Evaluate the Environmental Impact of the Production of FRP Components

How Sustainable Is Lightweight Design Really?

Lightweight design with fiber-reinforced plastics saves energy resources in the use phase of automobiles and aircraft. However, the savings are often offset by higher consumption in production. Therefore, the focus is increasingly shifting to sustainability in manufacturing. The Research Institute Neue Materialien Bayreuth has conducted a corresponding sustainability analysis for the processing of thermoplastic UD tapes into functionally integrated components.

According to a 2019 study by the opinion research institute Agora Verkehrswende, on average 42 % of the CO_2 emissions of electric vehicles over their entire life cycle are attributable to production, 56 % to the use phase, and 1 % each to disposal and recycling and other consumption [1]. Lightweight design makes it possible to reduce CO_2 emissions during the use phase. However, lightweight solutions often require higher energy consumption in production than conventional designs (**Fig. 1**). In the case of fiber-reinforced composites, relatively high CO_2 emissions are already generated during the production of the reinforcing fibers, especially in the energy-intensive production of carbon fibers, which the lightweight construction solution must first recoup during the use phase. At the end of the product life cycle, the consumption for recycling must also be taken into account, which is often higher for composites.

An important question for the sustainability is therefore how high the CO_2 emissions of production may be so that in the end there is still an advantage over conventional solutions in terms of savings in the use phase. The emission savings from lightweight design in the use phase can be easily calculated. For an overall balance, however, the footprint of production is also necessary. At the Research Institute Neue Materialien Bayreuth (NMB), Germany, corresponding studies were carried out on the carbon footprint of the production of components made of fiber-reinforced plastics.

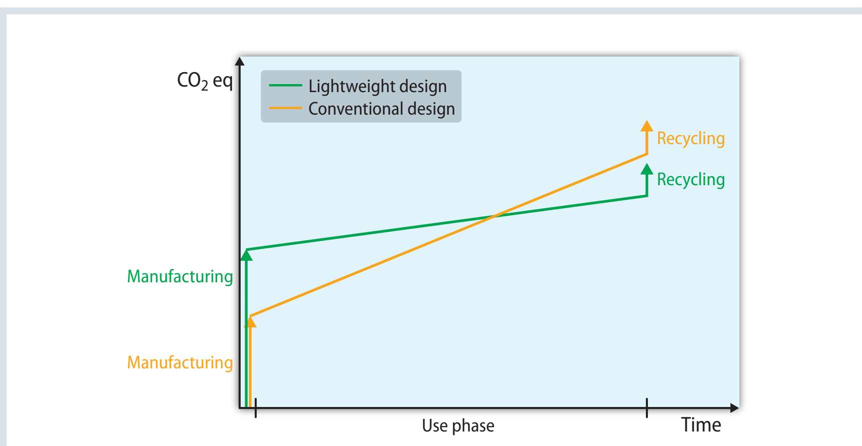

Fig. 1. Lightweight vs. conventional design: schematic representation of the increased energy requirements for lightweight solutions compared to conventional solutions in manufacturing and the subsequent resource savings in the use phase due to lower vehicle weight. Source: NMB; graphic: © Hanser

Life Cycle Assessment in Practice

The aim of the NMB's work was to create suitable models for the life cycle assessment of the manufacture of lightweight components based on continuously reinforced thermoplastic tapes (UD tapes). The life cycle assessment method (LCA) according to DIN EN ISO14040 and 14044 [2, 3] describes the procedure to quantitatively assess the potential environmental impact of a product over its entire life cycle. Depending on the purpose of a LCA, subsystems (e.g. cradle to gate, gate to gate, cradle to grave) can also be considered as a framework.

Establishing Framework and Impact Category

The first step is to establish a framework that defines the system boundaries, a functional unit, and the assumptions, methods, and constraints. Once the framework is defined, the subsequent life cycle inventory step quantifies all media flows in the production chain and, if necessary, supplements them with database values. Finally, the desired impact category for the assessment is defined. Examples of such impact categories with associated impact indicator values are the greenhouse effect or global warming poten-

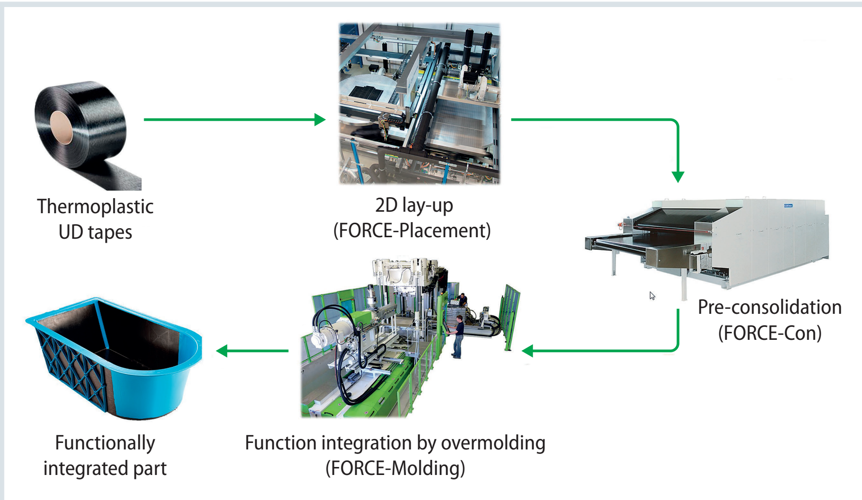

Fig. 2. The FORCE process chain enables the production of functionally integrated lightweight components based on UD tapes in short cycle times.. Source: NMB; graphic: © Hanser

tial in kgCO_2 eq. (kilograms of CO_2 equivalent), land use and unit area in km^2, or acidification and acidification potential in kgSO_2 eq. The assessment of LCA already takes place in parallel with all sub-steps.

Life Cycle Analysis of an FRP Process Chain

In recent years, fiber-reinforced thermoplastic composites, especially organosheets, have steadily made their way into automotive series production. UD tapes are a useful addition here, as they enable load-oriented preforms and reduce waste depending on the contour. Thermoplastic composites offer advantages such as short cycle times, functional integration through injection molding and recyclability. In addition to their use in the automotive sector, they also have great potential for other applications, such as sporting goods and the aerospace industry. In recent years, the NMB has developed the FORCE process chain (FORCE = Functionalized Oriented Composites), an approach for manufacturing thermoplastic lightweight components on an industrial scale that encompasses processing from the UD tape to the overmolded component (**Fig. 2**). [4–6]

The FORCE process chain is a good example to illustrate the LCA process for manufacturing fiber composite components. For the LCA, the flow of this process chain (flowchart in **Fig. 3**) is modeled in GaBi software (version 9.2.1, manufacturer: Sphera Solutions). For the sustainability assessment, a "cradle-to-gate" approach is chosen as the system boundary. This includes all data from the start of production, including raw materials and semi-finished products, to the "factory gate" when the component leaves the production facility. The production of raw materials is mapped using the "Professional" and "Carbon Composites Extension" databases of the GaBi software. A "component" is chosen as the functional unit and thus as the reference value for the evaluation. This also makes it possible to compare the effects of using different materials and layer structures for one and the same component. The effort required for the creation of the infrastructure as well as for personnel and transport routes is not taken into account in this evaluation.

Which Processing Steps Generate the Highest CO_2 Emissions?

The component used for the tests was a complex overmolded component from the 2D-MultiMat research project (**Fig. 4**), which was developed jointly with the companies Brose Fahrzeugteile and Rehau Automotive. It consists of a woven organosheet and a UD multilayer structure based on polypropylene (PP). A pure carbon fiber-reinforced (CF) component was compared with a cost optimized hybrid preform made of carbon and glass fibers (CF/GF hybrid) [7]. Long glass fiber-reinforced PP was used for functional integration in the injection molding step. The preforms were produced in a FORCE lay-up process followed by molding and functional integration by injection molding in a one-shot process on a 2500 t injection molding press.

In a first step, the production of a laminate-based demonstration component consisting only of PP-CF-UD tapes was investigated using the FORCE process chain. The evaluation results in CO_2 emissions totaling 17 kg CO_2 equivalent for the functional unit of a component. The dominant contributors to the overall CO_2 footprint are the CF tapes, which are energy-intensive to manufacture, and the tape laying processing step. Tape laying is dominated by the energy consumption of laying systems that use »

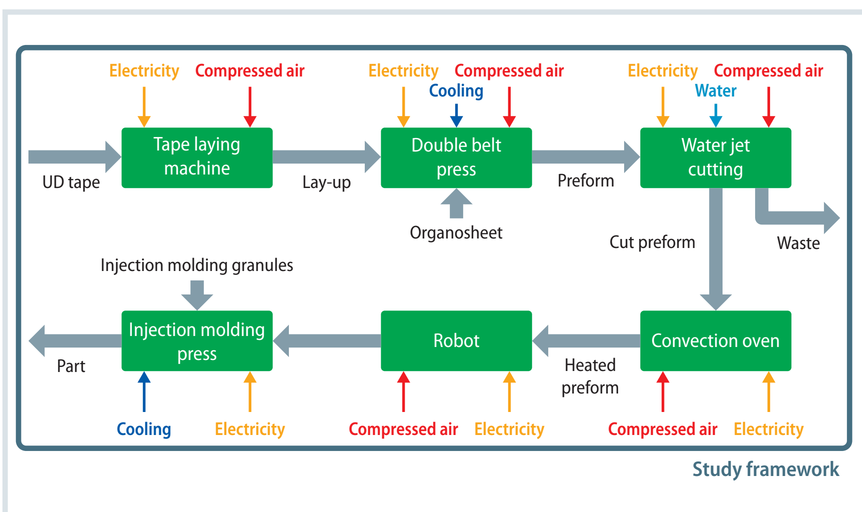

Fig. 3. The flow diagram shows the media flows of the FORCE process chain measured in operation and the scope of investigation. Source: NMB; graphic: © Hanser

partial vacuum. It should be noted that the FORCE laying system is designed for large-area laminates up to 1500 mm x 1500 mm, but in the case of the component studied, only a quarter of the possible laying area was used. A tape laying system for a series component, on the other hand, would be optimally adapted to the respective component size. In a next step, the tape laying system was therefore optimized for the component and the laying process was examined for optimization potential in a separate project.

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References & Digital Version

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Optimization of Tape Laying with Digital Twin

The greatest influence on the environmental impact of a lightweight component is exerted in the early stages of product development. Prototyping and the start of production increase the data quality for a sustainability assessment, as the materials are defined and the energy consumption in production can be accurately recorded. The result can therefore be well evaluated. However, it can hardly be influenced at this stage. For this reason, digital tools such as digital twins now offer the possibility to simulate not only the component but also the manufacturing process in the early stages of product development and to optimize it for sustainability and economic efficiency.

For the tape laying process, NMB and its partner SWMS Systemtechnik Ingenieurgesellschaft have extended the CAESA laying software to include the digital twin of the FORCE placement tape system as part of the OptiTape project (**Fig. 5**). This simulates and visualizes the complete laying process in advance. The variables laminate design, tape properties (such as price, CO_2 footprint of semi-finished products, width), permissible tolerances, angular cut and an optimization strategy based on an algorithm can be selected as input. Different optimization algorithms are available depending on the desired objective. Optimization can be based on emissions, costs or laying time. The optimal laying strategy is determined, visualized and validated for the given laminate design. If the UD tapes are not yet available in a specific width, e.g. because a master roll is available directly from production, the software can also determine optimal tape widths for cutting the master roll. The lay-up system can process two different strip widths or materials in parallel into a preform. Finally, the laying time, resource consumption and waste are specified for each component.

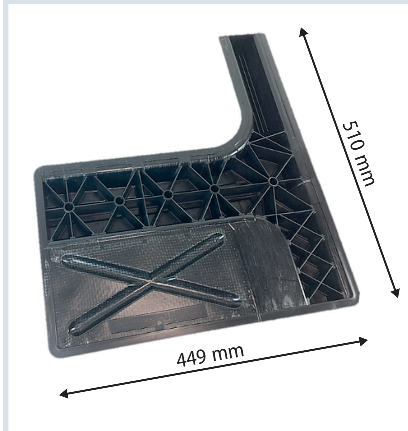

Fig. 4. The demonstrator component "2D-MultiMat" was manufactured with laminates of woven fabric organosheets and UD tapes (CF or GF/CF hybrid) based on PP and injection-molded functional integration (PP-GF) with the FORCE process chain. © NMB

Optimization of the CO_2 Balance for the Demonstrator Component

Two approaches were taken to optimize the CO_2 balance: firstly, adjusting the material mix in the component (layer structure) and secondly, optimiz-

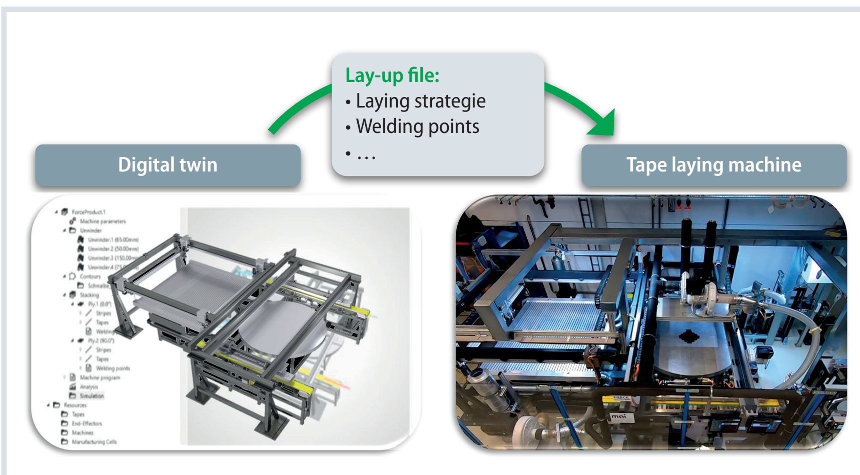

Fig. 5. The digital twin of the FORCE placement tape laying machine based on CAESA software enables optimization in terms of cost efficiency and sustainability in the early product phase. Source: NMB; graphic: © Hanser

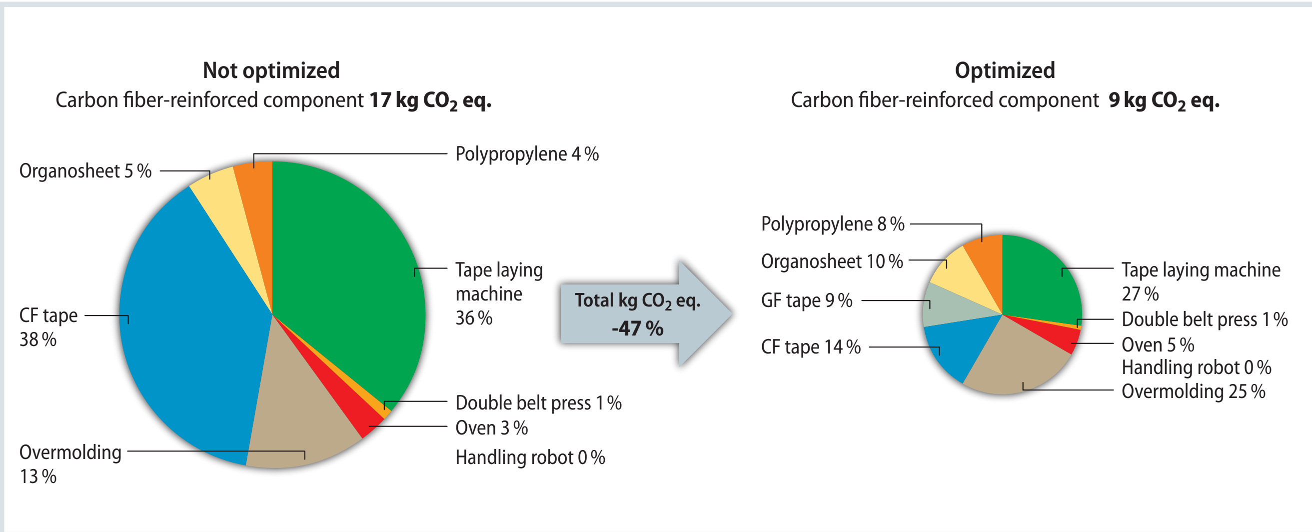

Fig. 6. By replacing the CF tapes with GF-CF hybrid variants and optimizing the energy consumption of the manufacturing process, the CO_2 footprint of the demonstrator component can be reduced by a total of 47 %. The example illustrates the large savings potential through adjustments in materials and manufacturing. Source: NMB; graphic: © Hanser

ing the energy consumption of the tape laying process. Both factors contribute significantly to the emissions of the pure CF component. In the layer build-up, narrower tapes can reduce the amount of waste. However, this leads to a longer machine running time and thus also to higher energy consumption of the tape laying system, as the utilization time of the partial vacuum system is extended. Both economically and ecologically, the optimum tape width is a compromise between the lowest possible waste and the shortest possible machine running time. To optimize the resource efficiency of the component, the layer structure was optimized by a GF-CF hybrid structure [7]. While the original laminate was reinforced only with CF tapes, the percentage of CF tapes is reduced to 16 wt. %. The rest are GF tapes. The CF tapes are used only at the highly stressed load paths in the component. This reduces material costs by 50 % and installation time by 18 %, while increasing component weight by 16 % and reducing component stiffness by 10 to 30 %, depending on the load case.

In addition to material substitution, the NMB has also implemented initial measures to optimize the energy consumption of the belt laying system. The partial vacuum systems are now only used in the required areas. In addition, less partial vacuum can be used to suck the tapes with low internal stresses. In addition, nesting for the build-up of up to four parallel preforms can be carried out on the large laying table. Overall, this reduced CO_2 equivalents per component by 47 % from 17 to 9 kg (**Fig. 6**). After the optimizations, energy consumption in the process is now dominated by the tape laying line with 27 % and the injection molding press with 25 %, followed by the CF tapes with 14 %. Comparing the added shares of CO_2 emissions, the materials contribute 41 % to the total emissions of the lightweight component through their production and 58 % through processing. From this, the clear objective for further research can be derived to further optimize the process chain of overmolding in terms of energy in order to minimize the CO_2 consumption of lightweight components in production.

The results show that in order to minimize the CO_2 footprint of lightweight components based on thermoplastic UD tapes, two key points must be taken into account: material savings potentials (offcuts, load-adapted hybrid structures) must be consistently exploited and the manufacturing process must be optimized in terms of energy. The combination of digital twin and LCA model of the manufacturing process makes it possible to optimize economic and ecological aspects at an early stage in component development. The NMB supports interested companies in the development of customized solutions for more sustainable FRP lightweight structures. ■