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Enhanced lightweight design – first results of the FP7 project ENLIGHT

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Abstract

The European Green Vehicle project ENLIGHT aims to advance highly innovative lightweight material technologies for application in structural vehicle parts of future volume produced Electric Vehicles (EVs) along four axes: performance, manufacturability, cost effectiveness and lifecycle footprint. The main target is to develop viable and sustainable solutions for medium production volume up to 50.000 EVs destined to reach the market in the next 8-12 years. The specific objectives of the ENLIGHT project are on holistic and integrated conceptual design and manufacturing concerning how the technologies and materials addressed can be combined into a representative medium-volume EV. The solutions will be demonstrated in five modules: a front module and central floor module, a front door, a sub-frame and suspension system as well as a cross-car beam. In this paper, a summary of the major results obtained up to the 3rd project year will be presented.

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Keywords: Lightweight design; composites; manufacturing; LCA

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1. Introduction

One of the key societal challenges of today is the decarbonisation of the road transport. The challenge of decarbonisation must be met among others by significantly reducing the vehicles weight reversing the weight spiral of the last decades on the other hand. However the need for weight reduction in future EVs, without unduly compromising performance and safety, is even stronger since additional weight translates into either reduced driving range or in larger, heavier and more expensive batteries. Striving for reduced weight as the only objective will not necessarily result in a reduced environmental impact of the EV fleets of the future: An-other two key and equally important drivers need to be pursued at the same time, namely affordability and life cycle impact minimization. Affordability is essential since it will allow for larger portion of the total EV fleet to adopt specific light-weighting solutions; and Life Cycle Impact effectively defines the total CO_2 impact over the lifetime of the vehicle.

Therefore, the EU-project ENLIGHT aims to advance highly innovative lightweight material technologies for application in structural vehicle parts of future volume produced Electric Vehicles (EVs) along four axes: performance, manufacturability, cost effectiveness and lifecycle footprint. The main target is to develop viable and sustainable solutions for medium production volume EVs destined to reach the market in the next 8-12 years. In ENLIGHT each of the principal major weight-incorporating parts of a vehicle will be addressed directly by the five modules: a front module and central floor module, a front door, a sub-frame and suspension system as well as an integrated cross car beam as part of the firewall. The specific objectives of the ENLIGHT project are on holistic and integrated conceptual design and manufacturing concerning how the technologies and materials addressed (in combination with materials / forming/ joining processes coming from other previous and on-going projects) can be combined into a representative medium-volume EV by around 2020. This design is targeted to have a 20% additional weight reduction compared to the complementary ALIVE project (ALIVE 2012).

ENLIGHT targets an ultra-compact four-seated passenger car as considered in the ELVA project (ELVA 2013). Based on this architecture, the five selected modules will be conceptually designed with respect to weight and CO2 balance over life-time. These designs will be evaluated and potential improvements assessed on vehicle level with respect to weight, safety and performance that result from the application the highly advanced material developed within ENLIGHT. The optimal combination of architecture & design, processes and materials requires a systemic technical cost modeling, ensuring sustainable solutions using LCA and accounting for externalities, while taking into account the necessary integration into the manufacturing strategy of each car manufacturer and supplier.

Within ENLIGHT highly advanced materials such as thermoplastic matrix composite, fiber-reinforced composites, advanced hybrids and sandwich materials as well as composites based on bio-material and renewables will be developed to a stage that they are applicable at least in medium volume production. The material development will be complemented by investigating the required manufacturing and assembly technologies as well. The relevant technologies being developed or available outside of the project will complete the input for the multi-criteria decision-making process needed to select which technologies will be finally applied in the final ENLIGHT demonstrators of the five modules. Overall, ENLIGHT will deliver

- highly innovative lightweight / low embedded CO_2 materials for their application in medium-volume automotive production,
- design capabilities for affordable medium-volume lightweight EVs,
- manufacturing and joining capabilities for affordable medium-volume lightweight EVs,
- experimental and simulation validation environments to enable rapid & reliable multi-parameter optimization when designing with these new materials,
- LCA and economic analysis taking into account all salient factors,
- 5 demonstrator modules (front module, suspension parts, door module, components for the cockpit/firewall section and the floor section), covering different distinguishing features of purpose-designed EVs.

The shortest term target market segment for ENLIGHT is the segment of mid volume (~50.000 units/year) premium vehicles (in 2020), which, selling at a premium price, are more likely (initially surely) to incorporate more costly components / modules into the vehicle structure. This will allow for the maturing of these advanced lightweight technologies in real market vehicles. Further research, know how from first application experiences and increasing economies of scale will then lead to lower unit costs and make the advanced lightweight technologies economically viable for mass volume electric (and ICE) vehicles in the next generational leap (in 2025), thus leveraging the benefits over the whole EU vehicle fleet.

2. The ENLIGHT consortium

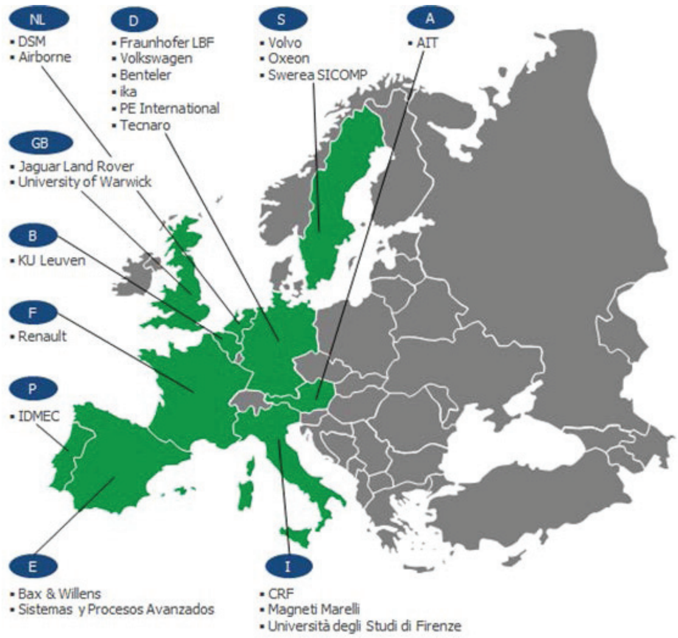

Fig. 1. The ENLIGHT consortium.

The ENLIGHT consortium is composed of 21 best-in-class organizations that lead their specific areas of RTD in Europe and which represent three EU level associations of the sector: EUCAR (carmakers), CLEPA (automotive suppliers) and EARPA (automotive R&D organizations). The consortium covers the full spectrum necessary for ensuring the successful development of the materials and the acceleration of their technological transfer from research to the European and global market. On the one side, it includes a pool of universities and research institutes with highly innovative materials and strong background in their respective fields. On the other side, leading European vehicle and part manufacturers, with practical experience on the processing and real-life use of the materials, will drive the innovations to the next level.

Industrial relevance is secured by the substantial participation of the majority of Europe's automotive OEMs (original equipment manufacturers): Volkswagen Group, Fiat (CRF), Renault, Volvo Group (trucks & busses) and Jaguar-Land Rover. The large representation of OEMs allows for excellent connection of the consortium with a broad range of past and parallel, local, national and European R&D projects. The industrial lead in the ENLIGHT consortium is further strengthened by the involvement of the three major EU-based, but globally present, suppliers Marelli, Benteler and DSM. Whereas the first two are leading suppliers for the automotive industry, DSM is a global player for plastics and composites bringing in innovative fiber reinforced thermoplastics. Applied research and academic excellence on advanced automotive material research and development is ensured by the presence of leading European RTOs and academia: Fraunhofer LBF, Swerea Sicomp, AIT-LKR, INEGI, KU Leuven, the University of Warwick, ika at the RWTH Aachen University and the University of Florence.

20% of partners are SMEs: innovative international companies Tecnaro, Oxeon, Airborne, Sispra, and Bax & Willems Consulting Venturing. The industrial SMEs do have advanced expertise in the field of advanced fibre reinforced composites and but do not yet have products apt for automotive mass production.

3. Scientific approach

The ENLIGHT project has been broken into 7 technical and two administrative work packages (management and dissemination & exploitation) (fig. 2). Their number and sequence reflect the natural and logical structure of the work.

The five considered modules of an advanced vehicle architecture are conceptually designed with respect to weight and CO_2 balance over life-time. The conceptual design of the modules uses as basis the vehicle architecture considered in ALIVE which again is taking into account the results of ELVA and SmartBatt. These designs are done with respect to weight, safety and performance that result from the application of the highly advanced material considered in ENLIGHT. In order to realise a full virtual vehicle design, the numerical model of each module will be incorporated into a simplified full vehicle model of the chosen vehicle architecture, allowing the evaluation of each module also on vehicle level.

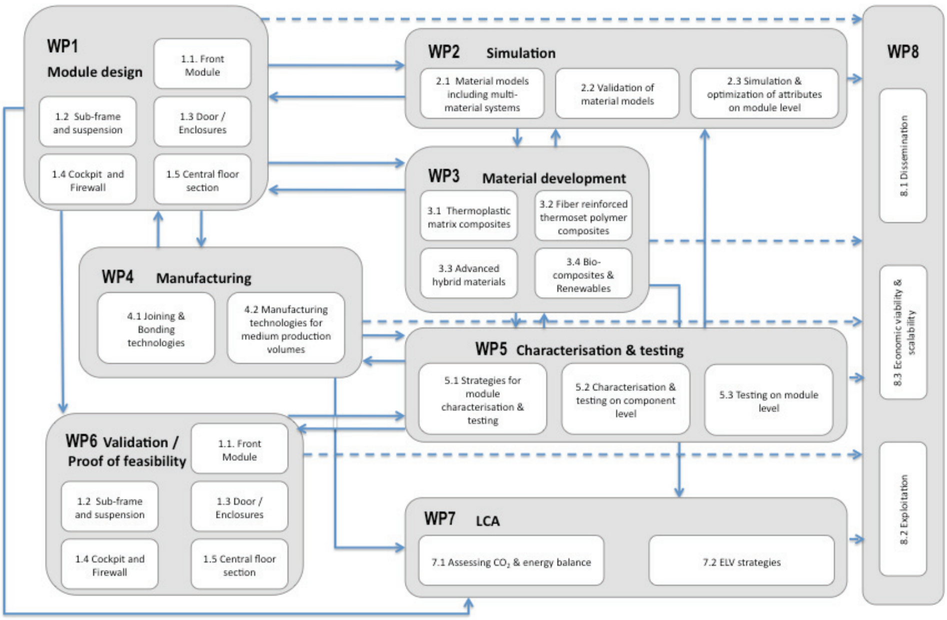

Fig. 2. ENLIGHT project structure.

Crucial for the designs is the development of new materials and associated manufacturing technologies. Within ENLIGHT highly advanced materials are developed to a stage that they are applicable at least in medium volume production. Only materials are considered which are currently not sufficiently matured to be applied in structural, safety-critical parts of vehicles and yet not suitable for medium to high volume production. In this context thermoplastic matrix composite materials are considered with various reinforcements and processes. Main objective is to realise high mechanical performance composites suitable for rapid manufacturing, injection/infusion moulding over casting and welding. A second class are fibre-reinforced composites with a focus on thermoset polymers. Although mainly carbon fibres are considered glass and hybrid fibre solution are being employed as well. Main focus is on the development of ultra-light composites ensuring the desired performance with minimum use of raw material. The approach is based on fabrics and textile reinforcement. In addition, the integration of function with respect to NVH and crash is being investigated. In parallel, composites based on bio-material and renewables showing a high potential with respect to the CO_2 balance are investigated. Bio-based resins as well as natural fibres are used to develop high performing bio-based composite suitable for automotive application. Finally, advanced hybrids (e.g. light-weight metals with fibre reinforced plastics) and sandwich materials (e.g. meta-materials [Claeys 2015]) are developed having a high potential to meet the targets of the module design.

The material development is complemented by investigating the required manufacturing technologies. In this context, the module design is being taken into account as well as required adaptations of the materials to the selected manufacturing process (e.g. surface treatments prior bonding). Additionally, ENLIGHT aims at realising corresponding manufacturing and assembly strategies. Consequently, joining and bonding of different material is considered as well as forming technologies for all considered materials required realising the modules.

All technology developments are taking into account a life cycle assessment which is being done in parallel. The European Regulations aimed to the reduction of the environmental impact of the vehicle during its life-cycle, particularly use (CO_2 emissions) and End-of-Life (ELV - 2000/53/EC directive), implies the necessity to integrate the environmental issues in the design phase, and, consequently, to apply dedicated methods/tools aimed to characterize and compare the impacts of different solutions (in terms of materials, components, technologies) and to support the designer in the identification and choice of those more sustainable. ENLIGHT applies a “from cradle to grave” assessment in order to calculate and compare the effects of different materials, related technologies and design solutions during the whole life cycle of vehicles components considered. This approach will allow to:

- screen highly innovative materials on the base of their environmental impact on different vehicle life cycle phases and choose the more eco-friendly options taking into account both design and technological issues;
- demonstrate the effects of changing component materials on emissions (GHG, energy footprint, etc.) related to the whole life-cycle of the vehicle;
- model and characterize the influence of weight reduction on GHG emissions related to use phase of vehicle;
- take into account the use of resources (e.g. energy, materials) and the waste production during manufacturing;
- model and simulate different sustainable scenarios for managing/valorising End-of-Life components and scrap materials according to the 3R (Reduce, Reuse, Recycling) policy.

3.1. Interconnection with other projects

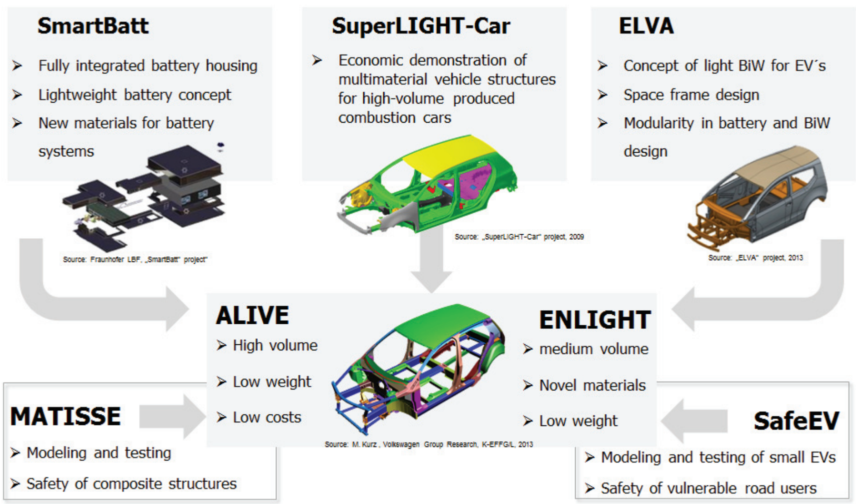

Fig. 3. ENLIGHT interconnection with other projects.

The ENLIGHT project is highly linked with past and running projects. Together with the Green Car Initiative (GCI) projects ALIVE, MATISSE (MATISSE 2012) and SafeEV (SafeEV 2012), the SEAM cluster (SEAM 2012) on lightweight technologies was formed mainly for joint dissemination. Particular with the project ALIVE a close collaboration was established considering the same overall vehicle architecture provide by ALIVE. This vehicle architecture considers the results of the past projects SuperLightCar (SLC 2005), SmartBatt (SmartBatt 2011) and ELVA. The interaction between all projects is shown in Fig. 3.

4. Selected results

In this chapter some selected results will be presented. The results presented are just a non-exhaustive summary of a few activities within ENLIGHT and cannot be considered as the final project results.

4.1. Module design

Within ENLIGHT five different modules are considered (see Fig. 4). However, due to the limited space available only results for the suspension and door module will be discussed. Nevertheless, the design of each module has been finalized utilizing the novel materials and associated manufacturing technologies developed in ENLIGHT. Currently, the manufacturing of prototypes with different degrees of complexity is being prepared.

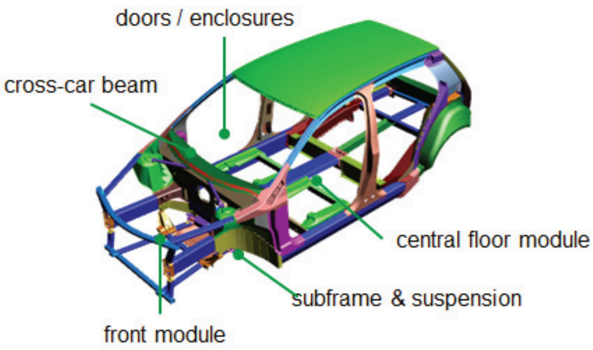

Fig. 4. ENLIGHT modules with the vehicle architecture of (ALIVE 2012).

Control arm as part of the suspension modul

Fig. 5. 2nd prototype of the CFRP control arm.

In ENLIGHT two different concepts for a control arm were developed, one focusing on hybrid materials, the other on function integration. In the first concept, aluminum parts at the connection points are being overmolded with vinyl ester resin reinforced with chopped long carbon fibers. In critical areas unidirectional reinforcement was introduced. For the medium-scale production advanced sheet compression molding is foreseen. With this concept 50%

weight reduction can be achieved compared to a state-of-the-art metallic one. The second concept is a full CFRP control arm with integrated piezo ceramics (Fig. 5). The piezo ceramics are used in a shunted configuration to fully control the first eigenfrequencies of the lightweight control arm improving the NVP properties. Despite the additional integration of piezo ceramics this concepts still achieve 45% weight reduction but with better NVH performance. The integrated piezo ceramics could also be used to monitor the health and endured operational loads of the full composite control arm. As industrial manufacturing concept a fast RTM-process is foreseen.

Door module

Within ENLIGHT a full composite door has been developed. The new door concept consists of the four main components door outer skin, intrusion beam, waist rail reinforcement and door structural inner, each designed with composites. The outer skin, the structural inner as well as the waist rail reinforcement are made of the TeXtreme® laminate based on carbon fiber reinforced UD tapes with DSM EcoPaxx® PA 410 as matrix. The components will be manufactured with a hot stamping process. The intrusion beam is made of UD carbon tapes using a continuous fibred placement process developed by Airborne. Three separate beams will be joined together to the intrusion beam by thermoplastic welding. This door concept weights about 7 kg and is 20% lighter as the reference door from ALIVE.

4.2. Materials

Bio-composites and renewable

The selection process for bio-based thermoplastic polymer matrix is heavily dependent upon the thermo-mechanical performance in accordance with design in the various applications, the compliance with regulations and standards, such as REACH as well upon a low embedded carbon footprint of both processes and materials. Next to the thermo-mechanical performance to fulfil the primary design function, components must also prove their capacity to be exposed to different conditions, and test methods for durability under environmental conditions and other external factors. Material used in these components should be evaluated in similar conditions and such tests included in the testing program. Compliance with regulations and Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) is required. Moreover for bio-materials and renewables materials, the impact on the environment of such materials has to be studied and analyzed versus the standards ISO14040 / 14044.

As the driving phase of electrical vehicles itself is generally considered carbon neutral (i.e. the CO2 produced to generate electricity is not considered as it is not directly related to tail pipe emission), an LCA approach is required taking into account the country specific energy mix as well as the carbon footprint of processes and materials in the value chain. Materials developed in ENLIGHT are either fully or partially bio-based, and are having an impact on both LCA and carbon footprint. PA410 from DSM for example is currently 70% bio-based and has a low embedded carbon footprint. The natural or bio-based fibers used by TECNARO are typically made from 100% renewable resources. The polymer matrices are made up-to 100 % from renewable resources with exact values depending on the feasible cost/performance ratio and its compatibility with the natural/bio-based fibers.

These bio-composites and renewables based on both chopped – compounds - and continuous fiber - composites - reinforcements as well as their initial material and processing behavior have been modified and made available to support different tasks such as design, simulation and manufacturing. Molding compounds were made with a variety of combinations of Polyolefines, bio-based regenerated cellulose fibers and natural fibers as well as with the bio-based polymer PA410 reinforced with chopped carbon fiber. The level of the reinforcement fibers (i.e. fiber wt-%) or additives were modified according to requirements of the modules. Similarly, composites were developed in the bio-based polymer PA410 reinforced with either continuous glass or carbon fiber to form a uni-directional tape. These tapes form the basis to build laminates that consist of either stacked plies or stacks of spread-tow woven tapes. Both stacked UD laminated and woven tape based laminates are used in design optimizations of the front module, the floor module, and the door.

Hybrid materials

Hybrid material systems may offer a variety of advantages over mono-material solutions. Several module concepts within ENLIGHT rely on the combination of thermoplastic CFRP with aluminum alloys (Table 1). The considered hybrids combine high strength, high stiffness and low weight of CFRP structures with the ductile, failsafe behavior of aluminum. Especially hybrid components with metal joining sections allow the cost-efficient integration of lightweight composites into automotive assembly processes: complex FRP-metal joining operations - such as adhesive bonding of thermoplastics with aluminum - can be realized on a module level at tier 1 suppliers, away from OEM assembly lines. The OEM may focus on a reduced number of joining technologies.

Table 1. Hybrid material systems: thermoplastic CFRP in combination with aluminum.

module	Implementation of hybrid materials
Front module	Roll formed bumper beam in Aluminium design with directly joined CFRP/GFRP patch
Suspension control arm	Thermoformed CFRP structure with aluminium sheet insert
Cross-car beam	Aluminium and CFRP inserts overmoulded with short fibre reinforced thermoplastic
Central floor section	Aluminium joining flanges bonded to CFRP/GFRP floor panel

The described hybrid structure concepts may partially be realized by separated metal and FRP manufacturing steps that lead to an assembly step. A typical joining technique suitable for monolithic FRP components is adhesive bonding. Presuming an Aluminium-PA410 multi-material module that has the characteristic of a hang-on part without the need for e-coating on body in white level, the target is to reduce the number of manufacturing steps, cycle time and surface pre-treatment effort for hybrid Aluminium-PA410 components. The basic approach for fabricating hybrid Aluminium-PA410 systems is to make use of the thermoplastic behavior of PA410: heating above the polymer melting temperature allows reshaping the FRP on the one hand; on the other hand the molecular polymer surface structure gets unbound and allows material bonds to solid or molten joining partners. Object of investigation was the potential of direct thermal joining methods for manufacturing structural hybrid Aluminium-PA410 components. A variety of heating methods is available for heating PA410 composites locally or thoroughly over the melting point for joining with metal substrates:

- Ultrasonic welding
- Hot gas welding
- Contact heating by metal joining partner (e. g. heat element induction welding)
- Infrared heating
- Laser heating
- Convection oven heating

However, the investigations on advanced hybrid material combinations do not focus the differences between heating techniques but emphasize methods for interface optimization with impact to the bond strength and corrosion resistance of the material joints established. The target was a comparative study between several interfacial design strategies for developing Aluminium-PA410 hybrids manufactured by means of highly integrated processes. The investigations result in a recommendation for design and process developments within ENLIGHT. A chosen interface configuration is being transferred to joining tests and to a hybrid demonstrator component as seen in Figure 6. This component works as a technology demonstrator for structural tests and CAE validation.

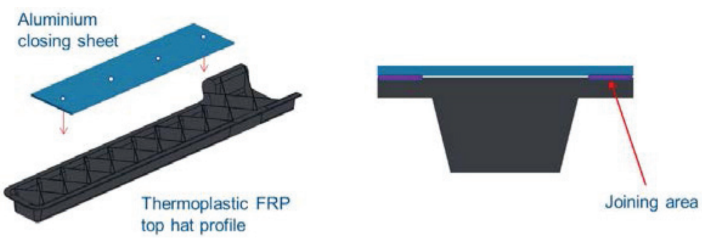

Fig. 6. Demonstrator for advanced hybrid material system.

The technical reference for the material joints evaluated is the structural adhesive joint between PA410 composites and aluminum sheets. Material investigations take results from the structural adhesive joint investigations as a benchmark and demonstrate the potential for alternative material joints based on more integrated manufacturing concepts than elementary adhesive joints.

4.3. Manufacturing

Among others, advance composites processing methods are being developed aiming to achieve efficient high volume RTM manufacturing of advanced composite products. Within this context thermoset composite materials were studied using TeXtreme® fabrics as reinforcement. To achieve high volume manufacturing with short cycle times the process must be automated. Therefore, the suitability of TeXtreme® fabrics for automated manufacturing, including cutting, pre-stacking and pick-and-place was investigated. It has been shown that not only automatic cutting, pick-and-place & pre-stacking of TeXtreme® fabrics are feasible but also that it presents no disintegration when cut at sharp angles and thin shapes, which is a clear advantage over conventional weaves and unidirectional fabrics. The reference station designed for this work allows both, removal of backing paper and re-gripping for more precise positioning. The robot was programmed to perform a sequence of tasks to achieve the placement of a realistic stacking sequence for a sandwich composite in a mold. That way it was shown that a complete automation of the pre-tool handling is possible. Another advantage of the TeXtreme® fabrics was proven to be its ability for pre-stacking, and the possibility for complete automation of this task could be shown. The possibility for handling of complex shapes and precise placement was once more proven by the automatic assembly of a puzzle from complex pieces of TeXtreme®.

Furthermore, multi-physical modelling of infusion was performed to increase the understanding of RTM processes and allow the prediction of process-related properties. To the author's knowledge, there is no available general poromechanical formulation for composites processing methods. In that sense, a special porous media formulation has been developed in ENLIGHT in order to model a dual-scale coupled flow-deformation process with constitutive relations concerning four different mechanisms governing all the processes involving (1) constitutive effective stress response of the fiber bed, (2) infiltration of resin into fiber plies, (3) elastic packing response of the plies, and (4) Darcy’s law governing the macroscopic interaction between the two phases. In addition, if necessary, the model accounts for the non-saturated behavior typical for the transition region at the flow front between full and non-saturation. A staggered finite element based solution procedure has been put forward for the total solution advancement, involving, on the one hand, the saturation degree dependent porous media formulation, and, on the other hand, the assessment of the saturation degree using a post-processing of the Darcian velocity field. Also by introducing the dual-scale formulation of the flow-deformation and an anisotropic permeability model, using packing response of the plies, we are able to track the saturation in both micro and macro scale.

Besides, an innovative method for fast infusion was investigated and optimized utilizing the results from the multi-physical modelling of infusion. The method is based on an injection-compression process, where the resin is injected into a gap formed by a partially opened tool, followed by compression. The process is facilitated by the use of spacer fabrics that circumvent the normally inaccurate position control of a hydraulic press. The investigations were performed using the novel heavy tow (50k) TeXtreme reinforcement and an innovative fast curing resin system with low viscosity for RTM.

4.4. Life Cycle Assessment

Within ENLIGHT, a LCA analysis is conducted on four of the five automotive modules in order to compare the environmental impacts related to different design solutions in terms of the adoption of highly novel lightweight materials and of associated manufacturing technologies. The approach applied in ENLIGHT has been developed according to the international LCA standard EN ISO 14040 taking also into account the outcomes of the International Reference Life Cycle Data System (ILCD) framework as well as the eLCAr (eLCAr 2012) project.

Life cycle of ENLIGHT modules is divided into the phase’s production, use and end-of-life. All activities involved in the three life-cycle phases which give an appreciable contribution to the overall environmental profile must be considered; at this regard raw materials extraction, manufacturing of subcomponents/auxiliaries, consumed energy production, logistics/transportations and EOL treatments are the main steps. The Functional Unit (FU) describes the primary function(s) fulfilled by a product system and indicates how much of this function is to be considered in the intended LCA study. A proposal of Functional Unit has been formulated as “The whole life cycle of the innovative ENLIGHT module: its production, use (on an electric vehicle of about 450 kg for 250.000 km) and

End-of-Life”. In the Life Cycle Inventory (LCI), data required for the LCA analysis are collected and processed to identify which exchanges with the ecosphere are triggered during the life cycle of the product. LCI is composed by two main steps: data collection and modelling. The first fulfils the collection of data regarding LC of examined module(s). The second identifies and quantifies all elementary flows that characterize environmental profile of such module(s). The findings of LCI analysis become the input for the subsequent Life Cycle Impact Assessment (LCIA) phase and also provide feedback to the scope definition phase as initial scope settings often need adjustments. The LCIA represents the phase in which inputs and outputs of elementary flows that have been collected in the inventory are translated into an ensemble of environmental impact indicators. The impact assessment analyses the potential environmental impacts caused by interventions that act both on the natural environment and on humans. The LCIA results should be seen as environmentally relevant impact potential indicators, rather than predictions of actual environmental effects. To perform LCIA analysis, many LCIA methods are available at the time; in the ENLIGHT LCA application the CML 2001 method has been adopted based of dataset availability for the novel materials and innovative technologies. CML 2001 is an impact assessment method which restricts quantitative modelling to relatively early stages in the cause-effect chain to limit uncertainties and group LCI results in so-called midpoint categories, according to themes. These themes are common mechanisms (e.g. climate change) or commonly accepted groupings (e.g. ecotoxicity).

Outcomes from the first iteration of LCA analysis of the innovative design solutions took into account the materials production and the use phases as the ones immediately affected by the application of multi-materials innovative solution. The analysis showed that the material production phase contributes to the majority of the impact categories for more than the 60% meaning that the benefits achieved by a weight reduction are otherwise combined with not negligible impacts due to raw materials extraction and processing.

5. Conclusion

The main challenge faced in ENLIGHT is the parallel approach of material development and design. This approach has high potential to result in innovative solutions, as the materials properties can be optimized for the application, at the same time as the parts are designed to exploit the materials properties in the best way. However, this approach is also a challenging task and requires close collaboration between material development and module design. Up to now the ENLIGHT project achieved new designs of specific vehicle modules in which highly advanced and particular adapted material solutions could be integrated. With this significant weight savings compared to the ALIVE project could be achieved. The remaining challenge until the end of the project is the validation of their cost-effective manufacturing for medium scale production.

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