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Affordable Multi-Material Lightweight Design - Selected Results of the H2020 Project ALLIANCE

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Abstract

In the last years, the research activities in the field of lightweighting have been advancing rapidly. The introduction of innovative materials and manufacturing technologies have allowed significant weight reduction. Despite this, novel technologies and materials have not reached a wide distribution. The reasons for this are mainly high production costs and environmental impacts of manufacturing that do not compensate benefits during operation.

The paper will discuss selected final results of the H2020 project AffordabLe LIghtweight Automobiles AlliaNCE (ALLIANCE, www.lightweight-alliance.eu) which has the goal of developing novel advanced automotive materials and production technologies, aiming at an average 30% weight reduction over 100k units/year, at costs of < 3 €/kg-saved. An overlook of the realized demonstrators will be given and the applied new materials and manufacturing technologies discussed. A special focus will be put on how the different concepts, materials and manufacturing technologies have been evaluated regarding GWP and costs.

Keywords: lightweighting, multi-material, manufacturing, LCA, full vehicle modelling, conceptual design

Nomenclature

BiW	Body-in-White	LCC	Life-cycle costs
ETWA	Extended Target Weighing Approach	NEDC	New European Driving Cycle
FLC	Forming Limit Curve	Q&P	Quenching & Partitioning (heat treatment)
(G)FRP	(Glas) Fiber Reinforced Plastic	TTW	Tank-to-Wheel
GWP	Global Warming Potential	WLTC	Worldwide Light Duty Test Cycle
LCA	Life-cycle assessment	WTT	Well-to-Tank

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1. Introduction

Car mass has continuously increased in the past decades due to the ever-increasing demands for safety, performance, comfort, reliability and other vehicle characteristics. The compliance with these requirements makes that new cars have more numerous and more complex parts with respect to previous vehicles generation. As the components are mutually dependent on each other, the addition of several parts involves secondary mass increases thus causing a spiral effect that makes the weight even higher. Against this background, lightweighting has been unanimously recognized as one of the key design strategies for achieving a wide range of both technical, economic and environmental advantages:

- improvement of driving behaviour, performance and comfort level;
- reduction of both cost and environmental impact due to lower use stage energy consumption;
- easier handling of parts and components during production and maintenance activities.

Research and industry have proposed a broad series of innovative lightweight solutions based on steel, aluminium, composites and hybrid materials. Most of efforts though have typically failed to adequately and comprehensively address the high cost issue of the innovative solutions. The excessive cost is caused by many factors, ranging from the considerable value of base materials, long cycle times, substantial investments for new machineries, to the modification of well-established manufacturing, assembly and supply chain processes.

Additional costs due to lightweight design might be accepted by the customer if the total cost of ownership is reduced (e.g. by lifetime fuel saving in case of conventional and hybrid drive trains). One challenge of the next decade is bringing down the production costs of the multi-material design to a level of singular steel and aluminium design. Besides, the availability of materials required for multi-material design, new demands for those materials coming from other markets, materials price instability and the competitive international context must be taken into account by selecting the right strategy for lightweight design (Bein et al., 2016). Therefore, the choice of material mix in the vehicle and the associated manufacturing processes must not only be determined by the costs but also by the CO_2 footprint over the entire life-cycle.

Within this context, the European Research Project AffordabLe LIghtweight Automobiles AlliaNCE (ALLIANCE, www.lightweight-alliance.eu) was initiated aiming at developing novel advanced materials (steel, aluminum, hybrid materials) and production technologies to achieve an average weight reduction of 30 % over 100k units/year, at costs less than 3 €/kg-saved and 6 % Global Warming Potential (GWP) reduction. This paper presents selected final results of the project ALLIANCE.

2. About ALLIANCE

The ALLIANCE project is composed of six European car manufacturer, four suppliers and eight knowledge partners (engineering services, SMEs, RTOs and universities) which have joined forces to foster the implementation of innovative lightweight technologies in series application. To reach the aforementioned targets, ALLIANCE developed advanced steel and aluminium alloys, such as high strength/high formable 6000 and 7000 series aluminium alloys and composites reinforced with glass fibres, as well as innovative steel sandwich materials. The project optimized these materials to become suitable for innovative manufacturing technologies such as

- production sequence for tailored extruded aluminium blanks with variable thickness;
- simultaneous forming of metal and FRP hybrids;
- one-step process combining injection moulding with Water Injection (WI) for the creation of braided, thermoplastic, glass fibres-reinforced hollow parts in high volume.

The manufacturing parameters have been adapted to leverage the particular properties of new materials while new technologies will enable the development of complex and tailored parts in high volume production. Joining technologies play a crucial role especially in hybrid design. To enable suitable assembly of car components made of innovative materials, the development of cost efficient joining methods at high volumes is required. Within the ALLIANCE project, a limited number of best promising joining technologies have been selected:

- self-piercing rivets combined with adhesive bonding;
- remote laser welding;
- friction-based methods (including friction element welding).

Besides, a holistic design and optimization methodology has been developed that balances cost, weight and CO_2 impact. This methodology was used for identifying the optimum solution for re-engineered demonstrator modules depending on module function as well as vehicle segment. In total, the six OEMs developed eight optimised demonstrator modules, which were very close to those from current series vehicles. Some demonstrators are fabricated physically and used for the validation of the advanced materials and manufacturing technologies developed in ALLIANCE, while some others are used as design and optimisation exercises to validate the respective new methodologies and tools developed and therefore will only be form "virtual" demonstrators (no physical prototype or testing). The optimised modules have been virtually implemented into a virtual full vehicle reference model derived from the German-funded "Light-eBody" project (see Fig. 1). This model served to analyse the lightweighting innovations at a higher level, as well as to validate the expected impact targets of the lightweighting technologies (energy efficiency, GWP, costs) by using a correlating LCA model. In doing so, two power train variants were considered, an Internal Combustion Engine Vehicle (ICEV) and a Battery Electric Vehicle (BEV).

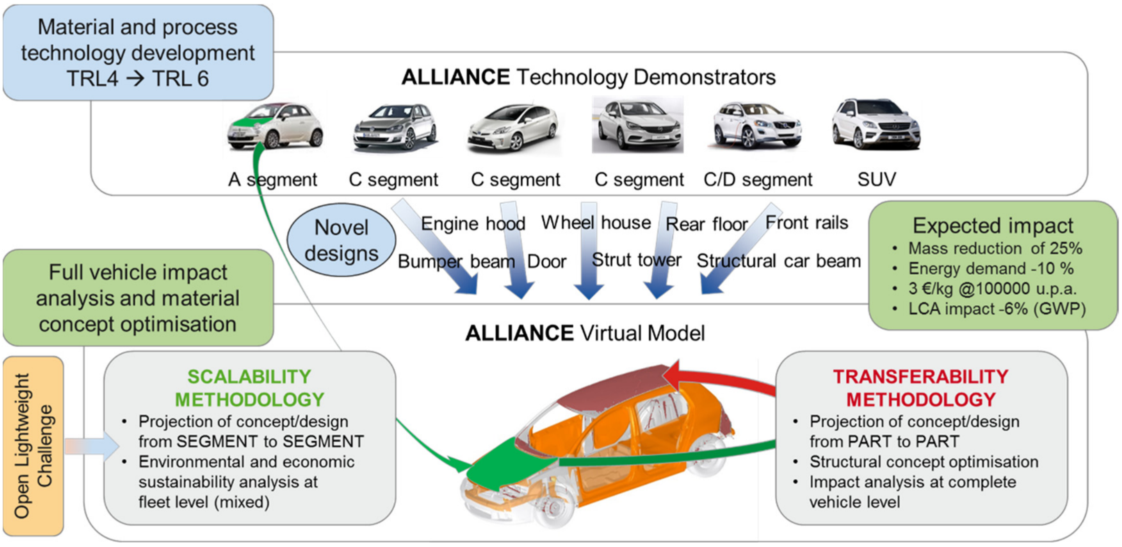

Figure 1 Visualisation of the ALLIANCE transferability and scalability methodologies.

3. Selected Results

3.1 Materials

3.1.1 Steel

Within the ALLIANCE project, novel Q&P steels have been developed. The developed materials belong to the family of Dual Phase steels which are ideally suited for safety and crash relevant components. The Q&P type materials DP-K® 330Y590T and DP-K® 700Y980T were produced in an industrial scale inside the ALLIANCE project and applied to the front bumper beam. The materials represent different strength classes and differentiate additional to their strength by its ductility. The high ductility of the Q&P Steel (A80< 13 %) offers advantages, comparable steels in this strength class have a significantly lower ductility. The high ductility enables the forming processes of complex geometries, which cannot be manufactured with comparable materials in this strength class. The forming limit curve (FLC) of the developed Q&P Steel (DP-K® 850Y1180T-DH) is at the same level as the FLC of the DP-K® 700Y980T and indicates that the Q&P Steel has an out-standing forming behaviour for this strength class. The high ductility increases as well the potential for energy absorption for crash relevant parts like bumper and longitudinal members.

3.1.2 Aluminium

In parallel to steel, high formable aluminium grades have been developed showing improved formability of 8-15% relative to conventional grades (2-4 points of % elongation absolute) and a very significant improvement of behaviour in sharp radii in highly stretched areas (Fusion^{TM} version). The developed high strength 6xxx exhibits a yield strength up to 350 MPa in service. Besides, Fusion^{TM} weldable grades have been developed on the base of both high formable and high strength 6xxx grades, allowing to reduce the sensitivity to hot cracking and facilitating the laser welding (no filler wire required, higher welding speeds achievable, tolerant to some gap between the sheets, allowing for welding closer to the edge). Regarding the 6xxx aluminium, a local softening of 6xxx aluminium extrusions is possible by induction heat treatment. Thus, a remarkable drop in the yield strength of 100 MPa can be realized. It has also been shown that a pre-deformation and/or a specific heat treatment as well as an increase of the Cu content of advanced 6xxx aluminium sheet materials in T4 temper condition causes a higher strength level of the alloys. The formability of such materials in a cold rolled F condition (without a heat treatment in the aluminium plant) reaches the best level immediately after solution annealing and quenching (i.e. when a w-temper condition is created). A natural ageing process decreases the formability level successively before the lowest level of formability is reached in case of forming a T6 temper condition. Thus, the formability decreases continuously and as a result joining and forming operations probably could be more difficult. Additional tests showed, that an artificial aged material (T6 condition) or a material with pre-deformation or a material with a low Cu content tend to be more corrosion resistant than a material in a paint bake condition or a material without pre-deformation or a material with a high Cu content.

3.2 Manufacturing Technologies

Within ALLIANCE various manufacturing technologies have been investigated in view of reducing energy consumption, increasing automation and decreasing cycle times. Among others, an innovative flexible hybrid metal-composites thermoforming process has been considered. The process consist of heating up aluminium sheets together with a thermoplastic material (Fiber Reinforced) and combine them directly into a stamping die with a traditional stamping tooling (see Fig. 2). The process can be suitable for both 5xxx and 6xxx alloy, depending on the final mechanical, or aesthetical component requirements. During the process development, optimal heating time and temperature have been adopted to properly provide higher hybrid sheet formability with surface adhesion. In the experimental campaign a GFRP reinforced sheet has been selected and the wave orientation (which is a key choice for feasibility) has been optimized, finding the 45° orientation for complex 3D component demonstrator as best, to provide enough relative sliding to compensate the lack of elongation with respect the aluminium without continuous fibers break. Nevertheless, during the experimental campaign improving the process from TRL 3 (proof of concept) to TRL 6 (technology demonstrated in relevant environment), a crashforming process (tool die and press without blanckholder) has been adopted. Due to the different materials elongation, shaped sandwich were affected by wrinkling on both aluminium faces, which could be likely avoided with blankholder adoption, to be considered in the final manufacturing process configuration. Further investigation to promote the technology to a TRL 7 (system prototype demonstration) will be focused on aluminium surface treatment to improve adhesion among different layers and improved numerical process simulation model.

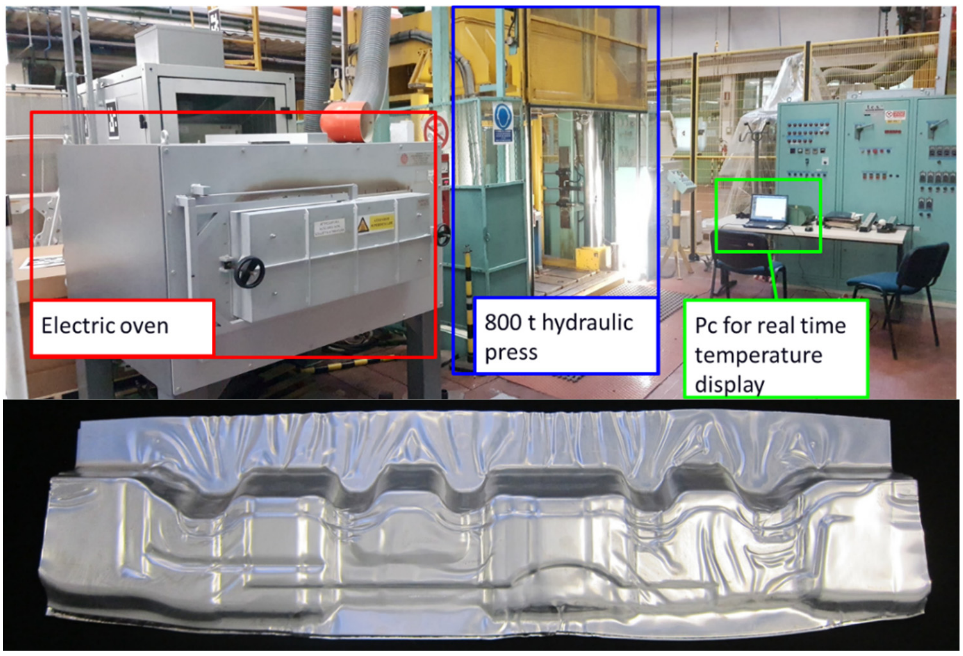

Figure 2 Thermoprocess equipment and selected result of trials.

On the joining technologies side, high-strength aluminium joining has been investigated by mechanical joints (self-piercing riveting and clinching). The process has been optimized by the adoption of specific parameters according the T-Temper heat treatment. However, for more demanding material combinations (Material with low ductility or thin and hard materials) an industrial method for SPR has been developed. This method, called PER (Plug Element Riveting) is based on adding an extra bottom layer in the form of a plug. The inter-locking is then formed in the plug. PER has been tried on many different non-rivetable stacks where the bottom sheet has been too thin or not ductile (see Fig. 3). The process has worked well with very good properties of the joint. Typical joining speed is around one element per sec.

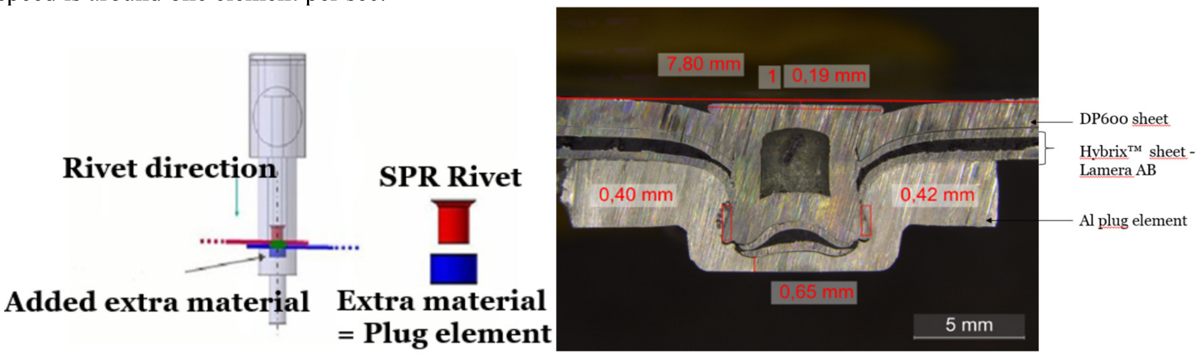

Figure 3 Principles of PER (left) and Example of PER for different materials against CFRP with plug against the bottom sheet of CFRP.

3.3 Design and Optimisation Methodology

In the ALLIANCE project, the so-called Extended Target Weighing Approach (ETWA) has been developed (Albers et al. 2018). It supports the identification and evaluation of lightweight design potentials, in early phases of product development. Systematically, it takes mass, costs and CO_2-emissions into account, with respect to technical uncertainties. The core of the method is the so-called "Function-Effort-Matrix". It assigns the estimated percent-age contribution of one subsystem of the product to the fulfilment of the functions of the considered system. Based on that, mass, costs and CO_2-emissions per function can be determined and search fields for lightweight design potentials can be derived. In these identified search fields, new lightweight design concepts are generated and evaluated.

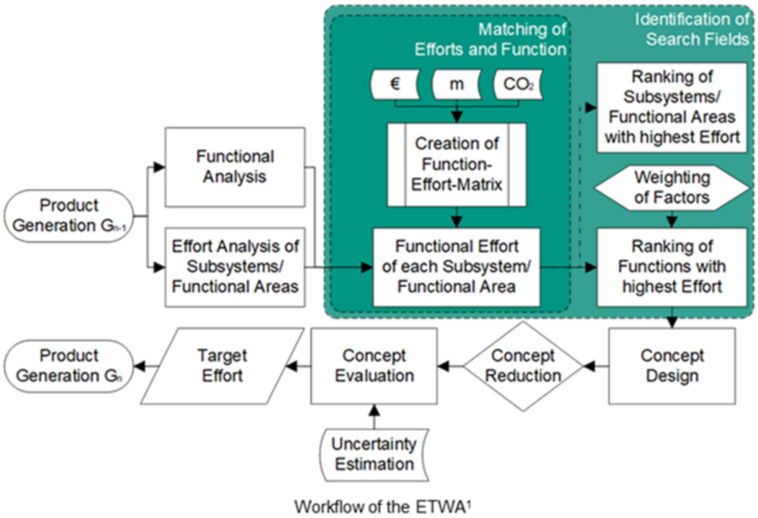

Figure 4 Workflow of the ETWA.

In addition, advanced numerical methods for a fast and efficient concept validation have been developed. These multi-parameter optimization methodologies and tools can be used in the early conceptual design phase as well as in the detailed design of automotive parts and systems. In early design stages, efficient and parametric models provide the opportunity of software based decisions through frontloading and will lead to a reduction of iterations in later development phases. Once a new concept is selected, the design needs to be detailed and optimized again with respects to the desired function, weight, costs and impact on the overall vehicle performance. Such an optimization needs to be done in a holistic approach where multiple parameters need to be considered.

Both, the ETWA approach as well as the multi-parameter optimisation have been applied to the demonstrator modules “strut tower” and “integrated rail” resulting in significant weight saving at even lower costs.

3.4 Design of Demonstrator Modules

Within ALLIANCE, seven physical and one virtual demonstrator(s) were designed mostly in steel and aluminium intensive multi-material approaches as shown in Fig. 5. All demonstrator parts are applications for a specific vehicle project of the related partners (OEMs). That means these parts have to fulfil certain specifications depending on the vehicle projects they are developed for. The demonstrators aim to cover the most characteristic parts “archetypes” in terms of pro-duction method (forming/deep- drawing, extrusion, casting) and the main functions they serve (crash, stiffness, appearance, NVH, etc.). Although the focus within ALLIANCE was on novel steel and aluminium grades, the rear floor pan was considered in reinforced plastic to cover all relevant material mixes of an advanced multi-material design. In the design phase, standard design tools as well as the ETWA was applied to find the optimal concept. Due to the space limit, only selected modules are described in the following.

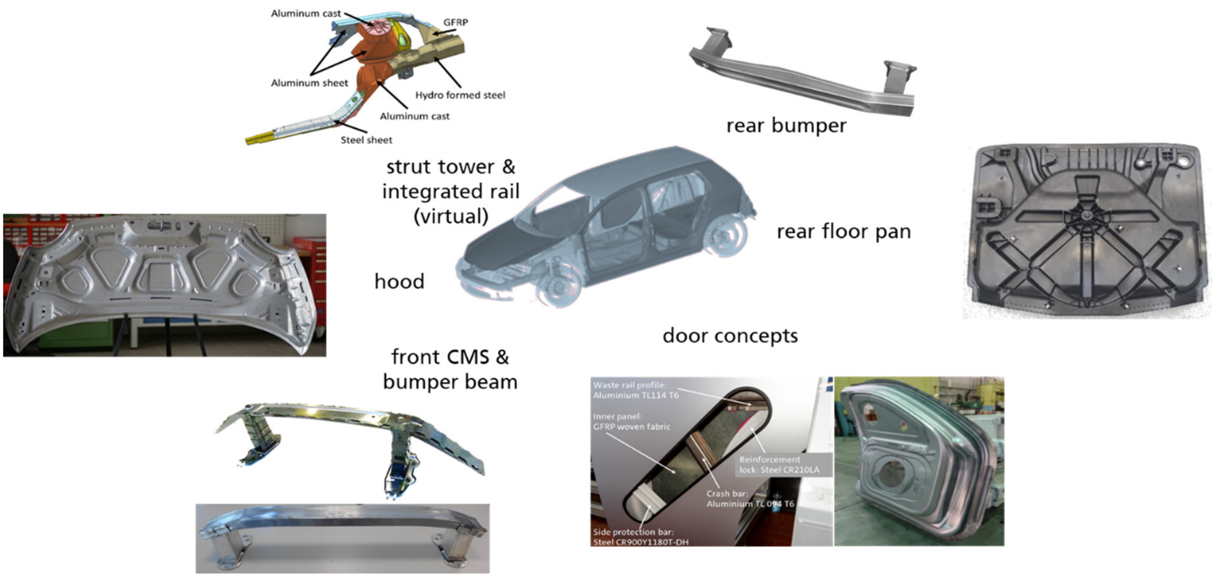

Figure 5 The ALLIANCE demonstrator modules.

Among others, a hybrid design of a swing door has been prototyped based on steel frames (different grades) and plastic parts. The structure was designed according to main load paths and crash performance requirements (e.g. side impact protection bar) based on a topology optimization. For the inner door, panel glass fibre reinforced plastic was applied with integrated metallic load paths as hybrid solution. Those metal sheet parts were necessary to distribute forces e.g. from door lockers into the plastic structure. For the outer panel, aluminium sheet was used to ensure surface quality and buckling strength. Integrated B-pillar of high strength steel together with several beams ensure side crash performance. The hardware was built-up by aluminium components as part of a multi-material design, e.g. an integrated horizontal / vertical side impact protection component and waste rail profile. A full plastic rear floor pan prototype was manufactured using a hybrid process technology combining reinforced plastic injection (using IMC) and water injection (WIT) to generate stiff inner hollow structures. This structure was adopted to reduce part weight while retaining the same performance as a conventional steel structure floor pan. The technical work done can be summarized as equivalent to a mass production development of the floor pan component and integration into the vehicle. Furthermore, new lightweight rear crash management systems were developed for EU and US requirements. For both EU and US version, components made of 7xxx series aluminium extrusions are proposed. The final design was a cost optimized open beam design using the ultra-high-strength alu-minium alloy AW 7046. The development focus was to find a good compromise between withstanding a high bending moment and providing a good ductility for the high-speed rear crash.

4. Impact Assessment

4.1 Life Cycle Assessment and Life Cycle Costs Methodology

4.1.1 Life cycle Assessment

Within ALLIANCE, a LCA "from-cradle-to-grave" was developed focusing on the Global Warming Potential (GWP) applying a breakdown approach was used based on vehicle assemblies/modules (Zanchi et al., 2016). As baseline the vehicle derived from the Light-eBody reference was used which is representative for both ICE and electric current compact class vehicles (Hören et al, 2016); a life-distance of 230,000 km and 150,000 km over 10 years is assumed respectively for ICEV and EV. Considering that the ICEV and EV have specific usage requirements and duration, two distinct values of LC mileages have been taken into account. The choice has been taken in order that use stage is modelled as accurately as possible basing on specific attributes of different propulsion technologies (Delogu et al., 2015). System boundaries include all processes within the vehicle life-cycle stages:

- materials production stage compels raw material extraction and process to semi-finished product (i.e. ingot, slab, billet);
- manufacturing stage includes process from semi-finished product to mono-material part;
- use stage includes fuel/energy production and tailpipe emissions;
- EoL stage considers car shredder technology, automotive shredder residue processing, materials sorting and recycling.

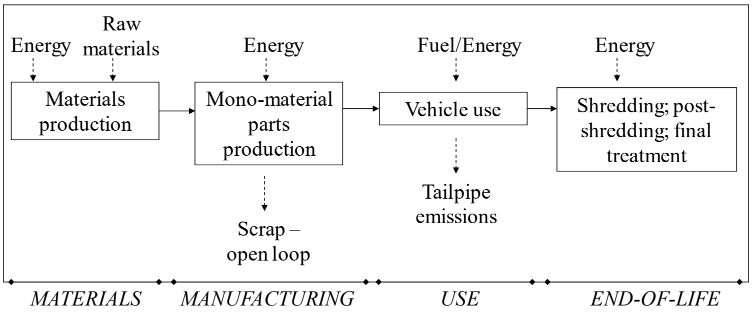

Figure 6 LCA system boundaries of reference vehicle.

The use stage modelling takes into account all impacts involved by vehicle operation including contribution due to fuel transformation processes (WTT) and Fuel Consumption (FC) for car driving (TTW). The WTT impacts are determined basing on resources consumption and emissions involved by production of fuel/electricity consumed during vehicle operation. The calculation was performed through the environmental software GaBi6 starting from the total amount of vehicle consumption. Considering the ICE configuration, TTW impacts are determined basing on FC and EURO 5 emission levels through the following equations (Del Pero et al., 2017):

$$emiss_i = emiss_{i\_km} * mileage_{use} \tag{1}$$

$$emiss_{SO2} = emiss_{SO2\_km} * mileage_{use} \tag{2}$$

$$emiss_{SO2\_km} = \frac{ppm_{sulphur}}{1.000.000} * 2 * FC_{use} \tag{3}$$

with

- $emiss_i$ = amount of emission i during operation [g] (considered emissions: benzene, CH_4, CO, CO_2, N_2O, NH_3, NMVOC, NO, NO_2, particulate)
- $emiss_{i\_km}$ = per-kilometre amount of emission i [g/km] (considered emissions: benzene, CH_4, CO, CO_2, N_2O, NH_3, NMVOC, NO, NO_2, particulate)
- $mileage_{use}$ = use stage mileage during operation [km]
- $emissSO_2$ = amount of SO_2 emission during operation [kg]
- $emissSO_2\_km$ = per-kilometre amount of SO_2 emission [kg/km]
- ppmsulphur = sulphur content in fuel [ppm]
- FC_{use} = amount of vehicle Fuel Consumption during operation [kg/km]

For both configurations (ICEV, BEV) the energy consumption has been determined through an analytical simulation model applying the NEDC and WLTC both. The End-of-Life (EoL) stage was modelled according to the 2000/53/EC Directive and the ISO standard 22628:2002.

4.1.2 Life cycle costs

Unlike LCA, there is no standardization of the methodology but only SETAC guidelines describing the main phases but not providing a unique approach for the cost modelling of life cycle stages (Swarr et al., 2011). For this reason, a specific modelling approach has been developed; in particular the manufacturing phase (including material costs) and use phase have been considered. Following a breakdown approach, firstly, the full vehicle is broken down into modules, which, in turn, are broken down into mono-material parts. The cost of each mono-material part comprised in the full vehicle is estimated according to its specific technical features (material type, geometry, mass, volume, etc.). Secondly, all the processes and subsequent of vehicle manufacturing are identified and broken down, including human and physical capital requirements (machinery, tooling, consumables, industrial space, employees, etc.) and related costs. Therefore, the cost per part is estimated taking into consideration the inherent properties of the part and its specific manufacturing parameters. Finally, all costs per part are aggregated, considering the vehicle structure and assembly processes (mono-material parts into modules, modules into vehicle assemblies) to obtain the full vehicle cost. This analysis was performed for both the ICEV and the BEV and it is based on the same boundary conditions assumed for the LCA study.

The total cost is built as the sum of several sub-costs, which are in turn a function of a large number of parameters and variables that are considered in the global manufacturing process. The equations hereunder illustrate the comprehensive assessment of the global vehicle manufacturing cost. Equation 4 displays the sub-costs that compose the total cost, thus showing the basis of the model's approach.

$$Cost_{Module} = Cost_{Material} + Cost_{Manufacturing} + Cost_{Use} \quad (4)$$

Where,

$$Cost_{Manufacturing} = Cost_{Machinery} + Cost_{Tooling} + Cost_{Consumables} + Cost_{Energy} + Cost_{Labour} \quad (5)$$

In order to assess the life-cycle cost of the selected modules, production and use stages are considered in the employed model for both the reference and the lightweight vehicle, thus allowing a comparison between the two solutions. Production cost includes material and manufacturing costs, which in turn includes machinery, tools, consumables, energy, and labour costs. Production cost is estimated for each mono-material part taking into consideration geometry, material, and manufacturing technology. The cost of use stage is based on the total lifetime FC attributable to each module, taking into consideration the average price for gasoline (2017), and electricity (2016) in the EU-28. Furthermore, following assumptions have been made:

- Cost of electricity [€/kWh]: last EU-28 average electricity price for industrial consumers (second half of 2016);
- Cost of natural gas [€/kWh]: last EU-28 average natural gas price for industrial consumers (second half of 2016);
- Cost of labour [€/h]: salary per hour worked per technology;
- Annual production [vehicles/year]: target annual production volume for the project (100,000 vehicles/year).

4.2 Assessment on Module Level

The above-described LCA and LCC approach was applied to each demonstrator module. The input data were provided and discussed with the respective industrial partner to ensure reliable input data as much as possible. However, since costs are affected by compliance regulations and are considered as confidential, input data for the LCC are not exact, either based on commonly agreed assumption or provide only as a range. Since the assumptions made and range of input data provided were applied to both, the reference part and the advanced lightweight version, the impact assessment is at least accurate in relation to each other. As such, the calculated costs for lightweighting are considered as feasible and sufficiently accurate.

The final results of the impact assessment for each demonstrator module are shown in Table 1. The assessment is provided only in relative numbers since the absolutes values for each demonstrator module are considered as confidential. Over all considered modules a weight reduction of 31%, a reduction of 25% in kg $CO_{2\ eq.}$ at 2.7 € additional costs for each kg saved have been achieved in total. However, the targets regarding relative weight savings and costs per kg-saved have not been met for all components but were compensated by components where the targets have been exceeded by far. Regarding weight savings, only the front bumper beam did not achieved the weight saving targets. The references system was already quite optimised in terms of weight. Nevertheless, the developed solution is better in his CO_2 footprint at additional costs close to the target so that the new design approach is still evaluated positive. Regarding the more complex door concepts in aluminium and consequent multi-material design, weight and CO_2 savings are as expected but at higher costs than targeted. This is mainly due higher material and manufacturing costs. However, the additional costs are still below 5 €/kg-saved, lower than the achievements in previous research projects and within the range accepted by the OEMs for C-D segments (VDI, 2014). Remarkable is that with a consequent design approach the overall production costs can be lowered for some components.

Table 1. Summary of achievements on component level

	Weight [%]	GWP, kg CO_2 eq.[1] [%]	Costs [€/kg saved]
Door concept 1 (multi-material)	-29,4	-18,3	+4,37
Door concept 2 (aluminium)	-44,1	-43,6	+4,45
Rear floor panel	-26,0	-20,1	-4,42
Hood	-52,6	-55,9	+1,96
Front CMS	-28,7	-22,7	-1,22
Front bumper beam	-12,3	-9,9	+3,18
Rear bumper system (EU version)	-39,3	-23,3	-1,55
Rear bumper system (US version)	-45,2	-39,2	-0,58
Strut tower w. integrated rail	-35,0	-28,0	+1,53
Total	**-32,1**	**-25,1**	**+2,67**

4.3 Assessment on Full Vehicle Level

In order to assess the ALLIANCE technologies and solution on full vehicle level (see Fig. 1), a virtual full vehicle model has been derived for an ICE and full battery electric vehicle. As final proof of concept, all technologies are scaled and transferred into this virtual ALLIANCE full vehicle model demonstrating that affordable and sustainable weight reduction can also be achieved at full vehicle level, within the range of the predefined targets while additionally considering secondary weight saving potentials.

The virtual vehicle was first broken down into different modules (Fig. 7) followed by an analysis of the technical requirements for individual modules and components and of potential design options regarding material and manufacturing. Based on this analysis the feasibility was assessed towards integrating ALLIANCE technologies into the overall structural concept, ratio between benefit and effort related to lightweighting and impact on costs and GWP. In a second step, material and manufacturing technologies were implemented such as

- Advanced high strength steel and aluminum alloys
- Fibre-reinforced plastics (FRP)
- Metal-FRP hybrids
- Advanced metal forming
- Tailored Extruded Blanks (TEB)
- Hybrid technologies
- Injection Moulding Compound (IMC)

In doing so, lightweight design principles like one piece solutions or “right materials at right places” were applied consequently. The transfer and up-scaling of ALLIANCE technologies developed on component level resulted in a weight reduction of about 9.4 % on full vehicle level (ICE version). When exploiting also secondary effects additional 6.2 % weight savings can be gained resulting in a total saving of 15.6 %. This directly results in 10 % less energy consumption.

[1] The assessment of the CO_2 footprint is only valid for the specific component and cannot be taken for the full vehicle.

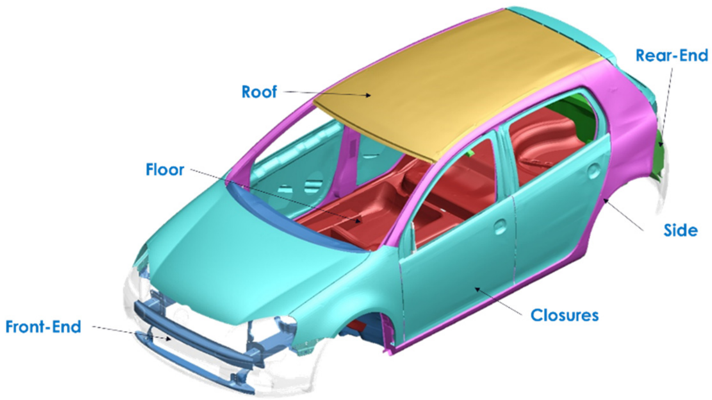

Figure 7 ALLIANCE full vehicle model with considered modules.

5. Conclusion

Within ALLIANCE affordable lightweight solutions based on advanced steel and aluminium grades and novel conceptual designs have been developed for eight exemplary structural components. Besides, a new approach to assess the impact regarding LCA and LCC on full vehicle level has been developed. The final results indicate that significant weight reduction up to 33% can be achieved while limiting the additional costs below 3 €/kg-saved. When taking into account LCA and LCC aspects already in the conceptual design phase, lightweight solutions can be realised with even reduced costs compared to the reference. The weight savings directly impact the GWP of each component leading to about 25% reduction in GWP on component level. However, the results of ALLIANCE also indicates that some components are already highly optimised regarding weight and radical new solutions might be needed to significant reduce weight (> 20 %) at acceptable cost.

The ALLIANCE project clearly showed that lightweighting should not be carried out for the purpose of making cars lighter but to reduce emissions (LCAs in early development stages). Within this context, holistic approaches are required to solve the issues related to lightweighting: a combination of technological, market awareness and ecosystem innovation is crucial. Besides, digital technologies in the design, testing, manufacturing and use phases will become essential to accelerate innovation.

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