AffordabLe LIghtweight Automobiles

ALLIANCE

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Extended Publishable Executive Summary

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CO	Confidential, only for members of the consortium (including the Commission Services)	
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Content

1 Overall objectives of ALLIANCE

The ALLIANCE project will produce a set of solutions and methodologies that enable carmakers to build a whole vehicle complying with a 10% energy consumption reduction, 3€/kg-saved for 100k vehicle production volume and 6% reduction in environmental impact. Six European OEMs (Daimler, FCA (represented by CRF), Opel, Toyota, Volkswagen and Volvo), four suppliers (Batz S. Coop., Benteler Automotive, Novelis Inc and ThyssenKrupp Steel Europe AG) and eight knowledge partners (Bax & Company, Fraunhofer LBF, Institute for Automotive Engineering ika of RWTH Aachen University, Karlsruhe Institute of Technology, inspire AG, Ricardo UK Ltd., Swerea KIMAB AB and Università degli Studi di Firenze) have joined forces to foster the implementation of innovative lightweight technologies in series application.

Overall, ALLIANCE aims to develop affordable lightweight strategies which have a high potential for being implemented into mass production and thus contributing to the decarbonisation of the road transport. The project will prototype and validate the innovations at module level and transfer the results to a full vehicle virtual model demonstrating the compounded impact at the vehicle level (see Figure 1). The ALLIANCE objectives in detail are as follows:

- ALLIANCE will aim for a 21-33% weight reduction on 8 demonstrator modules to reach a 10% or 1.4 kWh energy consumption reduction at vehicle level.
- ALLIANCE will aim for 3 €/kg-saved in average in the body, doors & closures and chassis parts, which corresponds to the ICE version of the vehicle.
- ALLIANCE will target a 6% improvement in GWP compared to the reference vehicle model in the body, doors & closures and chassis parts.
- Development and validation of novel, affordable materials for lightweighting (steel, aluminium and new hybrid materials) with superior performance but low cost and low embedded footprint.
- Development and validation of more energy efficient, cost efficient, high-volume manufacturing technologies for metal forming, high volume composite and hybrid materials as well as joining technologies, and their applicability in existing manufacturing processes and assembly lines.
- Development of multi-parameter optimisation methodologies and tools that can be used in the early conceptual design phase as well as in the detailed design of automotive parts and systems, taking into account weight, cost, environmental impact and manufacturability factors, and applying it in virtual demonstrator use cases.
- Leveraging the knowledge and innovative solutions from around Europe by organising an Open Lightweighting Challenge, which directly feeds promising materials and technologies into the ALLIANCE virtual vehicle model.

- Developing 8 lightweight and affordable demonstrator module concepts which come as close as possible to series car modules of the OEMs and complying with the decision criteria that internal design, pre-development and development departments of the OEMs use; that way aiming to ensuring the rapid adoption of the innovative solutions in the immediately next car generations processes of multiple European automotive OEMs.
- Developing hands-on methodologies and tools for the efficient projection of lightweighting innovations from one vehicle component to another and from one vehicle segment to another, thus supporting the adoption of innovative technologies into new structural concepts.

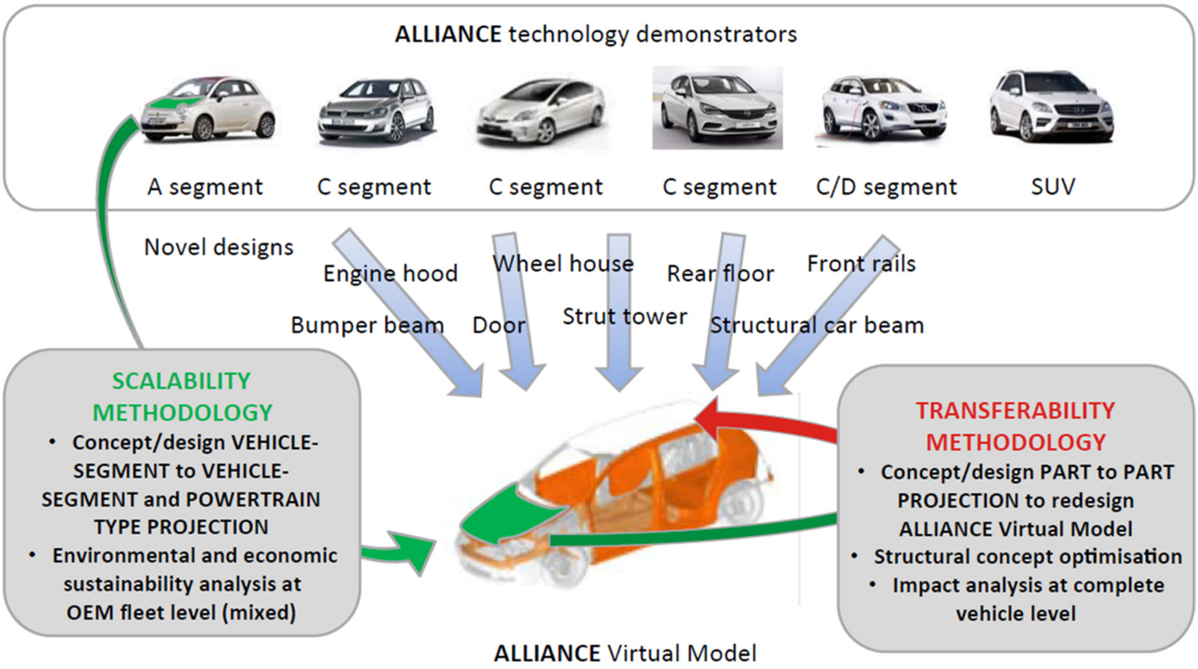

Figure 1. The ALLIANCE conceptual approach

2 Progress beyond the state of the art and potential impact

Automotive lightweight materials are a major research line prioritized among all OEMs and especially their material and part suppliers, given the promising market opportunity it represents: with a current estimated value of €206.8B by 2019 globally, it is growing at a healthy Compound Annual Growth Rate (CAGR) of 14.4%. The ALLIANCE consortium is placed in a favourable position to embrace this opportunity, translating the success in the project into tangible impact in the EU and worldwide society due to the high involvement of relevant industrial players. Specifically, 6 of the major automotive OEMs in Europe (Daimler, Volvo, VW, Toyota Motor Europe, Opel and FCA-CRF), accounting for approximately 50% of the market share in Europe and producing in total some 30 million vehicles that are sold globally (42% of global market share), will guarantee major market adoption of ALLIANCE benefits.

ALLIANCE reached an energy consumption reduction of 10% at vehicle level. This reduction in energy consumption resulted from a weight reduction for the body, doors & closures and chassis in the range of 170 kg (-13%) for an ICE vehicle and 275 kg for an EV (-18%), based on the reference vehicle (taken from the German project Light-eBody) and NEDC cycle. This impact can be directly attributed to the ALLIANCE innovations: the 30% lighter demonstrator modules in average, extrapolated to the rest of the body, doors & closures and chassis parts via the transferability methodology that the project has developed. Assuming that every 100 kg of vehicle weight reduction entail a benefit in average of 3-4 g less of CO_2 per km run (depending on the reference), the ALLIANCE weight savings results in 1,100 kg CO_2 reduction over a vehicle life time (200,000 km for an ICE). The ALLIANCE partners expect that the derived solutions will be applied at least in one new series car model within a timeframe of 5-6 years from project completion being produced at high volumes (hundreds of thousands of units annually).

Furthermore, lightweight design and optimization of the overall vehicle architecture and concept, based on advanced materials and production technologies, is definitely one of the most important skills and capabilities upon which carmakers will have to base their competitive advantage on. As such, ALLIANCE directly strengthens the capabilities of its partners in this key area. ALLIANCE will generate unique knowledge on different key topics within the lightweight field and will enable its partners to create such competitive vehicles that should enable them to attract customer preference in Europe and within the global market. Based on the above advantages, ALLIANCE will enable the European automotive industry to lower the weight of the vehicles, lower CO_2 emissions and fuel/energy consumption which is likely to create more attractive vehicles for the customers without (large) additional added cost. The increased attractiveness of the vehicles marketed (primarily) by the 6 OEMs participating in the project can be expected to provide a competitive edge that increase their market share globally by estimated 5% or 200.000 vehicles per year sold additionally. Also considering the annual growth rates of the automotive industry (reported by ACEA at 9.2% in 2015), that number is expected to be even higher by the time the first vehicles hit the market in 2026. Thus, there is a significant impact in the growth potential of the suppliers, large companies and SMEs, triggered by the new or extended opportunity of using the new innovative materials and technologies developed within ALLIANCE. This growth directly translates in maintaining or creating about 10,000 highly skilled jobs in Europe related to lightweight automotive manufacturing.

To reach the aforementioned targets and impacts, ALLIANCE focused on advanced steel and aluminum alloys, such as high strength/high formable 6000 and 7000 series aluminum alloys and composites reinforced with glass fibers, as well as innovative steel sandwich materials. The project optimized these materials to become suitable for the following innovative manufacturing technologies:

- production sequence for tailored extruded aluminum blanks with variable thickness;
- simultaneous forming of metal and FRP hybrids;
- one-step process combining injection molding with Water Injection (WI) for the creation of braided, thermoplastic, glass fibers-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).

The project struggles to address a series of key issues for accelerating the take-up of innovative material-process systems into mass volume production such as compatibility with current technology processes in terms of cycle times and process chain; to do so, ALLIANCE established an open inclusive framework towards external partners in this field, involving them through an open lightweight challenge and dedicated workshops.

3 Work performed and main results achieved

3.1 Tools for a holistic lightweight design

Vehicle mass reduction is a proven method to achieve vehicle efficiency improvement and reduce CO_2 and emissions. Engineers are faced with numerous complexities when undertaking mass reduction of a passenger car vehicle. Vehicles typically have 3,000 to 7,000 parts or modules vehicle and mass reduction usually is achieved by reducing the weight of a number of components. Therefore, the engineer is challenged to identify the most appropriate components that are suitable for mass reduction. There are numerous solutions, approaches and technologies available to engineers to reduce the weight of vehicle components and modules, with each solution having different potential cost, Global Warming Potential (GWP) and performance effects. The lightweighting solutions are often demonstrated or are in production on a single vehicle type/segment, therefore additional efforts are required to envisage and realise the effect of the solution on another (larger or smaller) vehicle type or segment. To address these issues, Ricardo's Vehicle Mass Manager software tool has undergone enhancement and improvement within the Alliance project. A new "Use Case Database" has been added, enabling light-weighting technologies to be stored/saved within Mass Manager. The database contains the lightweighting technologies as developed by the Alliance project partners as well as technologies from other projects. The user is able to apply these technologies to a complete vehicle and assess the mass, cost, GWP and performance impact. Additionally, a scalability function is provided, enabling a single lightweighting technology and its parameters to be scaled from the native/parent vehicle to another vehicle (size). The scaling is based on a statistical trend line which is obtained from a data sample of other reference benchmark vehicle data. A transferability function has also been developed, enabling the mass reduction, cost and GWP parameters from one "source" lightweight part to be transferred to another "target/candidate" part, again based on a statistical function derived from component benchmark data.

Besides, the Life Cycle Assessment (LCA) of new materials and manufacturing technologies developed within the project has been carried out in order to support the design of innovative lightweight modules in the achievement of project targets (both mass and environmental impact reduction). On top, a comparative LCA between the reference and lightweight modules has been implemented in order to evaluate the environmental effects of the lightweight design solutions developed within the project. The comparison should rely on the capability of the reference and lightweight design alternatives to provide the same mechanical and functional performances. Considering the assessment of materials, the Functional Unit (FU) is the production of 1 kg of semi-finished product and the system boundaries include raw materials extraction as well as manufacturing processes ("from cradle to gate" approach). For the assessment of manufacturing technologies, the FU is the manufacturing process involved in the production/processing of 1 kg of finished product and the system boundaries include all manufacturing processes involved in the production/processing of finished products ("from gate to gate" approach). For both materials and manufacturing technologies sections, the analysis takes the disposal of scrap materials produced by manufacturing processes into account. Scrap materials are assumed to be recycled (open loop recycling) and the avoided environmental impacts due to raw materials substitution are assessed as credits. Transportation is excluded from the system boundaries.

The Life Cycle Inventory (LCI) was carried out by means of GaBi software. The inventory was modelled as materials/energy consumption, waste production and emissions to the environment due to the production processes and the LCI elementary flows are from the GaBi LCI dataset. The modelling was based on primary data collection coming from direct measurements on process site. Primary data are collected by means of specific questionnaires filled out by partners involved in materials and technologies development. When no primary data are available, secondary data from the GaBi process dataset were used. Considering the comparative LCA of car modules, the FU was defined as the module installed on a specific vehicle over a LC mileage of 230,000 km; the use stage is assessed considering both the worldwide harmonized Lightduty Test Cycle (WLTC) and the New European Driving Cycle (NEDC). The system boundaries included all stages that compose the module's LC ("from-cradle-to-grave" approach): raw materials extraction and production (materials), manufacturing, use and End-of-Life (EoL). Assembly activities as well as transportation processes were excluded from the system boundaries of the LCA. The use stage took into account all impacts associated with module operation, including both fuel transformation processes upstream to Fuel Consumption (FC) and CO_2 emissions during car driving. The inventory is modelled as materials/energy consumption, waste production and emissions to the environment. The LCI model is based on the amount of FC as well as CO_2 emissions associated with the module (FRV-based approach). Resources consumption, waste production and emissions to the environment are modelled through LCI processes and elementary flows from the GaBi dataset. The EoL stage was assessed at vehicle level assuming a specific scenario representative of the current European technology level of automotive EoL processes and it is modelled according to 2000/53/EC (2000) and ISO 22628 (2002). The considered EoL scenario assumes that modules remain on the End-of-Life Vehicle (ELV) which is forwarded to the shredding process. After the shredding, different EoL scenarios were assumed basing on material type. Metal materials were assumed to be sorted and forwarded to recycling processes (open loop recycling). The modelling took into account the environmental credits due to raw materials substitution and the considered factors for the replacement of virgin raw materials are from the Gabi LCI database. On the other hand, non-metal materials are assumed to be forwarded to incineration with energy recovery. The inventory of EoL processes was modelled as materials/energy consumption, waste production and emissions to the environment and the LCI elementary flows are from the GaBi LCI dataset.

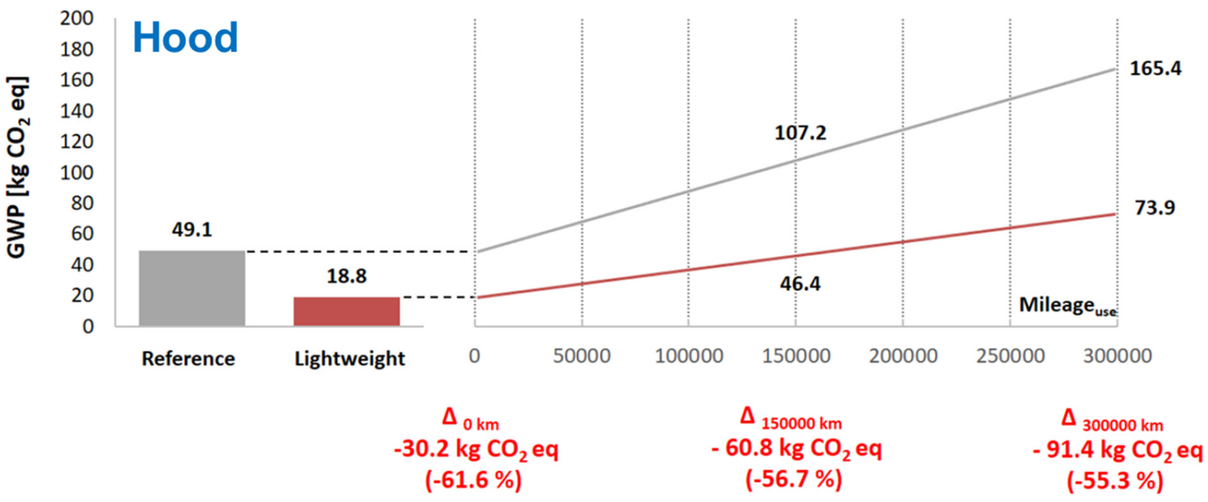

Figure 2. Break-even point analysis – example hood demonstrator

In order to perform the cost analysis, the relevant data on new material and manufacturing technologies required for the demonstrators' production was collected from project partners and literature. Based on this input, the LCC model was updated incorporating the new data and therefore allowing it to estimate the LCC of the new demonstrator designs. Subsequently, the initial results obtained were shared among the partners, bilaterally reviewed by each of them and finally discussed during project meetings. Based on the subsequent validations or feedback received, the model and the database was ultimately updated and fine-tuned. Finally, the final LCC results were analysed looking at the different cost phases and drivers of cost, with the aim of determining the relevance and impact of each of the cost drivers involved in each of the LCC phases. All in all, the average cost saved per kg-saved was 2.7 €. In some cases, the target is achieved mainly because of the considerable mass savings, higher compared to cost increases, which are derived from the replacement of conventional materials by much lighter materials. In other cases, in which the material change is not as significant, the target is achieved mainly due to indirect factors such as the reduction of scrap rates which can significantly reduce the amount of material needed and therefore the absolute material cost. Other factors that may have an impact on the cost performance of each model are dimensional and related to the module design (e.g. the new design of a component makes use of less material and could therefore be lighter and cheaper or counts with less mono-material parts, making thus the production process shorter and less costly). For this reason, it has been analysed if factors such as the difference in the number of mono-material parts or in mass had a direct influence on reducing costs per part. From the results it is not possible to claim that there exists a direct link between these and the cost given the low statistical significance, although there is a visible trend that suggest such behaviour. This is expected since after analysing the main cost drivers of each module it was observed that the cost saving depends on a combination of multiple parameters – and their interaction – for which their influence vary depending on the production processes selected, materials, module and mono-material part design, among others.

Over the course of the ALLIANCE project, a simultaneous development of a virtual full vehicle model and innovative material and manufacturing technologies has been pursued. These material and manufacturing technologies have been put into practice in the form of physical demonstrator concepts. In order to demonstrate the feasibility and lightweight potential of these concepts on full vehicle level, the virtual reference vehicle has been modified with these measures in mind. As a final proof of concept, all technologies were scaled and transferred into the virtual ALLIANCE full vehicle model (Fig. 3). The key target in this context was to prove the feasibility of the technology developments on full vehicle level. In order to achieve the ALLIANCE objectives on full vehicle level, fundamental modifications have been made to the virtual vehicle reference model. Around 90 components have been redesigned, adapted or substituted entirely to suit the requirements of the demonstrator technologies. For the purpose of meeting the weight targets further lightweight measures have been taken. Finally, the passive safety characteristics of the new lightweight vehicle model has been evaluated with the ALLIANCE full vehicle model. For the purpose of a thorough evaluation, as many as six different load cases has been considered. These contain two EuroNCAP front and side crash tests respectively as well as the United States FMVSS rear impact and roof crush tests. All tests have been passed in the virtual assessment.

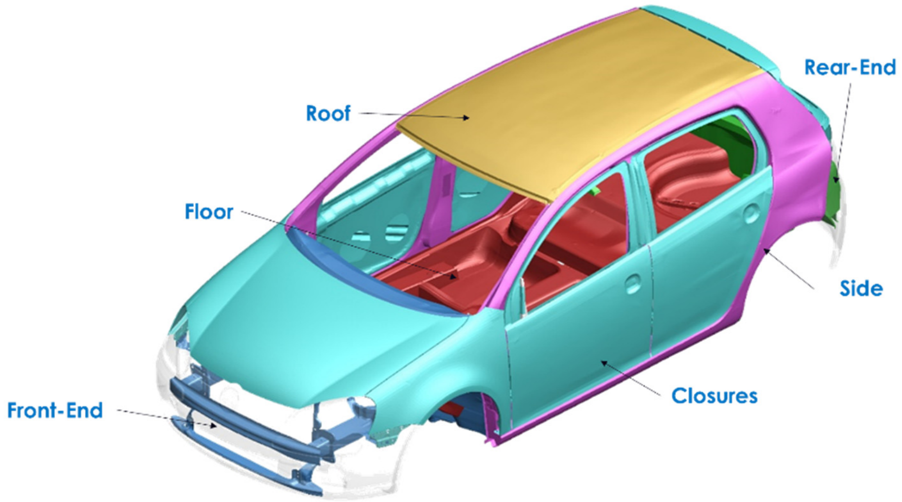

Figure 3. ALLIANCE full vehicle model with considered modules

3.2 Novel Lightweight Material

Within the ALLIANCE project, a 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 steel DP-K(R)850Y/1180T-DH was produced in an industrial scale inside the ALLI-ANCE project and applied to the front bumper beam. 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.

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 (FusionTM version). The developed high strength 6xxx exhibits a yield strength up to 350 MPa in service. Besides, FusionTM 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 tends 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.

3.3 Manufacturing Technologies

One of the goals of ALLIANCE was the development of manufacturing technologies suitable for the relevant production rate target of 100,000 units per year. In this context, various manufacturing technologies have been investigated in view of reducing energy consumption, increasing automation and decreasing cycle times. As multi-material design offers great lightweight potential reducing CO_2 emissions, hybrid components in combination with fibre-reinforced plastics (FRP) have been analysed. Mixed construction with FRP, for example in combination with aluminium alloys, offers promising prospects for success in the pursuit of weight-saving mixed construction rates and is gaining increasing interest on the market due to its high lightweight construction potential. For these reasons, a hybrid manufacturing process was developed that minimises the weight by adding high-strength composite reinforcements locally to highly loaded areas of a hybrid rear bumper. A PA6.6 was selected as the reinforcing material for the bumper beam and adhesive bonding as the most suitable joining method. Furthermore, bonding with several adhesives in a hot plate press and with contactless induction heating has been tested aiming for shorter cycle times, sufficient strengths and cohesive failure. The Kömmerling Körapur 784 turned out to be the most suitable adhesive, which should be used in an induction-based curing process.

Besides, an innovative flexible hybrid metal-composites thermoforming process has been considered. The process consists of heating up aluminium sheets together with a thermoplastic material (fibre reinforced) and combine them directly into a stamping die with a traditional stamping tooling (see Fig. 4). 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 pro-vide enough relative sliding to compensate the lack of elongation with respect the aluminium without continuous fibre breaks.

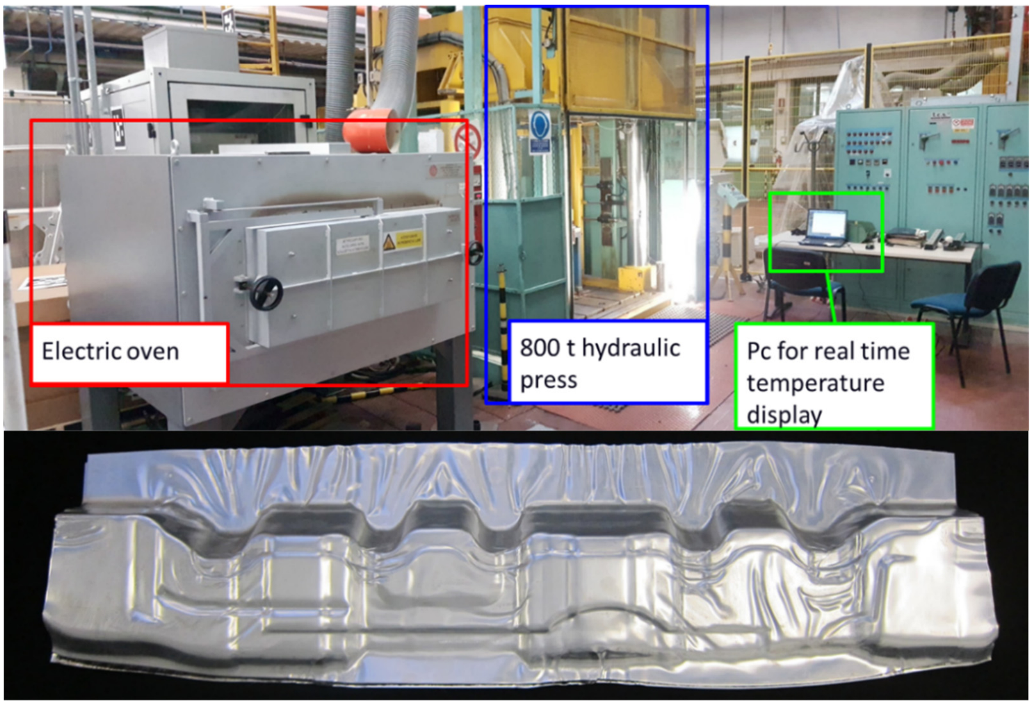

Figure 4. Thermoprocess equipment and selected result of trials.

Due to the different materials elongation, the shaped sandwiches were affected by wrinkling on both aluminium faces, which could be likely avoided with blank holder adoption, to be considered in the final manufacturing process configuration. Further investigation will be focused on aluminium surface treatment to improve adhesion among different layers and improved numerical process simulation model.

Another hybrid manufacturing process considered was the water injection technology in combination with long glass fibre reinforced composites made by injection moulding compound enabling hollow lightweight structures. Different process parameters and technic adaptation have been analysed and detailed focussing on obtaining a robust hybrid process for mass production. Cycles times around 60s are achievable independently the geometry and size of the hollow. Several raw materials have been analysed considering manufacturing process feasibility. It was observed that these materials must have some specific properties (crystallization speed, maximum glass fibre length, etc.) which allow their melt flow when the water is injected. As a result of this analyse, a compound of Polypropylene copolymer of long glass fibre in percentage of 40% was selected to use for the demonstrator manufactured by this technology. Characterization methods for reinforced plastic compounds have been optimized and validated taking into account the manufacturing process. Glass fibre orientations predicted by simulation have been evaluated and compared with experimental results, selecting the proper material model to use in FEM. The effects of different process parameters have been analysed by simulation. Through different iteration in process simulation, the level of prediction of hollow structure has been optimized obtaining more accurate results in terms of hollow design. The work carried out allows not only selecting the proper raw materials for this hybrid technology but also identifying the key process parameters to take into account for a feasible design and robust manufacturing process.

With respect to joining of multi-materials, 14 different technologies were investigated ranging from laser welding to riveting. For laser welding of aluminium, the possibility to avoid utilization of filler material was evaluated (using filler material is the more expensive and weight increasing solution to avoid hot cracking in aluminium welds). The oscillating beam trials could not fully avoid cracking, some small hot cracks occurred, and achieved tensile strength values were therefore not in the same range as the laser welds made with filler material (10-15% less). There are, however, many parameter combinations possible for the oscillating optics and all variants could not be evaluated during the test period. It is believed that with more time, these results can be improved. Joining speeds were in the range of 3.5 – 5 m/min. For the advanced MIG-welding, good results were achieved. The modern control systems offer many options for adapted heating and melting. Material softening in the HAZ (heat-affected zone) could be reduced although not avoided. For most cases the results are fully acceptable. Joining speeds were around 0.6 m/min. The Friction Stir Welding (FSW) results did not show any Heat Affected Zone softening in aluminium joints since the heat input is significantly less. More determining on the strength and quality of the joint was the tool geometry and its capability to achieve suitable level of stirring (material-mixing). Here, the highest strength values were achieved when a good material-mixing was established. FSW does not add weight in terms of filler material and the method is quite sustainable (electricity is required but no emissions and little wear of equipment). Joining speeds utilized were around 0.2 m/min but higher speeds are possible with the right fixturing (strong and correct clamping is essential). The FSW Stationary shoulder variant introduced even less heat but needed extra strong tool material and modified geometry to manage stirring the 7XXX aluminium alloy. Besides, Resistance Spot Welding (RSW) is a commonly used welding process in the automobile industry. In general, challenges increase with reduced material thickness, and large differences in material thicknesses. Also, when more aluminium materials are used in car bodies and parts new challenges arise. Good results were achieved for the evaluated thin material combinations and a lightweight hood can be realized. Typical joining speed is around spot weld one per second.

The new and innovative hybrid joining methods Friction Element Welding (FEW) and Resistance Element Welding (REW) were evaluated as well. These methods are combinations of welding and mechanical interlocking. FEW received better results in terms of high shear strength values and can enable successful joining of two very different material types. A new FEW version (SRE) is available with a lighter fastening element, although not the same joint strength is reachable. FEW will be utilized when other options are less suitable, and REW will find its applications, especially where an SPR method is already utilized on a component and extra parts mounting is needed in this area (and RSW is accessible). Both FEW and REW will often be used in combination with adhesives.

For self-piercing rivets (SPR), suitable material stack combinations and die and rivet geometries have been identified for many cases. For demanding material combinations utilizing an extra bracket can be an enabler. The bracket offers a softer material where the rivet can be set (deform and interlock) properly. This method variant is called PER (Plug-Element-Riveting). It adds weight with an extra bracket but can enable otherwise impossible material combinations to be joined with SPR. Typical joining speed is around one element per second. Flow Drill Fasteners (FDF) is an alternative to SPR and comparisons have been made between these methods for material combinations of interest. FDF received higher shear tensile joint strength and is removable and resettable. However, the FDF element weight is higher than for SPR. Both can be successfully used in hybrid joining with adhesives.

It is evident that the preferred joining processes differs totally from case to case, it is connected not only to joint strength and productivity but also manufacturing volumes, physical and carbon footprint, flexibility, investment cost, staff skills and earlier investments. In some cases, a well-optimised MIG welding pulsed arc can be a preferred choice. In other more high-volume cases can a laser welding system or one of the different FSW or SPR or hybrid process variants enable more cost-efficient manufacturing.

3.4 Design & Optimisation Tools

Besides above mentioned tools, dedicated methodologies for the conceptual design and optimisation phase has been developed. Among others, the so-called Extended Target Weighing Approach (ETWA) has been developed. 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 percentage 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.

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.

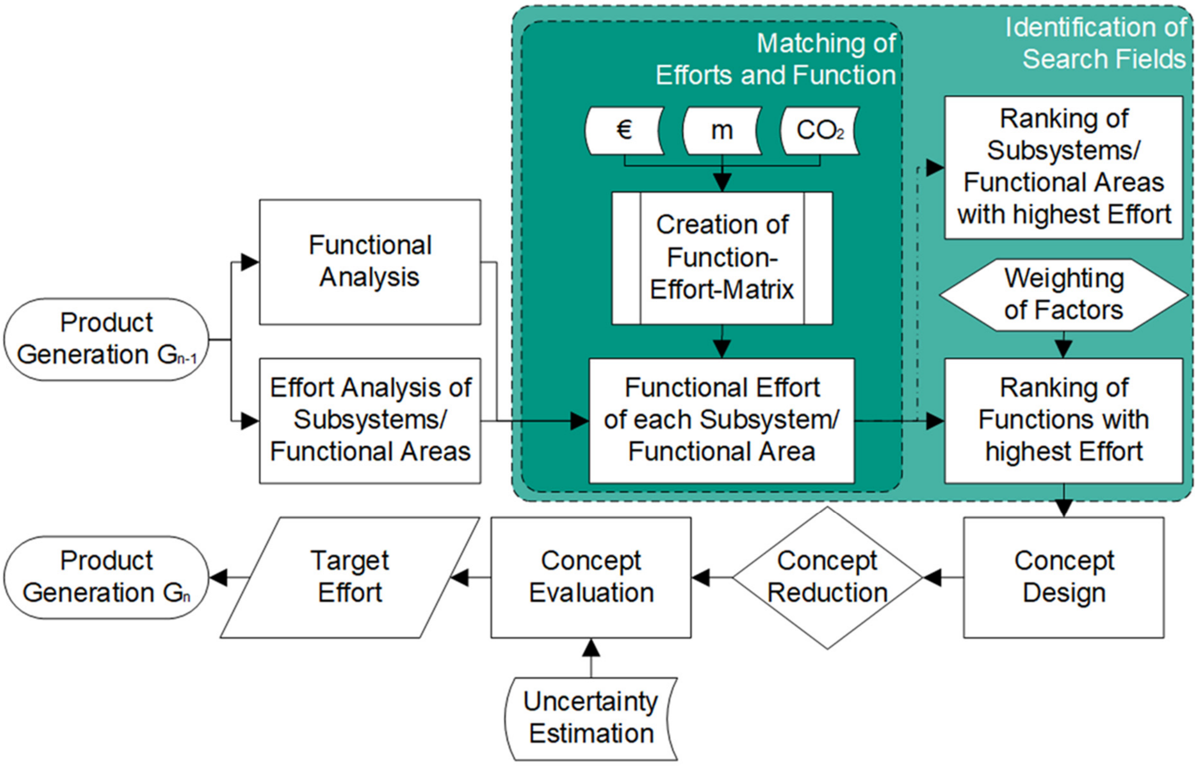

Figure 5. Extended Target Weighing Approach (ETWA)

3.5 Design and Prototyping 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 Figure 6. 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 production 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 were applied to find the optimal concept.

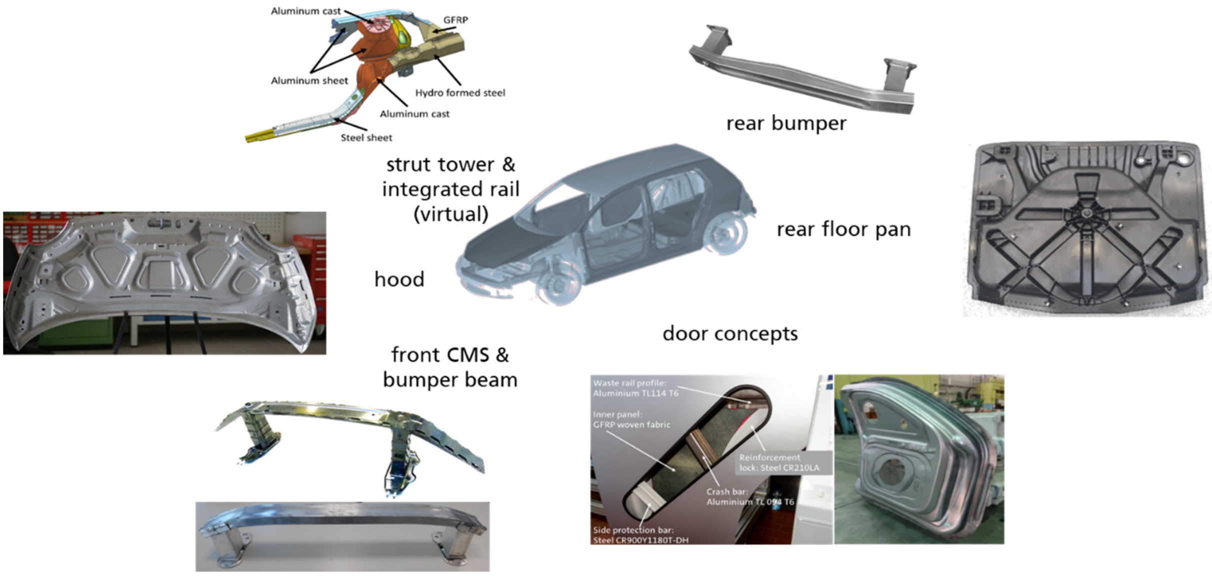

Figure 6. The ALLIANCE demonstrator modules.

In order to validate the design, defined but limited testing on fatigue, NVH and crash on module level was performed. Although not all attributes could be tested within ALLIANCE, the performed testing clearly demonstrated the validity of the new designs meeting all requirements considered important by the OEMs. The achieved weight savings are listed in Table a together with the estimated savings in GWP on module level as well the estimated costs per kilogram-saved.

3.6 Impact Assessment

The developed 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 absolute values for each demonstrator module are considered as confidential. Over all considered modules a weight reduction of 32%, 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**

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 (see above). As outlined, all technologies were 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. 3) 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

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

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 aluminium 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.

4 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.

Further, more detailed information as well as an outlook on further research needs can be found under

www.lightweight-alliance.eu