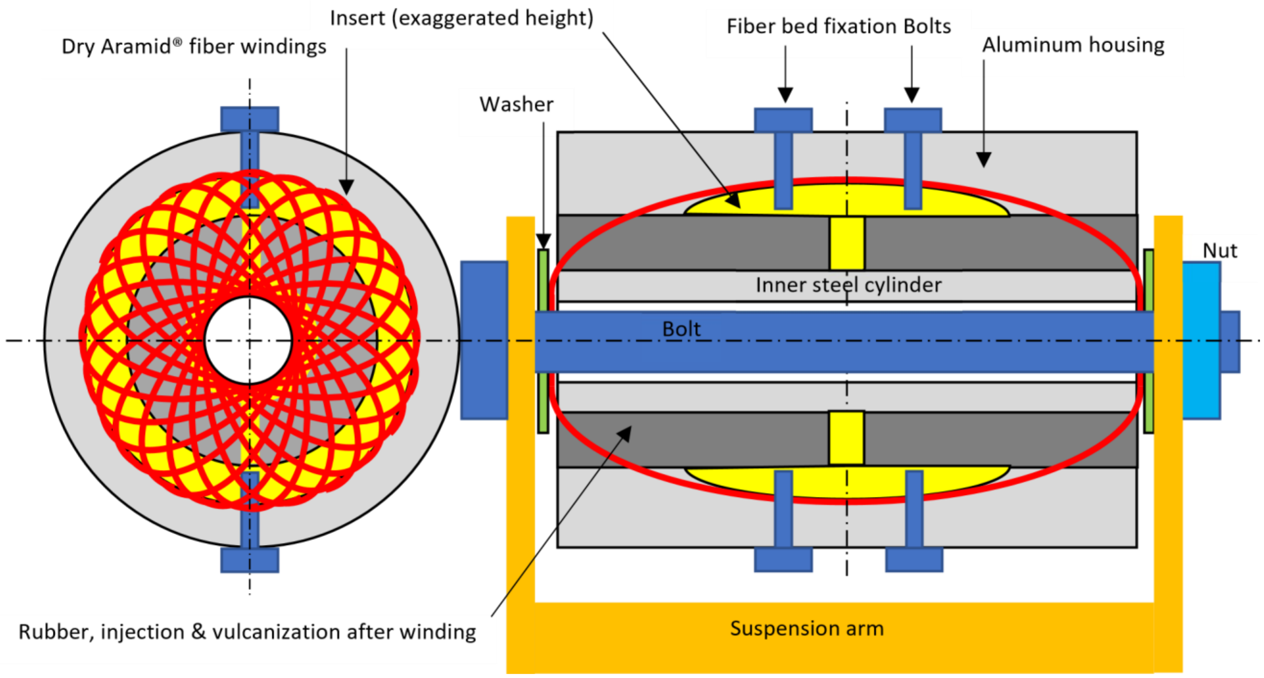

Fig. 6-5: Design principle for bushings with increased lateral load capabilities and increased fatigue resistance

Rims and tires

Light-alloy aluminum, magnesium and Carbon fiber rims are already produced in significant numbers. The latest category, however, is limited to very expensive exotic cars. As an example, the weight can then be reduced from 8.1 to 6.8 [kg]. Further performance increase is probably possible, but rims are mainly dominated by impact and shape accuracy requirements. With proper rotational preforming and pressing technologies for thermoplastics however, progress ca be achieved. Nevertheless, the main inhibitor for this step relies in the costs of carbon fiber (currently between the 10 and 20 € per kilogram for automotive companies with their own (carbon production lines).

Polymeric fibers, in combination with a steel carcass, are already being applied in tires. The share of in particular Twaron® and Aramid® fibers[9] is however increasing and brings significant advantages like reduced weight, improved resistance against puncturing and better preservation of the tire shape under increased contact area [81]. This mixture of steel and polymeric fibers is a spin-off from aerospace where tire integrity is a key issue.

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[9] 15 to 25 €/[kg] but due to low density, 1440 [kg/m^3], volumetrically acceptable.

6.3.6 Braking System

Calipers

Lightweight alloys for calipers are exclusively committed to high-end cars where multiple pistons are embedded. Due to high temperatures and tight tolerances, the replacement of these materials with polymer-fiber combinations is only feasible with advanced plastics (PEEK, PEKK) and fiber lengths beyond the couple of millimeters provided by LFTs (Long Fiber Thermoplastics). Despite several patents, this principle has not yet found its way to mass production.

Discs/ drums

Advanced braking disks are made out of Ceramic-Carbon composites. According to [12], they can realize a weight reduction of 5 to 6 [kg] per disc while shortening the braking distance from 100 km/hour to 0 with 3 meters in average. With improved affordability, it is expected that these materials will at least enter the higher end of the automotive commodity market. Contemporary cars, fitted with rear `disc brakes, have switched over from cast iron to specialized light metal alloys. A major contribution from the aerospace sector in this topic is the invention of ABS (Antilock Braking System) and EBD (Electronic Brakeforce Distribution).

Brake Tubing

Over the last 40 years, steel brake tubing has been replaced by dedicated Copper-Nickel alloys with better formability and corrosion resistance. High-end after-market retrofits consist of steel braids, placed over Teflon® liners (another aerospace solution).

Further improvements are possible in terms of using lighter fibers with proper puncture and impact properties. Polymer fibers could be a candidate albeit they do generally not favor high temperatures.

6.3.7 Body in White

Crash absorbers, sills

The strict regulations on crash performance (Euro NCAP and IIHS) have imposed usage of various high performance steel alloys for the passenger cage (life module) on critical areas. Ideally, a crash absorbing material or structure should exhibit maximized energy storage under allowable deformation and constrained deceleration. Finding the proper combination of materials in a design that satisfies the crash requirements under minimized production costs is a great challenge. Common applications in automotive rely on the combination of flexible, compliant bumper covers (injection molded), crash absorbers (extruded aluminum profiles or glass fiber reinforced toughened epoxy beams), progressively foldable main engine compartment beams, and reinforced passenger cages.

The introduction of (Advanced) high strengths steel alloys has significantly contributed to this solving the crash problem. However, with increasing requirements for light weighting, car manufacturers are increasingly looking at composites. Their stiffness, strength and energy absorption characteristics by particular stacking sequences, variable fiber orientation and eventual implementation of sandwich cores, is currently a key topic. As eventual buckling will significantly reduce the absorbed energy, tailored design can be created to shift to higher eigenmodes. In [33], Fig. below, the authors achieved 3 times higher buckling load than the optimized straight fibers-based layup by tailored stiffness distribution.

The same principle can work for absorbed energy maximization over restricted deformation. For example, in a ±45° layup, the effective contraction ratio under compression approaches the value 1 while the main failure mode becomes fiber-matrix separation among high strain values. This enables high energy dissipation while transferring lateral deformation to surrounding structural members.

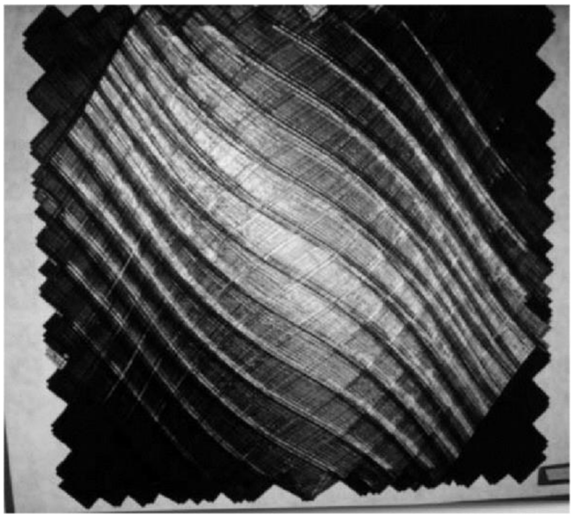

Fig. 6-6: Variable stiffness panel, optimized for maximum buckling load under monoaxial, uniform compression. Source: NASA.

To illustrate how the stiffness of a composite plate depends on the layup sequence, a symmetric stacking is here considered, based on the combination 0°, 90° and ±45° layers, Figs. 6-7 and 6-8. Depending on the percentage in which these layers are apparent, the stiffness in the 0° direction will attain certain values (Note:The most common books on composite mechanics are [19, 38-40, 42, 60, 84]).

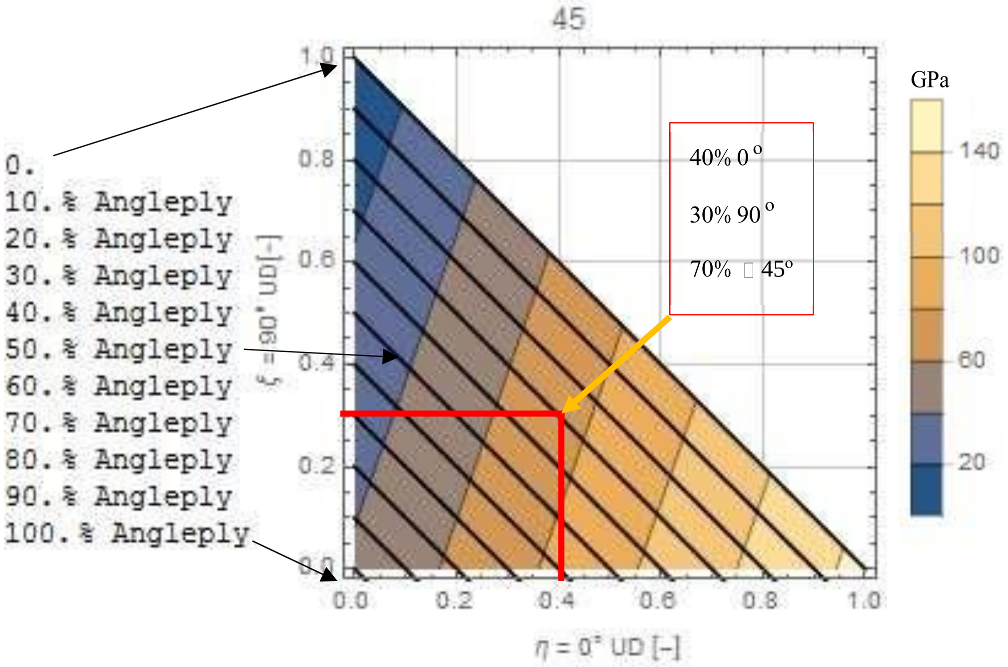

Fig. 6-7: Normal stiffness in 0-direction of a 0^{o}, 90^{o} and ± 45^{o} layup. Carbon-Epoxy, 50% fiber fraction by volume

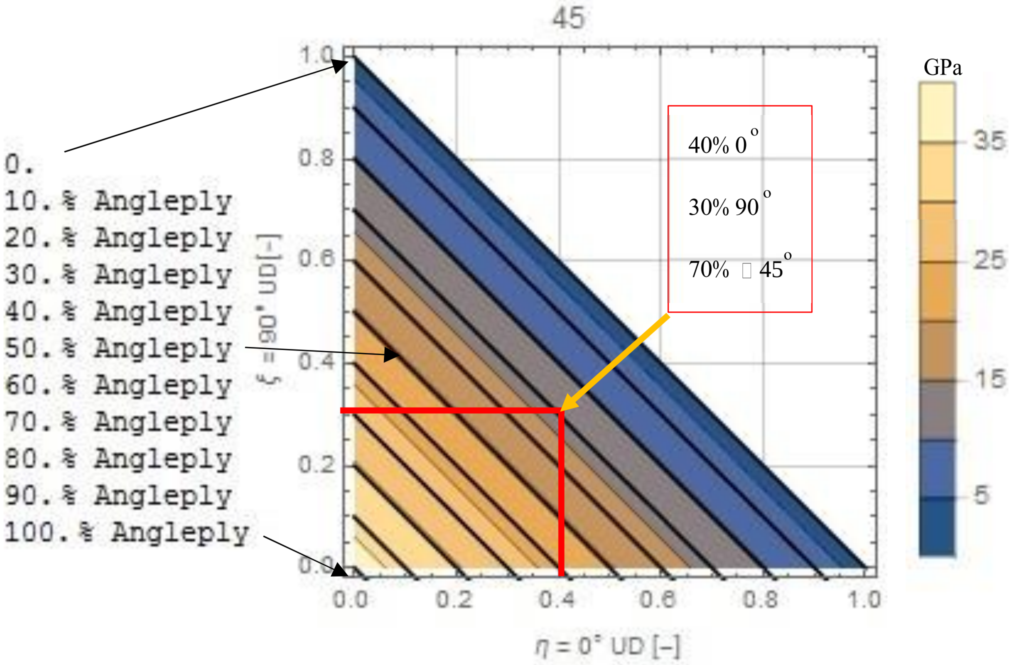

Fig. 6-8: Shear stiffness of a 0^{o}, 90^{o} and ± 45^{o} layup (maximized = 100% ± 45^{o}). Carbon-Epoxy, 50% fiber fraction by volume

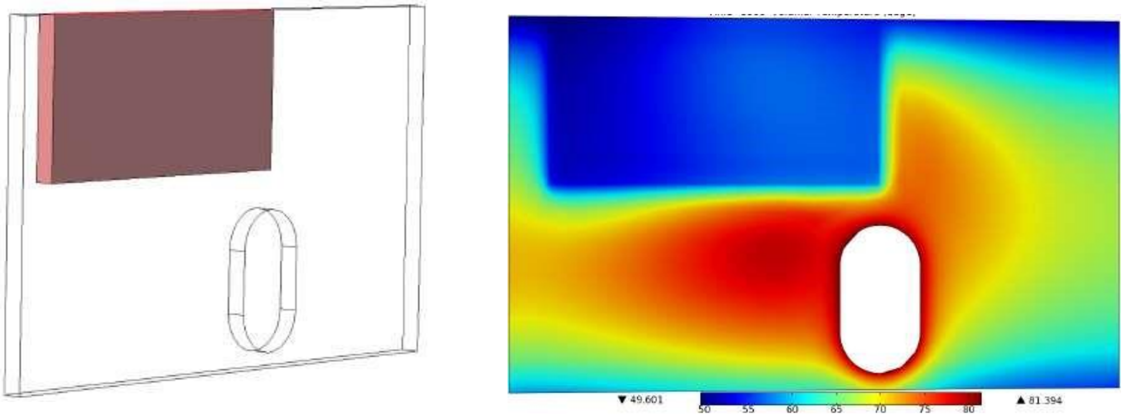

Fig. 6-9: Concept for Close-to-turbocharger heat sink in the composite engine bay of a Donkervoort and its resulting temperature distribution

Other aerospace-inspired solutions can be found in thick honeycomb cores that are embedded in the floor section of helicopters as ground collision measures. In addition, several studies have shown the benefits of specialized crash cones or concentric tube arrangements where progressive material failure or excessive shear-off in the adhesives is able to absorb significant amounts of energy. A real-world example example is the incorporation of carbon fiber-based sine wave girder into the seal of a Lamborghini, making it able to successfully pas the NCAP side pole impact test [62].

Incorporation of composites in engine bays may lead to thermal problems, particularly when located close to turbo chargers or exhaust manifolds and tubing. However, recent solutions did successfully demonstrate that the mounting of a copper heat sink plate was indeed able to mitigate this problem, Fig. 6-9.

Floor panels, A-B-C pillars

The typical material for load-carrying floor panels is steel. Some exotic cars employ aluminum or carbon/Aramid composites. For electric vehicles, the battery pack (mounted on the floor for stability and packaging reasons) has to be protected against impact and rupture by composites (the most effective protection is, once again, provided by polymeric fiber-based sandwich configurations).

Affordable glass fiber composites do not significantly add to torsional stiffness, albeit they do clearly offer higher strength per mass[10]. Carbon panels are beyond affordability, but this game is changing quickly as they become cheaper (see also chapter 5). Full composite passenger cages or life modules are only found in high-end sports cars or some particular series of electric vehicles [30, 41], Fig. 6-10. Their main drawback however is not their pricing but the lack of proper reparation techniques. Typically, when such a module is affected, it has to be replaced entirely.

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[10] For an original A-pillar design comprising HSS and internal rhomboid-based composite reinforcements, see chapter 7.

Fig. 6-10: Lightweight, carbon fiber-based composite life module of the BMW i3. Source: BMW.

A recent, theoretical t study for the replacement of the Donkervoort DB8 [82] spaceframe by a composites monocoque, proved able to increase the torsional stiffness by more than 300% with a weight reduction of 50%, at least as a TRL3 case study, Fig. below.

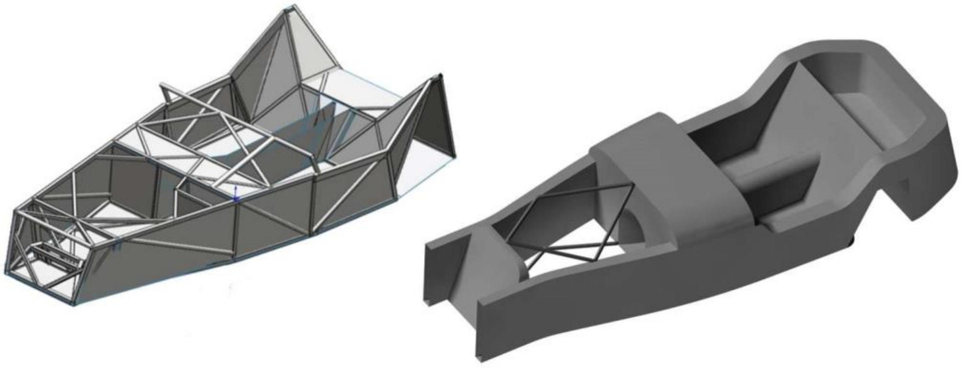

Fig. 6-11: Donkervoort DB8 chassis: the existing space frame and its monocoque replacement

6.3.8 Exterior parts

The typical thickness of steel body exterior parts is 0.8 millimeters. The main requirements here are aesthetics, A-class surface, and a small contribution to crash resistance. Some high-end cars incorporate aluminum panels (like the new Alpine by Renault and several Audi models) at higher costs. In the past, several attempts have been made to use plastics for that purpose. Some early models of SAAB that embraced these materials were afflicted by soft hanging doors, particularly at elevated temperatures. With the improvement of polymers and the addition of short or long fibers, plastic fenders, hoods, trunk lids and roofs have found their way into automobiles, although not in an extensive scale. Without added reinforcement, the main problem was not a lack of stiffness but the showing up of the underlying ribs when exposed to temperature or humidity changes (Citroen BX, which however was an ideal car for the police due to the hood’s radar transparency). Carbon fiber roofs are probably the most viable application area for these materials as they impose unsurpassed specific stiffness and strength values; with lighter roofing (see chapter 7), coupe to cabrio configurations become easier while the center of gravity can remain low.

Plastic panels allow for A-quality surfaces, reduced sensitivity to dents, no corrosion, better damping, less vibrations and less danger to pedestrians. For pure plastic panels, repair procedures can become as easy as the ones for bumpers. However, when long or continuous fibers are embedded, special measures have to be taken like careful grinding-off with a very shallow angle of attack, proper surface preparation (sanding and chemical), accurate repair patch production, welding or gluing, and finishing of the repair. As stated in the literature [18], regaining the original stiffness might be possible. However, the original strength cannot be reached without the patch’s thickness being increased: in some cases, this might be possible for example when the added thickness is located in the inside of a fender. In this way, exterior surface smoothness can be preserved.

The aerospace principle of load-carrying skin is difficult for automobiles as they contain many, rather big openings. In addition, a damaged load-carrying item would require new certification by the national authorities.

6.3.9 Interior parts

With an exception for seat frames, supports and rails, most interior parts are made by plastics. For the rear shelf (or hat rack), pressed natural fibers/ plastics combinations are used. The same applies on several interior panels, roof covers, load floors and seat backs.

Some space for light weighting can be attributed to composite seat frames relying on the combination of 3D printing with continuous fibers, followed by injection molding or co-consolidation pressing. Another way for emission reduction is the increased incorporation of recycled materials and enlarging the share of recycled fiber, rovings, tapes, and fabrics. For the latter, thermoplastic composites do form an ideal candidate.

6.3.10 Hydrogen Containment

Comparison to batteries

Li-ion battery packs in automobiles have not yet reached attractive energy density figures. While this concept is convenient for short trips, extensive travelling might become problematic due to the limited range and long recharge times. In addition, after their lifetime of approximately 8 years, the batteries need to be recycled. On the other hand, hydrogen cars (assuming efficient fuel cells) have the potential to overcome the short range, charging time and recycling issues, table below.

With an energy density of 260 Watt-hours per kilogram, there is a consensus that electric vehicles may become widely accepted when this number will surpass the number 400. However, the added weight is significantly higher than that for hydrogen storage under 850 bars. Nevertheless, the potential dangers of highly pressurized containment of a very flammable substance have not yet been fully accepted by consumers.

Table 6-1: Comparison of the Tesla model S with an equivalent H_2 – fuel cell car (total weight effect is neglected)

	Units	Tesla Model S	H_2 + Fuel Cell
Gravimetric energy density	KJ/kg	936	152.000
Contained energy	KJ	468.000	547.000[11]
Source to e-motor efficiency	%	90	80
Range	km	500	520 (combustion: 200)
Charging time	Hours	5 -15	0.085 (5 minutes)
Total fuel system weight[12]	kg	700	200 (combustion: 250)

Structural efficiency

For the storage of H_2, a working pressure of 750 [bar] is required with a certification value of 1750 [bar]. The efficiency of a pressure vessel is measured by the ratio of the contained volumetric energy, pressure □ volume, divided by the system's weight [85]. This quantity should be smaller than the (simplified) corresponding material performance indicator, a function of tensile strength, density, and the gravitational constant:

$$\mathrm{perf} \; \square \; \square \frac{PV}{gm} \square \; \square \frac{\square_{tensile}}{\square} \square \; \square \frac{1}{\square 3g} \square$$

Assuming a tank of 90 liters with a certification pressure of 1750 [bar] and the anticipated, future shortterm performance requirement of 0.5 [kg] per stored liter of hydrogen, the required structural efficiency becomes 32.100 [m]. The associated data of common materials for that goal are presented in the table below:

Table 6-2: Pressure vessel performance of common material combinations, compared to the required threshold.

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[11] One liter of H_2 at 20 ºC and 750 bars = 0.04 [kg]. Tank volume = 90 liters. Efficiency of combustion = 32 %.

[12] The state-of-the-art dictates that 0.9 [kg] of tank structure is needed for 1-liter of H_2. Weight of H_2 for the presented conditions = 3.6 [k]g, the total weight with additional systems is assumed at 200 [kg]. For Tesla, this number is 700 [kg]. For both, the weight of wiring and e-motors is not included.

Required performance = 32.100 [m]			
Material	Tensile strength [MPa][12]	Density [kg/m^3][13]	Performance [m]
Steel	254	7800	1.106
Aluminum	222	2700	2.794
Glass composites	1500	2000	25.484
Aramid composites	2000	1500	45.305
Carbon composites	2500	1800	47.193

It becomes evident that in these cases, only composites are able to meet the requirements. The technology of these artefacts originates in aerospace applications, in particular for fuel storage, nitrogen and helium containment, and rocket engine cases.

Alternative vessels

It should be mentioned here that the required performance is very challenging; at these pressure levels, the wall thicknesses become considerable, thereby introducing secondary loading effects like bending and transverse shear/ through-thickness compression. In addition, the traditional cylindrical shape with endcaps does not provide the best solution for minimum weight [43]. Possible alternatives can be found in multi-cell arrangements and Isotensoid toroids, Fig. below:

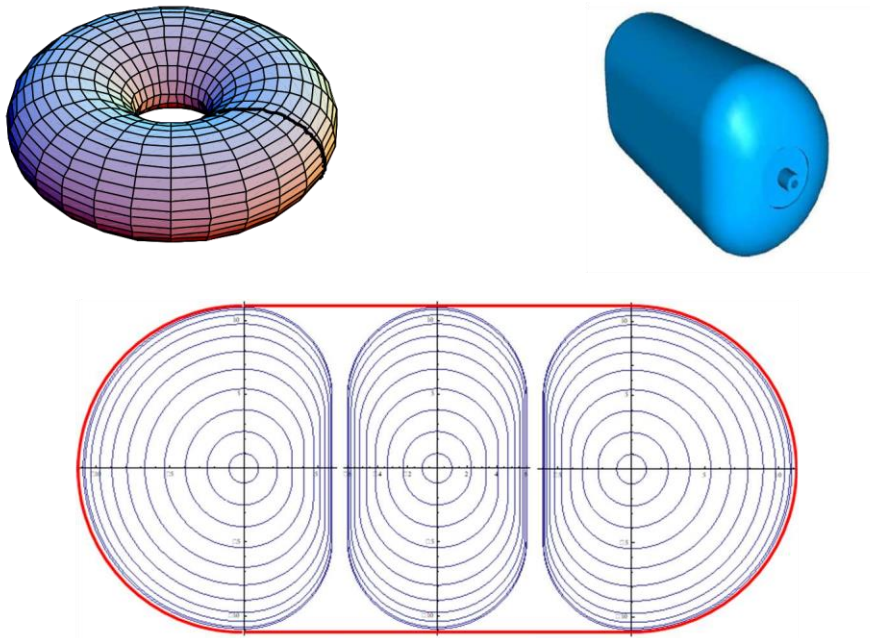

Fig. 6-12: Alternative geometries for improved gravimetric efficiency (toroid) and packaging efficiency (multi vessel).

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[12] Continuum theory based Isotensoid design, 50% fiber volume fraction.

[13] The density is based on 50% volume by fiber and 50% volume by epoxy.

A recent study by [80] proved the viability of a multi-spherical vessel designs for cryogenic hydrogen storage:

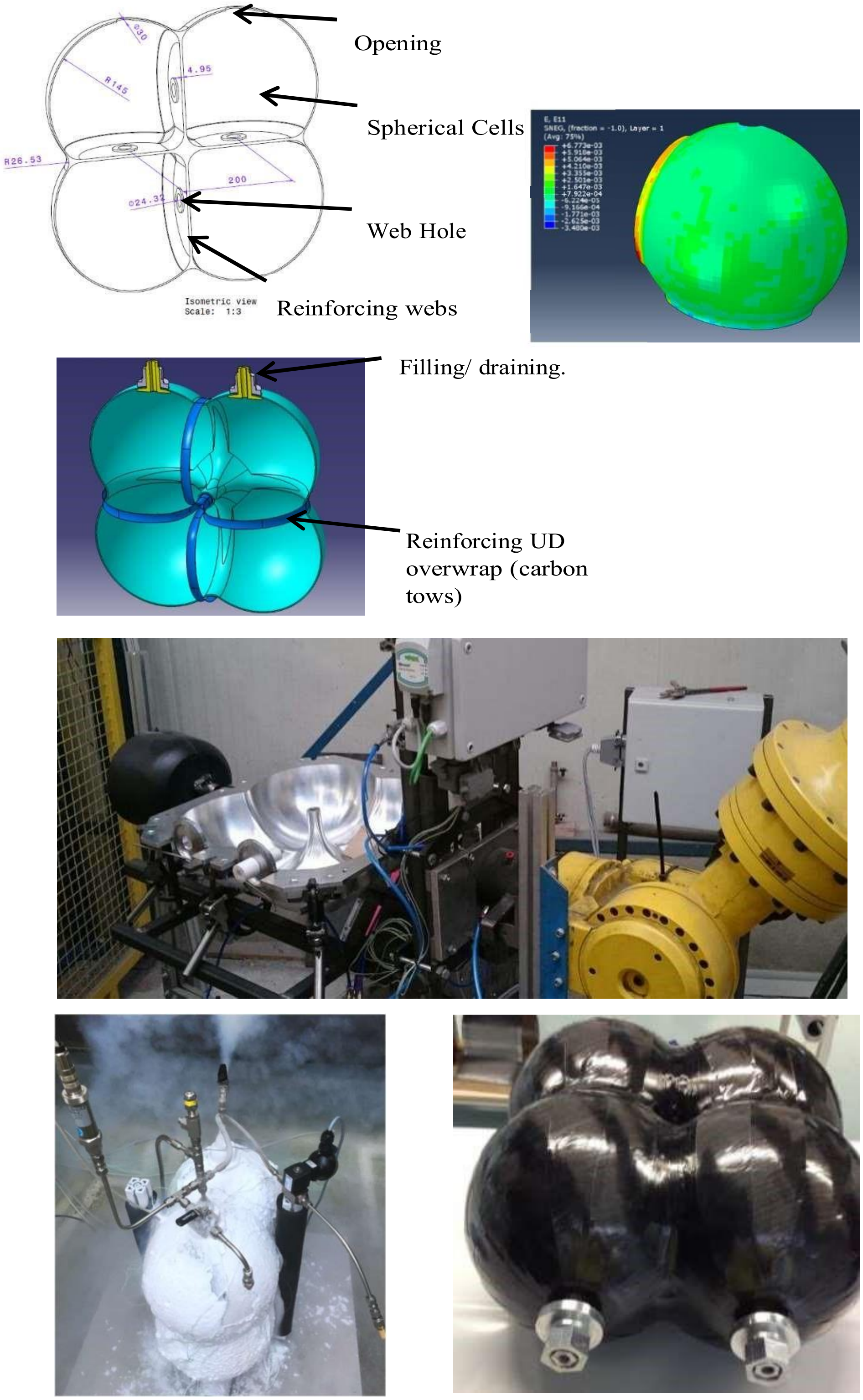

Fig. 6-13: A multi-spherical cryogenic vessel for H_2 storage: design, fabrication and testing.

6.3.11 Multifunctional Structures

The application of active aerodynamic and handling components in sports cars is well-known in the form of adjustable spoilers, diffusors, inlet canals, variable ride height and suspension characteristics. These innovations rely on electro-mechanical actuators, steered by sensors and computers. Novel techniques can be found in piezo-electric elements, integrated in a structural member. For the time being, the only widely spread application can be found in the injectors for GDI (Gasoline Direct Injection) engines.

Research in morphing wings and piezo-electric control of wind turbine blades is currently in full progress [30] with however no high TRL (Technology Readiness Level) applications yet. Some hyper car designers claim the full development of morphing exterior panels for speed and cornering-related aerodynamic optimization during driving [64]. However, concrete results are yet to be seen.

Passive aerodynamic aids are quite often applied to big trucks in the following forms [49]:

- Extended, faired-in nose cone for frontal tractor drag reduction.
- Trailor gap sealer to minimize turbulence.
- Side skirts to reduce overall drag.
- Boot tail fairings at the back of the trailer to reduce the induced low-pressure area.

Fig. 6-14: The Starship tractor-trailer combination. Source: Airflow Truck Company.

6.4 Automotive to Aerospace

Aerospace structures are at the edge of the optimization possibilities for performance per weight unit. A large number of tailored aluminums, magnesium and titanium alloys, in conjunction with steel parts for heavily loaded structural members, provide sophisticated, minimal-weight solutions.

With the introduction of composites, further weight reduction is estimated at 30% with a 25% fuel consumption decrease. These numbers are however theoretical and prove not achievable in practice due joining, stress concentrations, multi-material interfaces and safety requirements for the anticipation of long-term, environmental effects. These effects are thermal exposure, moisture ingression, polymer osmosis, operation in tropic climates, fatigue, and long-term degradation like increased brittleness, stress relaxation and ultra-violet radiation. Typical (estimated) numbers, employed by Airbus and Boeing for strain allowables in composites, are [59]:

Table 6-3: Determination of strain allowables by structural and environmental safety factors in aerospace.

Strain type	Ultimate Bbasis[14] [%]	Safety factor	Long-term Knock-down	Resulting safety factor	Strain limit [%]
Tension	0.90	1.50	1.70	2.55	0.35 – 0.40
Compression	0.72	1.50	1.80	2.70	0.27 – 0.30

To lower the combined factors for aging/ temperature/ moisture exposure over 30 years (airframe lifetime), extensive research efforts are required. These goal does not match the main objective of the automotive sector: low price, a lifespan of 10 to 15 years, and design-driven competition. Therefore, in the author's opinion, potential contributions from the automotive sector to aerospace will mainly regard facets like:

- Production & automation
- Standardization & parts suppliers
- Lean manufacturing

Further possible contributions can perhaps be found in the introduction of automotive HSS (High-Strength Steel) and AHSS (Advanced High-Strength Steel) for particular joints, frames and stringers. An idea, inspired by the automotive sector relies in the developments of new, weldable aluminum alloys.

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[14] At least 90% of the tested population equals or exceeds the selected value with 95% confidence.

6.4.1 Production & Automation

Automotive components are mainly designed with the manufacturing process being highly placed in the hierarchy of importance. The intended production process (or combinations thereof) should perfectly match morphology and material properties. In addition, the degree of integration is typically the result of a comprehensive trade-off between costs and manufacturability. With increased material costs for composites in aerospace, [11] highlights the importance of part integration. Large assemblies mitigate the risks and weight penalties associated with joining but require intensified design and manufacturing methods. This proposal agrees with [75], in which emphasis is directed towards costs estimation. Furthermore, according to the SWOT analysis provided by [77], composites and advanced lightweight materials do still suffer by limited property databases (mechanical , physical , economical), uncertainties about the employed testing methods, and the need for specialized repair techniques.

Lessons from the automotive sector could be contained in increased integration of structural elements, the willingness to invest in bigger presses for e.g., the compression molding of bigger parts, and the incorporation of more automation for positioning and transporting half-products. Novel techniques like image recognition, auto-referencing, scanning, and advanced electronic measurement methods (in-line) will improve quality and reliability through the entire production chain. In addition, intensified research efforts should be directed towards demountable joints (either mechanical or thermal by reheating) to ensure easier repair methods among more standardized fasteners, mounting procedures and means for quality control. Despite the advantages of fusion bonding, permanent joints form a significant problem for repair and inspection. Though most composites researchers do not appreciate the stress concentrations caused by mechanical fastening, there is significant number of publications that outline mitigation methods for this issue. As these methods require a certain form of cylindrical orthotropy [36, 48, 74], and in conjunction with the lack of automated fiber steering methods in the past, they did not find the general appraisal they deserve. In this respect, automation is game changer now; redesign on the basis of current manufacturing abilities can provide a plethora of “re-invented” solutions.

6.4.2 Standardization & Part Suppliers

The classic struggle between the Imperial and metric system from the Ford T model to current automobiles has more or less converged to the latter. However, brake lines, rims, tires and some fittings remained Imperial. As most aircraft components originate from the United States, Canada and the United Kingdom, applications of the metric system did originally not represent a majority. However, most modern aircraft use both systems, providing more opportunities to non-Imperial manufacturers, but at the same time raising the risks for errors. Learning from the automotive industry, aircraft parts will probably follow the same path by increasingly designing in the metric systems while keeping some “classic” parts in the “old” one.

From the previous, on may conclude that more directed efforts should take place towards standardization of the employed systems and the determination of typical sizes for e.g. bolts, and tooling. A great example can be found in Japanese cars where all bolts do correspond to wrench sizes 8, 10, 12, 14 and 17 with 13 for the alternator’s cable fixation.

Most automobile manufacturers rely for almost 90% on parts delivered by third parties. With an exception for in-house developed body parts and, sometime, engines and gearboxes, all remaining parts are built by so-called OEM suppliers (Original Equipment Manufacturers). These builders do also provide after-market parts. A simple search for particular car part may lead to the conclusion that the same set of brake pads or even a steering house, is used by at least 5 different brands and 10 to 20 models. The main suppliers per category are [5]:

- Gearboxes & drivetrains o Aisin Seiki o Allison Transmission o Borgwarner o Continental o Continental AG o Eaton o GKN o Hyundai Dymos o JATOC o Magna (formerly GETRAG) o Magneti-Marelli o Schaeffler o Valeo o ZF Friedrichshafen
- Emission control systems o Borgwarner o Bosal o Faurecia o KSPG AG o Tenneco o Walker
- Chassis & exterior parts o Aisin Seiki o Benteler o Flex-N-gate corp. o Gestamp Automocion S.A.
  - Magna
  - Magneti-Marelli o Plastic omnium o ZF Friedrichshafen Suspension, steering & brakes.
  - Bendix o Bosch o Brembo o Delphi o Federal-Mogul corp.
  - Ferodo o Mando corp.
  - Mapco o Moog o NSK o QH o SKF o Tenneco o Thyssen-Krupp o TRW
- Interior parts o Continental o IAC group o Lear o Magna

  - Plastic omnium o Takata o Visteon corp.
- Safety systems o Autoliv o Bosch o Hyundai o Takata o Tokai

The number of OEM suppliers in aerospace is obviously smaller while freely available after-market parts are forbidden for safety reasons. Airbus and Boing do share a significant number of suppliers with a slight emphasis on location; Airbus tends to use more European parts. The main suppliers are [1]:

- Engines o GE aviation
  - Collins Aerospace (Pratt and Whitney) o Safran o Honeywell o Rolls Royce

- Structures:
  - Spirit AeroSystems o GKN o Triumph o Mitsubishi (MH) o Alenia o Sumitomo o Kawasaki Avionics:
  - Thales o Esterline o Meggitt o BAE Systems o Collins Aerospace o Crane Aerospace o Safran o Moog o Cobham o L3 Communication o Teledyne Technologies Landing Gear:
  - Heroux Devtek o Collins Aerospace o Safran Cabin:
  - Safran (Zodiac) o Collins Aerospace o Encore

- Fuel and fluid management:
  - Parker Aerospace
    o Eaton o
    Triumph

By comparing the automotive and aerospace supplier lists to each other, the conclusion can be drawn that the first category involves companies that operate in various car parts: from chassis to braking systems and electronics. In aerospace, most companies are specialized in a particular item like engines; this can be attributed to the small production volume, high development costs and stringent requirements. It is therefore unreasonable to expect them to evolve at the low-costs, high-competition level of automotive suppliers. However, as more parties are entering the field of dominant aircraft builders, a slight motion towards that direction may be anticipated.

Inspired from the automotive supply-chain, the aerospace industry can profit from attracting an increased number of possible suppliers for a particular structural or electronic part. This will force tier 1 suppliers to invest in new specialisms, advanced production methods and improved compatibility/ interchangeability of the delivered items as they will have to compete with newcomers characterized by more flexibility.

6.4.3 Lean Manufacturing

The automotive industry has organized its development and manufacturing principles according to the Lean Manufacturing strategy. The main associated five steps are:

- Determination of value: this item reflects on current, known customer needs but also on future requirements and wishes, typically not yet determined for 100%. Extensive surveys, market forecasts and anticipation for future regulation are key issues.
- Mapping of the value stream: the entire chain, up to the final product, has to mapped in terms of intermediate value. During this process, some “waste” may occur, consisting of two types: nonvalue added but necessary (not directly related infrastructure etc.) and non-valued, unnecessary waste like complicated, multi-step production steps that can be replaced by simpler, more affordable ones.
- Flow creation: a perfectly organized manufacturing process without interruptions and nonconformities, based on flexible training of the employees to switch, if necessary, to alternative production activities.
- Pull establishment: organizing material and tooling flow in such a way that expensive stock is minimized, and everything is delivered just on time.
- Pursue of perfection: active monitoring of flaws and possibilities for improvements and costs reduction in production by continuous critical evaluation and active employee involvement.

These principles originate in the Japanese automotive sector and widely known as the Toyota system. The aerospace sector does strive to apply these principles, but it has to be admitted that they work quite differently as the production rate is not massive. Monitoring of material, half-products and machinery/ processes is very stringent (airworthiness requirements) but the chance for non-conformities is significant. However, the 5th principle may probably provide a framework to increase attention for selfimprovement.

For both sectors, the application of artificial intelligence on big data from manufacturing may provide several directions for improvement. Currently, significant research efforts are directed towards this theme.

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7 Auto-Aero Transferability: Success Stories

As can be concluded from the previous chapter, the technology transfer stream from aeronautics to automotive is much profounder than the opposite direction. In addition, one may conclude that the biggest share of this transfer stream can be attributed to lightweight materials like magnesium, titanium and aluminum alloys, alongside with composites. After a short outline of aero-to-auto safety systems and a short, historic consideration of composites use in the automotive sector, the main composites suppliers and recent light weighting examples are to be presented. Since composites are recognized as the key materials family for weight reduction, metal alloys will be here omitted. The last section here is dedicated to the most recent trends, breakthroughs, and developments, particularly with regard to composites.

7.1 Safety Systems

The first non-experimental application of ABS was applied during the 1950s on aircraft by Vickers, HawkerSiddeley, Avro, BAC and Fokker. The first computerized ABS system in cars was applied during 1971 in the Toyota Crown. Fiat, Mercedes-Benz, Ford and BMW followed in the 1980s. Currently, practically all cars have this system, complemented by electronic brake distribution capabilities and ride stability programs.

Black boxes are currently widely applied in cars. Similar to their application in the aerospace sector, they monitor all sensor inputs like engine running parameters, suspension and braking input, ride velocities and acceleration, in conjunction with g-forces during an eventual crash, number of airbags activated etc. Based on that input, they do also automatically call emergency services.

The Tire Pressure Monitoring System (TPMS) originated in 1980s as an option for luxury cars. This technology is currently also applied in the aerospace with a number of specialized companies retrofitting existing airplanes.

7.2 Composites in Automotive

7.2.1 Historic overview

Among the first cars employing a significant share of composites, the Stout 46 did employ a fiberglass body shell thanks to the company Owens Corning, which is regarded as the initiator of composites by being the first glass fiber producer in the world [58]. In the 1950s, Chevrolet did use fiberglass body panels for the Corvette. With the invention of the Sheet Molding Compound Technique, the forming and curing of an impregnated glass fiber fabric layup, applications accelerated. Typical examples of this technology are the Chrysler Station Wagon and the 1972 Corvette.

Meanwhile in Europe, some manufacturers introduced glass-fiber polyester cab body parts like the roof of the elongated Renault Estafette. In particular Simca - Matra tried to maximally employ these materials in their Bagheera and Murena sportscars models. The same idea was later applied on several generations of the Renault Espace (initially built at the Matra plant). At the same time, SAAB re-introduced the Sonett which however proved problematic due to insufficient body panel stiffness. McLaren was the first one to introduce a composites monocoque for their formula 1 racing cars in 1981. At nearly the same time, the third Corvette generation was equipped with the first composite leaf spring, a trend picked-up by Volvo a decade later.

The first composite structural part was the front bumper beam for the Mercury Tracer in 1987. The first composite drive shaft can be attributed to the Dana corporation, applying it on the Ford Econoline in 1987. The same company introduced an SMC front end system on the Taurus and Sable in 1998. In the early 2000s, front end bumper beams, along with SMC exterior parts became a commodity. An alternative approach by Citroen to employ injection-molded stiffened hood and trunk lid panels was, in general terms, successful although the stiffeners would show up through the skin during ambient temperature differences.

With an exception for the BMW i3, practically all Carbon composites applications are exclusively dedicated to high-end sports cars like Ferrari, Lamborghini, Porsche, Mercedes-Bens, Bugatti, Koenigsegg, Pagani, McLaren etc. [87]. The most affordable Carbon-based car in the sports class is still the Alfa Romeo 4C.

7.2.2 Forecast

According to [55], usage of composites in automotive (semi-) structural members is expected to increase from the current 1.6% to 2.2% in weight share. Therein, the biggest part is attributed to glass fiber parts, mainly for exterior panels, trims, roof systems and some engine components. Nowadays, the share of carbon fiber composites is only 0.02%. Other plastic parts, mainly injection molded, account for 4.6%. However, it is not clear whether short fiber reinforced plastics are here considered as composites or not.

Table 7-1: Trends and forecast of automotive composites.

	Year			Weight share in automotive materials market [%]	
Composite types	2009	2014	2025	Continuous + Long fibers	Including short fibers[15]
Glass [kiloton]	1380	4400	7000	1.6	4-5
Carbon [kiloton]	8	20	120	1.6	5-6
Natural [kiloton]	70	120	300	2.2	6-8

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[15] Estimated numbers for optimistic scenarios.

7.2.3 Research Clusters

The majority of automotive composites research clusters are located in Germany [21]. Actual research topics comprise automated manufacturing, defect detection and reduction, costs minimization, NonDestructive Testing (NDT), novel material combinations, and optimized design and analysis methods.

Traditionally, an overwhelming majority of automotive composites is represented by thermoset polymers as the matrix material. While they provide proper fiber impregnation and predictable curing cycles, their biggest drawback is lack of recyclability, typically resulting in incineration or landfill activities. Therefore, state-of-the-art research is now focused on thermoplastic composites (for which a short assessment is provided in chapter 6).

Fig. 7-1: Automotive composites research clusters in Europe [21]

7.2.4 Main Material Suppliers

According to [51], there is a significant numbers of composite material providers for the automotive industry with, as compared to metal suppliers, have a rather low sells volume.

- AOC, LLC
- Ashland Global Holdings Inc.
- BASF
- Benteler SGL
- Continental Structural Plastics
- DSM
- E. I. du Pont de Nemours and Company
- Gurit
- Hanwha
- Hexcel
- Hexion Inc.
- Huntsman Corporation
- Hutchinson
- Lanxess GmbH
- LORENZ Kunststofftechnik GmbH
- Magna International Corporation
- Menzolit
- Mitsubishi Grafil
- Owens Corning Corporation
- Plastic Omnium
- Quadrant Plastic Composites
- Ranger Italiana
- SABIC (Saudi Basic Industries Corporation) □ Solvay S.A.
- Teijin
- Toray Industries, Inc.

Most automotive carbon fiber production plants are owned by the manufacturers, which tend to control the entire production chain, even from the point of electric power generation up to the final assembly in the car. Known alliances are BWM-Benteler, Mitsubishi-Grafil etc.

7.2.5 Pioneers in Carbon

McLaren was the first one to build a street version of a full carbon monocoque sports car. In 1993, the McLaren F1 was very expensive as it additionally used 24 karat golden plating in the engine bay area for thermal protection.

Fig. 7-2: The McLaren F1, the first street car with a carbon composites-based monocoque. Source: McLaren.

In the last 2 decades particular carbon-based sports cars have demonstrated that one of the main issues for a monocoque is raised by elevated temperatures in the engine bay area, occasionally resulting in fire. As a compromise, most builders embraced a combination of a carbon life module (the bathtub) and aluminum subframes/ space frames. A typical demonstration of this is the McLaren MP4-12C, Fig. below:

Fig. 7-3: The McLaren MP4-12C relies on the combination of carbon bathtub and aluminum subframes. Source: McLaren.

Among the first cars with integrated bathtub-roof arrangements, the Lamborghini Sesto Elemento was able to keep its curb weight under 1000 [kg]. The same principle was applied on the Aventador. However, these cars have aluminum subframes. One of the first roadsters with a carbon bathtub, the Murcielago, demonstrated that the required torsional stiffness could only be achieved by high-end composites [62].

Fig. 7-4: Carbon bathtub Lamborghini cars: (a) Sesto Elemento, (b) Aventador structure, (c) Murcielago. Source: Lamborghini.

The concept of aluminum help frames was not used in the Porsche Carrera GT that employed a full composite structure for both the bathtub and the upper part of the engine bay spaceframes. Another concept has been added by Pagani where the stressed engine contributes to the overall stiffness (an idea from formula 1 cars).

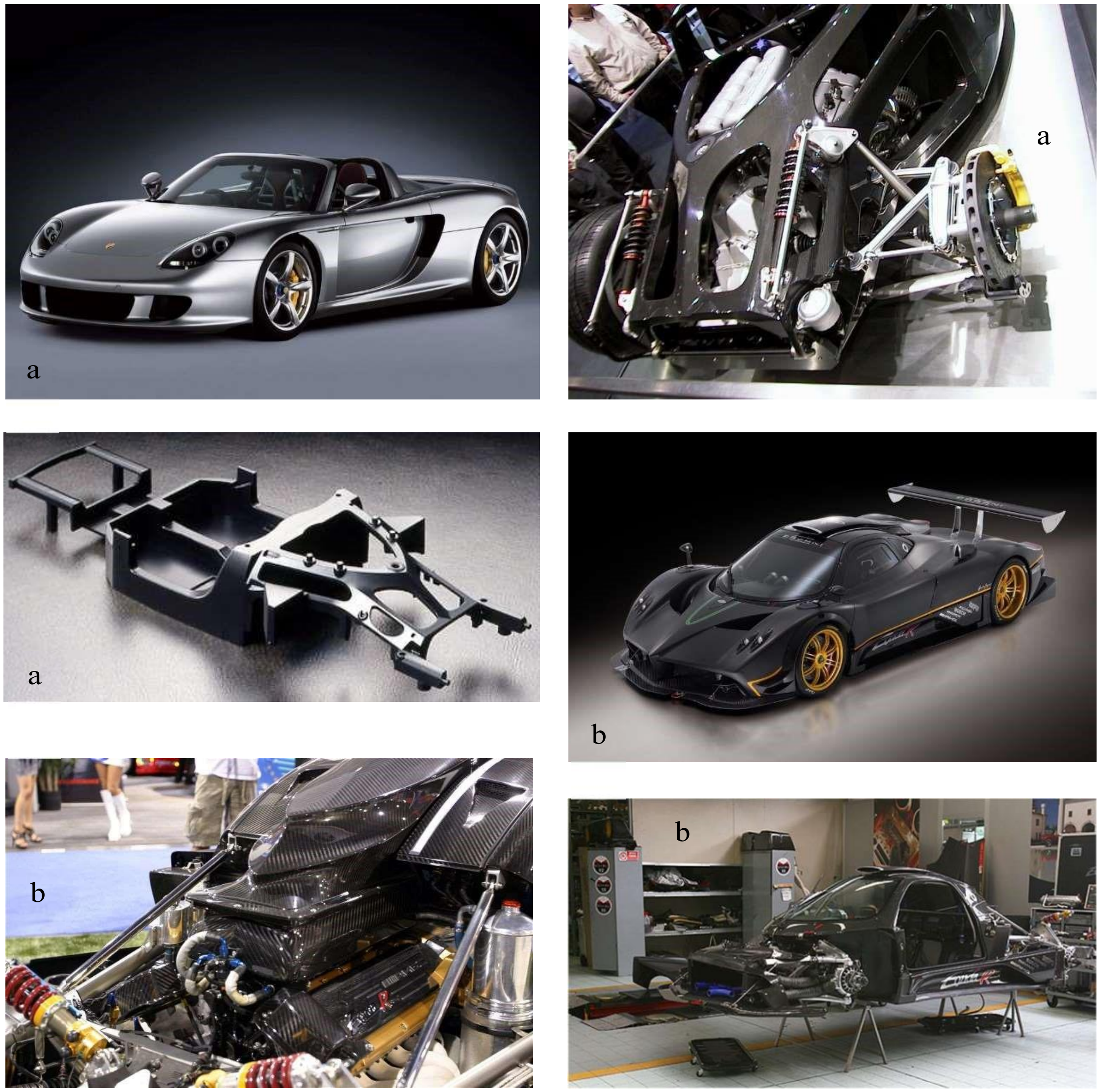

Fig. 7-5: Porsche Carrera GT (a) and Pagani Zonda (b) composite structures. Sources: Porsche, Pagani.

Leaving the exotic car segment (at least, partially), BMW was the first manufacturer to apply full-carbon body shells to production cars. The i3 is fully electric while the i8 is a hybrid. They are both manufactured by RTM (Resin Transfer Molding) techniques that are based on special resin formulations for short cycle times. Having an in-house carbon supplier, BMW managed to limit the selling price to affordable numbers for their class.

By approaching more reasonable pricing levels, Alfa Romeo was the first to launch a full carbon composites car for the public, with a horsepower to weight ratio of only 4 [kg/ps]; for 240 [ps] the weight becomes only 960 [kg].

Fig. 7-6: BMW i3,(a), i8 (b) and Alfa Romeo 4C. Sources: BMW, Alfa Romeo.

7.2.6 Latest Trends and Developments

The article [65] contains a thorough description of emerging trends in automotive composites with a focus on natural fibers and their application, hybrid materials, and cellulose microfiber hybrid composites. These have successful been applied as demonstrators for engine/cam covers and oil pans by the University of Toronto.

In [72], novel, cost effective enhancements on Resin Transfer Molding techniques (RTM) are presented like the high-pressure and compression variants, complemented with Reaction-Injection Molding. A comprehensive cost-effectiveness study, in comparison with other techniques as well, is presented in conjunction with quality assessments in terms of warpage, void formation and suitability for assembly. An original idea in this paper is the application the filament joining techniques for space frames.

In [86], the authors provide an extensive review of materials, processes and related challenges regarding additive manufacturing as a means to produce automotive parts. After the outline of the mechanical and thermal operation ranges for automotive body parts, the authors proceed to a comprehensive comparison of 4 additive manufacturing techniques:

- Powder bed fusion
- Material extrusion
- Material jetting
- VAT photopolymerization

Mechanical properties, temperature ranges, costs and compatibility ranges are systematically presented. It is then concluded that the material jetting and material extrusion techniques do not provide sufficiently performing artefacts unless reinforced with fibers. In addition, the authors point out the limited choice for high-performance materials.

In [61], a JEC innovation award for glass fiber-reinforced thermoplastic sunroof guide rails has been awarded to a Dutch company, Polyscope. Their 15% glass-reinforced copolymer was chosen by Webasto France as the material to make guide rails for the Renault Scenic and Grand Scenic. Before this, Polyscope was able to realize thermoplastic roof rails for the DS3 cabrio.

A state-of-the-art overview is provided in [52] where the authors do not limit themselves to cars but also to hybrid concepts. In this article, recent successes with composites are outlined:

- Jaguar F-type bumper and undercover (in production).
- Damen marine interceptor (in production).
- Frank Rinderknecht’s Rinspeed Splash (successfully tested).
- Velomobile of the Slovak company Aeromobil (recent successful maiden flight).
- PAL-V velomobile (preproduction stage).

In a dedicated article[16], an extensive interview with a Mercedes AMG representative is presented on carbon composites in automobiles. In addition, the authors mention the transition from steel belts to aramid fibers (Twaron, Kevlar) as a means for lighter tires with increased puncture resistance for the Dunlop company.

In regard to heavy transport, a recent success in The Netherlands has been the development and production of a full composite ISO tank-container for maritime and road transport [45]. This tank is based on optimal Isotensoid shapes and fast filament winding. The company CPT has launched this innovative tank nearly a decade ago. After thorough certification procedures, CPT has nowadays a considerable market share and full production capabilities. In the table below, the benefits of composites become clear[17]:

Table 7-2: Performance of steel and composites for a 20 feet container under 2.5 [bar] pressure

	Weight including insulation, appendages and frame kg]	Relative Costs

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[16] https://www.automotivemanufacturingsolutions.com/composites-in-carmaking/6691.article

[17] This design is strength-dominated, the benefits of glass fiber composites would otherwise be marginal.

Steel	3800	1
Glass fiber/ Vinyl ester	2500	1- 1.2
Aramid fiber/ Epoxy	1500	1.4
Carbon fiber/ Epoxy	1500	1.3

Fig. 7-7: The CPT tank container: Winding process and finished product including frame appendages and insulation.

The project was not entirely novel in its intentions; prior to this success, a two-decade period of failed attempts was not very encouraging. However, by the combination of optimal design, maximized fiber performance and dedicated, accelerated production processes, these barriers were successfully overtaken.

In [46], the latest developments by Porsche in light weighting are highlighted: a full composite brake pedal is the first one to break with the stringent requirements that do only accept forged metal ones. Other breakthroughs are the internal glass-fiber reinforced rhomboid structures in A-pillars, 3D printed complex shapes, lightweight interior glass, and Laser-cut micro structured cores for electric motors. Next, for a convenient helicopter view on automotive composites, [69] is a proper reference work.

A very interesting and illustrative article, published by Composites World, does outline the very latest developments [25, 65]:

- Third row seatback by Toyota.
- Composite tension leaf spring by Mubea.
- Full composite glass fiber panels for the 2020 Corvette.

- Rea suspension knuckle by Ford.
- SMC steering knuckle by Magneti-Marelli.
- Hybrid carbon fiber/aluminum suspension knuckle by Saint Jean Industries.
- Carbon fiber/epoxy suspension links, press-formed over aluminum by Shape Machining Ltd.
- CFRP stabilizer bars by IFA Composite.
- Carbon fiber reinforced wishbones made in 90 seconds by Williams Advanced Engineering.
- Carbon fiber reinforced output (propeller) shaft by Dynexa.

In the same Composites World article, the presentation of recent advancements in Sheet Molding Compound processes that enable density numbers close to 1 [kg/m^3] and production times in the order of seconds, is complemented with an extensive outline of natural fiber composites and the latest developments in affordable, fast-produced carbon fiber panels. Notably, the article states that pultrusion and tape laying are currently obtaining a larger role as light weighting manufacturing processes. Overwound aluminum or LFT beams are also mentioned. Another very interesting but still experimental technique is the 3D printing of space frames for seats on specialized molds. As a last item, the article mentions increased use of natural fibers composites beyond interior parts as they are now entering exterior applications.

8 Conclusions and Recommendations

The main objective of the Interreg Rightweight project, a European Regional Development Fund opportunity for North-West Europe and Italy [70], is the reduction of CO_{2e} emissions for land and air transportation by light weighting. The corresponding voucher scheme allows for SMEs to allocate budget at research institutes and field labs to solve actual problems as detected and proposed by the so-called champions, the main companies in aircraft and automobile manufacturing, among key suppliers.

In the framework of this project, an extensive assessment regarding possible technology transfer between the aerospace and automotive sectors was regarded as essential. The main question was rather simple: how can both sectors benefit from each other in terms of technology transfer and beyond: design and certification philosophy, materials development and selection, design optimization and testing, production organization and manufacturing principles.

To thoroughly assess possible technology transfer manners, the current emission reduction requirements have been analyzed in conjunction with elaborations on the industrial landscapes in aerospace and automotive, in terms of markets, employed materials and principles, and manufacturing practices. The main argument in this project, the fact that weight reduction contributes to CO_{2e} cutdown for land and air transportation, is then demonstrated by not only generic numbers, but also in terms of concrete examples. Thereafter, the interaction between design, materials, and related production processes has shortly been elaborated in terms of structural efficiency and expected costs. As composites turned out to be among the best candidates for weight reduction, in the main chapter regarding auto-aero technology transfer, these materials attained a short description in terms of production technology (other properties have been outlined in the previous chapters). The aero-to-auto technology transfer areas have then be presented in terms of the main automotive sub-structures: Powertrain, body-in-white, suspension and steering, braking system, body in white etc. Special emphasis has been directed towards hydrogen containment as an alternative for batteries. For the auto-to-aero transfer, the areas of automated, Artificial Intelligence-assisted production, Extensive standardization, extended part suppliers biotope and lean manufacturing principles have been identified as suitable opportunities. In the last chapter, several technology transfer-examples have been given, mainly focused on composites, for which a list of main suppliers is provided. After the outline of several successful technology transfer cases in terms of safety systems and novel materials, the chapter concluded with recent trends and developments.

The first main conclusion of this report is that weight reduction can indeed lower CO_{2e} emissions; while the reduction numbers per automotive kilometer or passenger-kilometer (aircraft) do not impress at a first glance, the savings per year of operation become significant:

- Airbus A320, 100 [kg] less -> Savings per year = 19000 [kg] less kerosene or 57000 [kg] less CO_{2e}.
- Renault Clio, 15000 [km/year] and 95 [g] CO_{2e} per [km] . 100 [kg] less -> 8.5 [g] less CO_{2e} per [km] (from 26 [km/liter] to 28.6 [km/liter]). Savings per year = 52.7 liters or 130 [kg] CO_{2e}.

The second main conclusion is that alternative materials, in conjunction with tailored production processes, can indeed realize significant weight savings. However, geometric, manufacturing, functionality and joining issues will add to the resulting theoretical weight as anticipated by the basic Design Efficiency Indicators. In the table below, it is anticipated that these effects will knock down the weight saving potential by 50% (pessimistic scenario). For composites, the highest values correspond to pure fibers; the lowest ones represent of quasi-isotropic fabric with 40 to 50% fiber volume fraction. For non-critical sub-structures, the savings will obviously become larger.

Table 8-1: Weight saving potential numbers of various materials for primary structures with 50% discount in efficiency due to joining and manufacturing defects.

Knock down factor for theoretical values = 2: only 50% of the predicted weight reduction potential can be preserved	Density [kg/m^3]	Stiffness [GPa]	Tensional Strength [MPa]	Specific stiffness [mm^2/s^2]	Specific tensional strength [mm^2/s^2]	Relative material price	Percentage of original weight that can be canceled, based on stiffness	Percentage of original weight that can be canceled, based on strength
Steel	7800	210	250-400	26.92	0.03-0.05	1	ref	ref
Aluminum	2700	70	200-300	25.93	0.07-0.11	4-12	0	15-35%
Glass composites	2000	25-45	700-3000	12.5-22.5	0.35-1.50	3-7	0	30-45%
Aramid composites	1500	35-110	1000-3000	23.3-73.3	0.67-2.00	15-30	0-30%	20-50%
Carbon composites	1800	70-240	1000-4000	38.9-133	0.55-2.22	15-25	15-40%	30-50%

To provide an order of magnitude for weight savings, the potential reduction for a premium class SUV can ultimately reach 100 (small adaptations) to 300 [kg] (full carbon body). For aircraft, as recently demonstrated by Boeing and Airbus, the weight reduction can be in the order of 20 to 30% as compared to the original aluminum aircraft.

The third main conclusion is that, despite the weight saving potential, the levels for additional pricing are very tight in the automotive industry: 7 to 8 € per kilogram, while the aerospace industry is prepared to pay 800 € per saved [kg]. It is therefore essential to lower the prices of raw materials for lightweight solutions by improved production processes, dedicated design methods and mass production. Another important issue that needs resolving is the improvement of joints (mechanical and fusion-based) for reliable load transfer in primary structures (like composite wishbones).

The last main conclusion is that the possibilities in technology transfer between the automotive and the aerospace sector are indeed present, but mainly in terms of aero to auto streams. Regardless, with a synergistic co-development of lightweight solutions, it is believed that the issues of high material costs and limited availability can gradually be resolved. When people claim that carbon is expensive because of the 3-kilometer plants they need, the author always replies with the message ‘oh, the same as for steel production‘.

Finally, the recommendations, as deducted from the inhibiting factors for further transportation light weighting, can be formulated as follows:

- Increase awareness of lightweight materials by low threshold workshops, in particular regarding mechanics, production technologies and advantages/ drawbacks.
- Cross-link advanced materials supply chains over the automotive and aerospace sectors to increase availability and variability in suppliers, thus enhancing competition.
- Increase auto-aero synergy in early development phases.
- Provide accessible and affordable engineering and field lab services to enhance low risk design options for both the automotive and aerospace industry.

Technological areas that require increased attention are:

- Mass production of affordable fibers and polymers.
- Reduced cycle times.
- Maximized part integration.
- Fast and high-load-bearing capability joining.
- Improved thermoplastic welding techniques (both permanent demountable).
- Means for electro galvanic compatibility.
- Application of fully recyclable materials.

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9 References

1. Aerospace Export. Main Tier 1 Companies. https://aerospaceexport.com/main-tier-1-aerospacecompanies/

2. Airbus. Global Market Forecast 2019-2038. Airbus Europe. https://www.airbus.com/aircraft/market/global-market-forecast.html

3. Anonymous: Aerospace Composites Market 2020. Report ID 5130161, July 2020. https://www.researchandmarkets.com/reports/5130161

4. Ashby M. Materials Selection in Mechanical Design. Second edition, Butterworth-Heinemann, Oxford, 1999.

5. Automotive News. Top Suppliers: Europe, America, and the World. https://www.autonews.com/assets/PDF/CA89220617.PDF

6. Bachmann J., Xiaosu Yi, Hugh Gong, Xavier Martinez, Gabriel Bugeda, Sergio Oller, Konstantinos Tserpes, Eric Ramon, Christophe Paris, Pedro Moreira, Zhengping Fang, Yan Li, Yanfeng Liu, Xiaoqing Liu, Guijun Xian, Jianfeng Tong, Jiahu Wei, Xufeng Zhang, Jin Zhu, Songqi Ma & Tao Yu, . Outlook on Ecologically improved Composites for Aviation Interior and Secondary Structures. CEAS Aeronautical Journal, 9 533-543 (2018).

7. Bailey J. Airbus A250 Break Even Target Achieved in 2019. News item, February 2019. https://simpleflying.com/airbus-a350-break-even/

8. Banik N. (2018). A review on the Use of Thermoplastic Composites and their Effects in Induction Welding Method. Materials Today: Proceedings 5 (2018) 20239–20249.

9. Beukers A., Hinte van, E. Lightness: the Inevitable Renaissance of Minimum Energy Structures. Fourth, revised dition, 010 Publishers, Rotterdam, 2005.

10. Blomaard S. Automation for Mandrel Built Products Not Possible? News item, February 2012. https://static1.squarespace.com/static/568b88c87086d7219d11953a/t/57334b0ff8508218bba3ac99/1462979343717/TANIQ-Automation-of-mandrel-built-products.pdf

11. Boyer R.R., Cotton J.D., Mohaghegh M. Schafrik R.E. Materials Considerations for Aerospace Applications. Cambridge University Press, 2015).

12. Brembo. Carbon-Ceramic Discs: High Performance, Minimum Weight. https://www.brembo.com/en/car/original-equipment/products/carbon-ceramic-discs

13. Bruijn de, T. Rotorcraft Access Panel from Recycled Carbon PPS–The World’s First Flying Fully Recycled Thermoplastic Composite Application in Aerospace. Reinforced Plastics 65 (3), 2021.

14. Carpenter J.A., Jr. Challenges and Opportunities for Automotive Composites. Presentation. SPE Automotive Composites Conference and Exhibition (ACCE). MSU Management Education Center, Troy, MI, September 16, 2008.

15. Chirag Moro. Different Materials used in the Making of our Cars. News item, February 2021. https://www.team-bhp.com/news/different-materials-used-making-our-cars

16. Ciftci B. Break Even Point for the US Domestic Auto Industry. News item, January 2010, https://ezinearticles.com/?Break-Even-Point-For-The-US-Domestic-Auto-Industry&id=3511968

17. Composites Today: Automotive News. 2021. https://www.compositestoday.com/category/automotive/

18. Da Silva, F.M., Ochsner A., Adams R.D. (2011). Handbook of Adhesion Technology, Vol. 2. SpringerVerlag, Berlin-Heidelberg.

19. Daniel I.M., Ishai O. Engineering Mechanics of Composite Materials. Second Edition, Oxford University Press, Oxford - New York, 2006.

20. Delft University of Technology. Flex, Sag and Wobble: Stiffness-Limited Design. Open Courseware, September 2011. https://ocw.tudelft.nl/wpcontent/uploads/Materiaalkunde_1_slides_chapter5.pdf

21. Devic A.C., Ierides M., Fernandez V., Verbenkov M., Bax L. Polymer Composites Circularity. White paper. European Technology Platform for Sustainable Chemistry. www.suschem.org

22. European Commission. Greenhouse Emission from Transport in Europe, 2021. https://www.eea.europa.eu/data-and-maps/indicators/transport-emissions-of-greenhouse-gases7/assessment

23. European Commission. Reducing Emissions from Aviation. https://ec.europa.eu/clima/policies/transport/aviation_en

24. European Commission: Horizon Europe Work Programme 2021-2022: 7. Digital, Industry and Aerospace, 2021. https://ec.europa.eu/info/funding-tenders/opportunities/docs/2021-2027/horizon/wp-call/2021-2022/wp-7-digital-industry-and-space_horizon-2021-2022_en.pdf

25. Gardiner G. The Markets, Automotive (2021). News item. Composites World, 2020. https://www.compositesworld.com/articles/the-markets-automotive

26. Gondaliya R. Improving Damage Tolerance of Composites Sandwich Structure Subjected to Low Velocity Impact Loading. Conference Proceedings, 31st American Society for Composites Conference, Williamsburg, VA, 2016.

27. Granta corp. Material and Process Selection Charts. CES Edupack presentation, 2010. http://users.fs.cvut.cz/libor.benes/vyuka/engineeringmaterials/2-Materials-Charts-2010.pdf

28. Granta corp. Material Property Charts. https://www.grantadesign.com/education/students/charts/

29. Gurit Company. Guide to Composites. Publication ID: GTC-6-0417-1. www.gurit.com

30. Gutowski W., Weidong Yang, Sheng Li, dean K. Lightweight Nanocomposite Materials. Chapter in book: Lightweight and Sustainable Materials for Automotive Applications (pp. 277-302), 2017.

31. Hale J. Boeing 787: From the Ground Up. QTR_04 06. Quarterly Publication, www.Boeing.com/commercia/aeromagazine (% materials)

32. Holmes M. Aerospace Looks to Composites for Solutions. Reinforced Plastics, Vol. 61, Number 4, July/ August 2017.

33. Ijsselmuiden, Samuel & Abdalla, Mostafa & Gürdal, Z. Thickness Tailoring of Variable Stiffness Panels for Maximum Buckling Load. ICCM International Conferences on Composite Materials, 2009.

34. International Council on Clear Transportation. Air pollution From the Main Sources - Air Emissions from Road Vehicles, https://ec.europa.eu/environment/air/sources/road.htm

35. Jin Zhang, Venkata S. Chevali, Hao Wang, Chun-Hui Wang. Current Status of Carbon Fiber Composites Recycling. Composites Part B 193 (2020) 108053.

36. Jong, de, Th. On the Calculation of Stresses in Pin-Loaded Anisotropic Plates. PhD. thesis. Faculty of Aerospace Engineering, Delft University of Technology, Delft, 1987.

37. Kamali G., Ashokkumar N., Sugash K., Magesh V. Advanced Composite Materials of the Future in Aerospace Engineering. International Journal of Research in Applied Science and Engineering, Vol. 2, Issue 2, February 2017.

38. Kassapoglou Ch. Design and Analysis of Composite Structures: With application to Aerospace Structures. Wiley, West Sussex, 2010.

39. Kaw A.K. Mechanics of Composite Materials. Second Edition. Taylor & Francis, Boca Raton, 2006.

40. Kollar L., Springer G.S. Mechanics of Composite Structures. Cambridge University Press, New York, 2003.

41. Komornicki J., Bax L., Vasiliadis H., Magallon I., Ong K. Polymer Composites for Automotive Sustainability. Report: European Technology Platform for Sustainable Chemistry, December 2015, http://www.suschem.org/publications.aspx

42. Koussios S. Fiber-Reinforced Materials in Aerospace Structures. Lecture Notes. Faculty of Aerospace Engineering, Delft University of Technology, 2018.

43. Koussios S. Filament Winding: a Unified Approach. PhD Dissertation. Faculty of Aerospace Engineering, Delft University of Technology. 2004.

44. Koussios S., Paeshyuse L., Ridolfi G. Beukers A. Fully Integrated Composite Exhaust System. In: Proceedings of the SAMPE Conference, Baltimore MD, 2012.

45. Koussios S., Wentzel C. Design and Production of Full-Composite Tank Container for Road Transport. Internal report. Faculty of Aerospace Engineering, Delft University of Technology, 2013.

46. Krotz R. Materials of the Future. Review article. Porsche A.G. ,https://www.porsche.com/international/aboutporsche/christophorusmagazine/archive/385/articleoverview/article02/

47. Kunzwa L. Aircraft Manufacturing. Lecture slides, University of Hertfordshire, January 2020.

48. Lekhnitskii S.G. Anisotropic Plates, 2d ed., S.W. Tsai and T. Cheron, trans., Gordon and Breach Science, New York, 1968.

49. Lobner P. The Airflow Truck Company Concepts and Test Trucks. News item, April 2020, https://lynceans.org/wp-content/uploads/2020/04/AirFlow-Truck-Company-converted.pdf

50. Low8: The Next Generation of Composites LPG Cylinders, https://www.low8.com/

51. Lucintel Company: European Automotive Composites Market Report: Trends, Forecast and Competitive Analysis. Report ID: 5006315, March 2020.

52. Mathijsen D. What Does the Future Hold for Composites in Transportation Markets? Reinforced Plastics, Vol. 61, Nr. 1, January/ February 2017.

53. Mazareanu E. Size of Aircraft Fleets by Region Worldwide in 2019 and 2039. News item, Statista, 2020, https://www.statista.com/statistics/262971/aircraft-fleets-by-region-worldwide/

54. Mazareanu E. Worldwide Numbers of Airbus Aircraft deliveries from 2002 to 2020. News item, Statista, https://www.statista.com/statistics/264493/airbus-worldwide-aircraft-deliveries/

55. Mazumdar S. Driving Fuel Efficiency in the Automotive Industry Using Composites. Presentation: Composites Europe 2015, www.lucintel.com

56. Mazumdar S.K. Composites Manufacturing. CRC Press, Boka Raton, 2002.

57. Meysam Toozandehjani, Nuruldiyanah Kamarudin, Zahra Dashtizadeh, E. Yee Lim, Ashen Gomes, Chandima Gomes. Conventional and Advanced Composites in Aerospace Industry: Technologies Revisited. American Journal of Aerospace Engineering, 5(1):9-15, 2018.

58. Milberg E. History of Automotive Composites. News item, https://www.sutori.com/story/history-ofautomotive-composites--1yJrnDNy2bwyet92mgYPVa47

59. Military Handbook 17 (1994). Department of Defense Handbook. USA, 1994.

60. Miracle D.B., Donaldson L. ASM Handbook 21: Composites. ASM International, 2001.

61. Nickels L. New Innovations in Automotive Thermoplastics. Reinforced Plastics, Vol. 63, Nr. 4, July/ August 2019.

62. NLR. NLR Develops Composite Components for Lamborghini. News item, June 2011, https://www.nlr.org/news/nlr-develops-composite-components-for-lamborghini/

63. Oudheusden van, A.A. Recycling of Composite Materials. Report. Faculty of Industrial Design Engineering, Delft University of Technology, 2010.

64. Panopoulos S. Project 'Chaos', https://www.spyrospanopoulos.com/

65. Pervaiz M., Panthapulakka S.,Birat K.C., Sain M., Tjong J. Emerging Trends in Automotive Lightweighting through Novel Composite Materials. Materials Sciences and Applications, 2016, 2638.

66. Plastics.gl. Composite Coil Spring for Automotive Suspension System, https://www.plastics.gl/automotive/composite-coil-springs-for-automotive-suspension-systems/

67. Pruncu C.I., Gurgen S., Hoque E., Eds. Fiber-Reinforced Polymers: Processes and Applications. Polymer Science and Technology Series, Nova Science Publishers, New York, 2021.

68. Reurings, C., Koussios, S., Bergsma, O. K., Breugem, W. P., Vergote, K., Paeshuyse, L., & Benedictus,
R. The Influence of a Porous, Compliant Layer with Overlying Discrete Roughness Elements as Exhaust Pipe Wall on Friction and Heat Transfer. Heat and Mass Transfer/Waerme- und Stoffuebertragung, 56(8), 2367-2387, 2020. https://doi.org/10.1007/s00231-020-02855-4.

69. Reux F. (Media Director & Editor-in-Chief). The Global Composites Market. JEC Group Presentation February 9, 2017 -Nantes.

70. Rightweight Internet Site. https://www.rightweightnwe.com/home

71. Ritchie H. Cars, Planes and Trains: Where do CO_2 Emissions from Transport Come from? Our world in data, 2020, https://ourworldindata.org/co2-emissions-from-transport

72. Salman Sarfraz M., Hong H., Kim S.S. Recent Developments in the Manufacturing Technologies of Composite Components and their Cost-Effectiveness in the Automotive Industry: A review Study. Composite Structures, 226 (2021) 113864.

73. Savin G.N. Stress Concentrations around Holes. Pergamon Press. Oxford, 1961.

74. Schlosser A., Knab D., Samih Coskun Baban, Seidel Ph.,Knoblinger Th., Lok C. After the Hype: Where is the Carbon Car? News item, 2019, https://www.adlittle.com/en/insights/viewpoints/after-hypewhere-carbon-car

75. Shebab E., Wasim A. Manufacturing Cost Modelling for Aerospace Composite Applications. In: Stjepandic J. et al. (Eds.) Concurrent Engineering Approaches for sustainable Product Development in a Multi-Disciplinary Environment. Springer Verlag, London, 2013.
76. Sloan J. The Markets: Aerospace (2021). News item, Composites World, https://www.compositesworld.com/articles/the-markets-aerospace-2021

77. Smith F. The Use of Composites in Aerospace: Past Present and Future Challenges. Presentation. Avalon Consultancy Services Ltd., 2013.

78. Statista Research Department: Estimated Worldwide Motor Vehicle Production Between 2017 and 2020, by Type. News item, 2021, https://www.statista.com/statistics/1097293/worldwide-motorvehicle-production-by-type/

79. Statista Research Department: Motor Vehicle Production Volume Worldwide in 2020, by Country. News item, 2021, https://www.statista.com/statistics/584968/leading-car-manufacturing-countriesworldwide/

80. Tapeinos I. Multi-Spherical Composite-Overwrapped Cryogenic Fuel Tanks for Hypersonic Aircrafts. PhD Thesis, Faculty of Aerospace Engineering, Delft University of Technology, 2019.

81. Teijin Aramid. Twaron Drives Tires, https://www.teijinaramid.com/wpcontent/uploads/2011/08/Teijin-Aramid-Whitepaper-Twaron-drives-tires.pdf

82. Terdu J. Design of an Affordable High-Performance CompositeCchassis., MSc. Thesis, Faculty of Aerospace Engineering, Delft University of Technology, 2011.

83. Vagman T. Automotive Manufacturing: Processes Overview. Hexagon presentation, Directory Product Strategy, 2013, https://www.slideshare.net/TalVagman/automotive-manufacturingprocess-overview

84. Vasiliev V.V. Morozov E.V. Advanced Mechanics of Composites Materials. Second Edition, Elsevier, Oxford-Amsterdam, 2007.

85. Vasiliev V.V., Jones R. (editor). Composite Pressure Vessels: Analysis, Design, and Manufacturing. Bull Ridge Publishing, Blacksburg VA, 2009.

86. Wiese M., Thiede S., Herrmann Ch. Rapid Manufacturing of Polymer Series Parts: A Systematic Review of Processes, Materials and Challenges. Additive Manufacturing 36 (2020) 101582.

87. Wikipedia. List of Carbon Fiber Monocoque Cars. https://en.wikipedia.org/wiki/List_of_carbon_fiber_monocoque_cars

88. Witten E., Sauer M., Kuhnel M. Composites Market Report 2017. German Federation of Reinforced Plastics, September 2017.