

Use Case 3: Modular Car Parts Disassembly and Remanufacturing



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Abstract Cars designed for reuse are a novelty. The disassembly and remanufacturing of major vehicle structures is not an established process yet. This means new tasks and within that, new business models must be found to close the loop. New facilities and logistics are part of the process chain. In this chapter the processes will be outlined on basis of a car-sharing vehicle as an example of a fleet ownership. The reusable platform and the seat structure are the basis of this model-based consideration. The technical issues and obstacles will be discussed as well as economic and ecologic questions.

Keywords Remanufacturing · Inspection · Repair · Logistics · Detachable joints · Car-sharing · Fleet owned vehicles · Life-cycle assessment

1 Introduction: New Opportunities for Car-Sharing Vehicles

Cars are one of the best examples of progress over the last century. Today about 1.2 Billion cars are in use [1]. The numbers are growing fast due to a growing middle class in the developing countries. Buying a car is still a major step in life for most people, showing independency and comfort. Nevertheless, this trend has also led to increased traffic jams and high cost for parking spaces, because the infrastructure cannot grow accordingly. Today none of the cities with the highest traffic jam level is to be found in the western world [2]. This means the problem has already become

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worldwide and it cannot be solved due to high demand for space in the city. Today, parking slots take up about 10% of traffic areas in cities [3]. Since vehicles are not in use for the major time of the day, the whole system is not very inefficient. The vehicles in parking spaces are blocking spaces for buildings, green areas and streets. The low utilization rates of cars in combination with the fast loss of value show that the private owned car in many cases is not the predestined solution for cities.

Classic solutions to improve mobility are to expand public transport like busses and metro lines. However, these solutions are not addressing the independency and comfort. Car-sharing as an alternative to owning a car could help to improve this challenge. This means the ownership of the car goes to the car sharing provider together with many changes of valuation and utilization.

For the FiberEUUse project, sharing vehicles also show another benefit of high importance. These vehicles are not privately owned which means, the owner is always interested to earn money with these vehicles. The owner will act as a homo economicus and always decide the option for himself. This makes the decisions calculable and comprehensible. Another major aspect is logistics and knowledge. While a privately owned car can be sold to a new owner at any time, the car may be used anywhere in the EU or in other countries. To close the loop, the vehicles must be brought to a collection point with a very high logistic effort. For the car sharing cars this factor is different. Their position and sometimes even their condition are known and they can be collected comparatively easy. This lowers the cost from the start and it is seen to be a precondition for a first implementation of reusable car structures.

The idea of reusing structures led to the design of a vehicle platform and a seating structure visible Fig. 1 with special purposes that will be discussed in the following. Both together are demonstrating how reuse of vehicle parts made of CFRP will become possible to achieve improved life cycles.

1.1 Use-Phase of a Sharing Vehicle

The car sharing provider follows a simple basic business model. The user must rent the cars he possesses for a long time and distance. This means the cars intently designed for private utilization will be used for a much longer time per day resulting in a much younger age of the car when it reaches the maximum distance it was designed for. This distance varies from producer to producer. An experience value is about 160,000 km.

The owner of the car—this could also be a leasing company—will only keep it in the portfolio while it makes sense in an economic way. The cost for inspection repair is growing with more years and kilometres. The design of the car on the other hand must be kept young. The users want to drive a modern car with new technologies. These technologies are not only the powertrain, but also the electric components and connectable devices in the interior. The users are not the owners of the car. They have low experience in driving it. Not owning the car also leads to lower caution and



Fig. 1 Demonstrator of use-case 3—reusable structures for vehicles

sometimes vandalism. These effects lead to a comparatively short phase of utilization in car-sharing of about 4 years [4].

The overall distance of a carsharing car is not the only driver of value loss. The fleet management will always try to keep the fleet in a modern state to lower inspection costs. Today the desired 160,000 km distance is usually not reached. With increasing market penetration of car-sharing this value seems to be realistic, resulting in 40,000 km per year. The usual distances vary from only about 10 kms in particular for free-floating to 30–60 km for station-based systems [5].

Car-sharing is a growing business segment in Europe. In Germany only 25,400 sharing vehicles exist. This number has increased from 15,000 within 5 years. The number of users has reached 2.5 Mio. A very interesting point is that the share of electric vehicles is more than 20%. This shows the high affinity to new technologies within the users. It can be shown that a single car-sharing vehicle may replace about 10 privately owned cars [5].

1.2 Basic Steps of a Car with Reusable Structures

The reusable car shows a life-cycle differing from a standard vehicle. While many elements are similar, new phases and in particular a circular phase is added. The production of the car and a first utilization phase are similar to the standard process. But after this first use-phase an innovative procedure begins. Already during use, it is possible to gather as much information about the vehicle as possible. This can indicate how to proceed (Fig. 2).

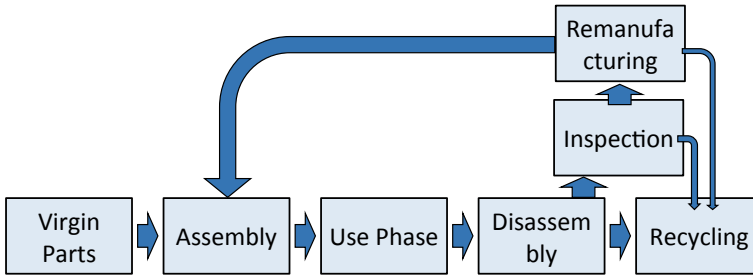


Fig. 2 Basic steps for reuse of structures in cars

The first new step is the detachment of structures. This step is not a novelty, but the result here is not separated materials, but separated healthy reusable structures on one hand and not reusable parts and materials ready for recycling on the other hand. For the recycling, the developed technologies of the two other use-cases are predestined. Here, detachable connections as designed in the discussed car structures can play out their benefits.

It follows the inspection phase. Here, a first visual check is followed by precise measurements of the structure conditions. In an usual case, the precise measurement is not necessary, because the reusable structures were designed for a longer lifespan and several reuse cycles. However, crashes and unforeseen event can lower the mechanical properties and can be a risk. This is a reason why data collection can help to improve the process. Possible technologies are simple measurements of acceleration forces or structural health monitoring.

The remanufacturing phase will be conducted for all structures intended to be reused. To achieve ecologic processes, this must be a very high share. In the remanufacturing step, first the joints are cleaned. Since the structures are made by composites, adhesive connections are preferred. The novel detachable adhesive connections will leave residual adhesive since they are failing cohesively in the adhesive layer. After cleaning, another inspection could take place. The cleaned parts can then be repaired if smaller cracks or surface deflections occurred.

Last step is to bring these parts back into production. This means a logistic effort to bring the structures to the vehicle manufacturer. By tracking the parts, it is possible to retrace the history of any structure. Long-term failures can be detected.

The new procedure begins, when the owner of the car decides, that maintaining the existing vehicle causes more cost than a new vehicle. This can also be induced by new technologies or designs influencing the market. The car sharing provider is always intended to achieve the highest return on his investment. Different business models could be applied to determine the ideal point of re-investment in form of a new vehicle based on the reusable structures.

When the decision is made, the cars first must be recollected. This is a work-intensive logistics process. For station-based car-sharing the vehicles will be located at the stations while for free floating car-sharing the cars must be located and collected. The place for the disassembly, inspection and remanufacturing process is

preferably located centralized to reduce logistics and investment costs. Here, it must be noted, that the transport of the cars for longer distances reduces the economic and ecologic assessment of the circular value chain.

2 Disassembly

The disassembly process begins at the centralized remanufacturing facility. The disassembly is conducted similar to classic disassembly. The components worth to be reused as a spare part or using the new reuse procedure must be recovered from the parts for the recycling. The main goal is to separate the vehicle into the different categories. The novel reuse parts are another group beside the spare parts and the different recycling grades.

Usually, the process begins with the add-on parts like doors and front ends. These parts can easily be reused in form of spare parts. It can be necessary to perform a remanufacturing step like dent removal or painting. The processes can be seen in Fig. 3.

In the next steps the reuse-parts can be recovered as well as many other spare parts or recycling material. The battery housing is a bohemian part for battery electric vehicles. The prepared detachable joints are used to recover the battery housing easily. It is assumed that the capacity is usually still high enough for another car life. Due to a high dynamic development in this area, it is not part of this consideration.

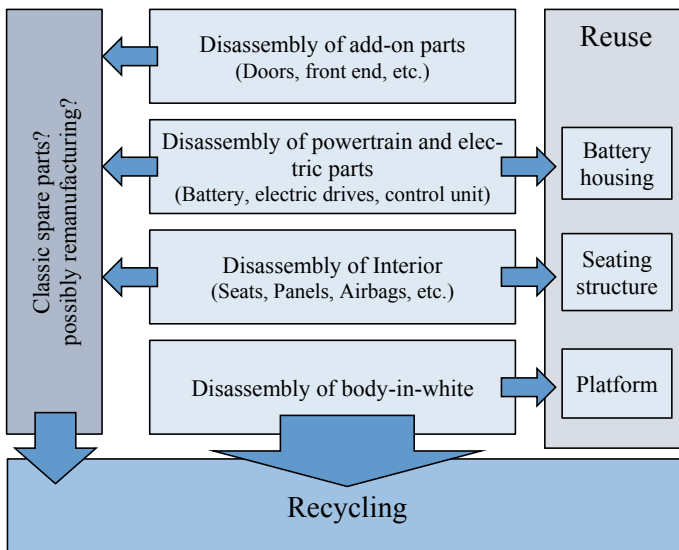


Fig. 3 Schematic disassembly procedure

During the third step the interior is disassembled. Here, the seat can be recovered and goes to the specialized station for reusable seats that will be discussed in Sect. 2.2.

The body-in-white usually is not part of the disassembly process, because all connections are non-detachable. Here, the novel design enables an additional dismantling step.

2.1 Platform Disassembly

The platform is the most important part of the vehicle that consists only of a dismantled body-in-white. To recover the platform several connecting elements must be removed. This is a quite simple process for the numerous bolt connections at the front and the back of the car. They connect the aluminum front-end and back-end to the so-called hat with the passenger cell.

For the rocker panel, the process is more complicated. To meet all crash safety requirements, the aluminum crash structure is connected to the platform with a sealing and structural polyurethane adhesive. A simple technology to cut this connection is to use a wire saw. This is a thin wire with cutting teeth or a specialized geometry to cut through adhesives. These wires are also in use for removing windshields. In an experiment visible in Fig. 4 the disconnection of two carbon fiber reinforced parts was investigated.

It could be shown that cutting through the adhesive is more energy intensive than cutting through a simple sealing adhesive for windshields, but it is possible. Hence, it is highly recommended to use a commercially available CNC-wire-saw. Here, high precision cuts can be performed not influencing the fiber reinforced parts. Using this technology requires a non-curved connection surface. The components can be reused after a following remanufacturing process.

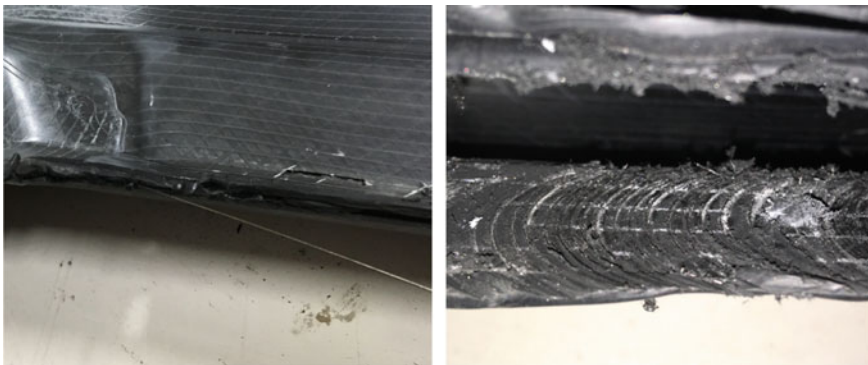
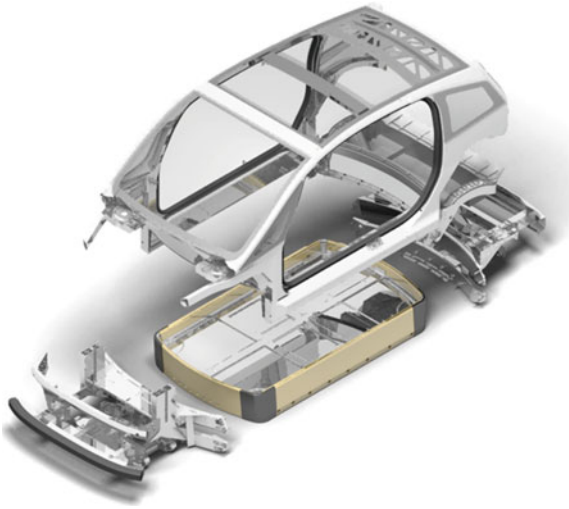


Fig. 4 Disassembly procedure for adhesive joints using the wire saw technology, cutting process (left) and cutting edge after separation (right)

Fig. 5 Disassembly of the body-in-white



Cutting the connection between the platform and the rocker panel only makes the whole platform ready for reuse (Fig. 5). It is clear that in many cases another step must be performed to disassemble the front-end and the back-end of the car to exchange parts or to achieve another vehicle lifespan for the platform designed for at least seven lifespans. Thus, a last disassembly step is necessary.

Front-end and back-end are connected in a combination of a bolt connection and a sealing structural polyurethane adhesive connection. The connection surface is curved. The wire-saw technology is not applicable here. However, it is possible to separate the connection if the detachable adhesive technology is applied. This means the platform must be put into an oven at the desired temperature to lower the cohesion of the adhesive. After a short time, the platform can be separated mechanically. The use of jigs is recommended here. Theoretically this technology could also be used for the connection at the rocker panel.

2.2 Seating Structure Disassembly

In contrast to the platform described in Sect. 2.1, other or further steps must be observed when dismantling the seating structure.

After removing the seat structure from the vehicle, all moving or mounted parts such as the head restraint or seat belt latch must first be dismantled. Then, it is possible to proceed with the removal of the cover and upholstery from the actual seating structure. In most cases, this requires a specific force, as the cover is usually glued, see Fig. 6.

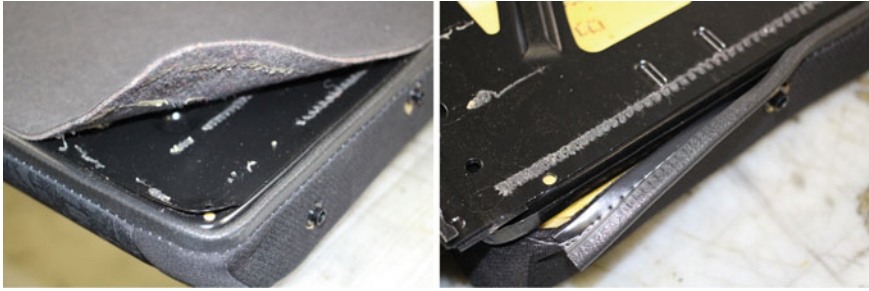


Fig. 6 Exemplary removal of the cover of an Opel Zafira

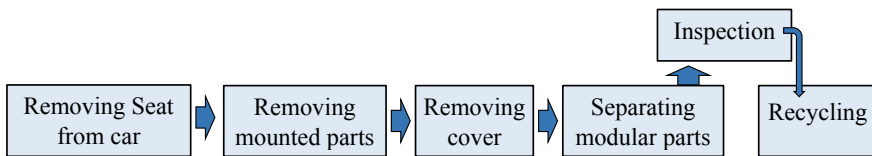


Fig. 7 Basic steps for the disassembly of a seating structure

These steps describe the removal of the visible components that can be replaced each time during a vehicle refurbishment to implement modern new designs in a new life cycle.

Thus, from this point on, the pure seating structure suitable for reuse is present, as described in Chap. 12 (Modular Car Design for Reuse). From here on, the separation of the modular components has to be realized. This is possible by applying for example the technique of non-destructive separation of adhesive bonds as described in Chap. 10 (Composite repair and remanufacturing).

These described individual steps as well as the subsequent steps can be seen in an overview form in Fig. 7.

3 Inspection Process

After the end of the life cycle and the subsequent dismantling of a vehicle with the associated interior, an assessment of the condition of the components and structures designed for reuse is necessary. For reuse, the components must be intact or at least repairable in order to meet the safety requirements for the next life cycle. An inspection process was developed to determine the component status, which consists of various process steps and decisions. The inspection process chain is shown in Fig. 8.

At the centre of the inspection process is non-destructive testing. Prior to this, pre-sorting is carried out by means of a visual inspection. Components are generally

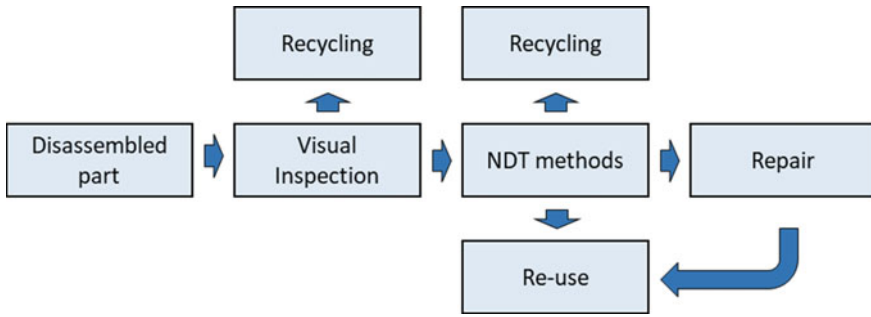


Fig. 8 Process chain for inspection process of reusable composite parts

classified into three categories: direct reuse, reuse after repair, no reuse and continued use in material recycling processes.

3.1 Visual Inspection

The first step in the inspection process chain is the visual inspection. The dismantled components are assessed by trained specialist staff. This can also be done during dismantling. The visual inspection is intended to sort out severely damaged components, which can no longer meet the requirements for the component even through repair.

3.2 Non-destructive Testing

Not all component damage is visible from the outside. Internal damage for which the detection method must be used is also possible. Non-destructive testing methods offer a very good option here. As part of the project, three different non-destructive testing methods were examined: ultrasonic testing, hyperspectral imaging and active thermography. The technical details of the methods and the tests performed are described in Chap. 10.

Complete automation is crucial for the sensible and effective use of non-destructive testing methods. To do this, it is necessary to install the appropriate test equipment, such as sensors on robots that automatically scan the components. Special software programs are required to evaluate the sensor data and detect possible damage. Ideally, the software can be used to decide whether the components can or cannot be reused, or whether they need to be repaired.

3.3 *Recycling Strategies*

Components that are so badly damaged that they cannot be prepared for a further life cycle even after being repaired should continue to be used in material recycling processes in the interests of sustainable industry. In use cases 1 and 2, mechanical and thermal recycling processes and corresponding processes for manufacturing products using recycling materials were developed.

For non-reusable components from use cases, the thermal processes from use case 2 are particularly suitable due to the use of carbon fibers. However, the use of mechanical processes is also conceivable, especially in the case of very badly damaged components that did not have broken fibers. In any case, the recovery of continuous fibers through the thermal processes is no longer possible here.

4 *Remanufacturing Procedure*

After a classification of the components has been carried out, which can be transferred into a remanufacturing process, a construction of an overall structure with these reused components is possible. However, specific boundary conditions must be observed for a reuse process. As described in the previous chapter, the components have been tested for their suitability and freedom from damage or damage limitation. Nevertheless, reprocessing must be carried out.

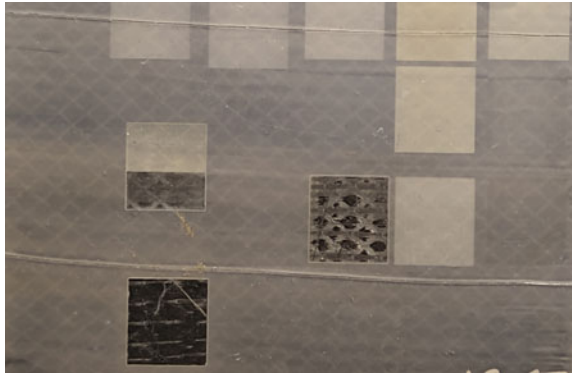
This is necessary for isotropic materials such as metals. But especially this is true for composites, an anisotropic material. This class of material require among other things a special pretreatment. These steps are described in the following sub-chapters.

4.1 *Remanufacturing of Adhesive Joints*

Adhesive bonds are one of the most important structural connections for composites due to the damage-free and homogeneous joint bond. However, after a separation of the overall structure, adhesive residues are likely to still adhere to the sub-components. These adhesive residues must be removed, and the surfaces prepared before a new bond is made.

This removal of the material is possible by various techniques, for example by grinding, milling or laser processing. Laser and milling can be automated, which enables precise processing. This is recommended for thin adhesive layers and composite materials. Here, the thickness of the layer to be processed can be set very precisely, which ideally means that no fiber layers are employed. Figure 9 shows the results of a series of tests in which various laser parameters were tested. The aim was to obtain an ideal ablation pattern. The lowest box shows a laser processing in

Fig. 9 Test series of laser processing



which as much adhesive as possible was achieved with as little damage to the fibers as possible.

A manual and rather rough processing is grinding, which is recommended for thick-walled adhesive layers and metal components, see Fig. 10. Due to the manual guidance, the machining depth can vary depending on the processor and, in the worst-case scenario, damage the fiber layers of composites. However, this process is the economically ideal one when adhesive has to be removed in a layer several millimeters thick. It is applicable for the rocker panel of the platform, where a thick layer of adhesive is necessary to equalize the thermal stresses between the aluminum and the CFRP part.

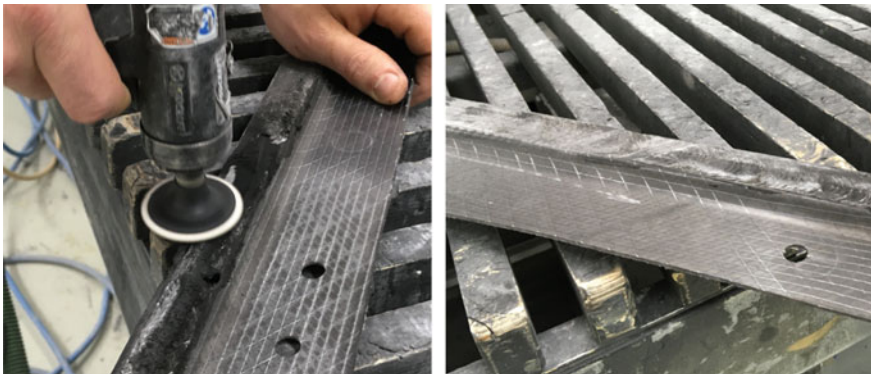


Fig. 10 Removal of adhesive by grinding

4.2 *Repair*

To get the remanufactured components into a renewed use, a possible repair is necessary. The non-destructive inspection already carried out and described in the previous section has revealed the extent as well as the positions. This makes it possible to carry out a specifically defined repair.

There are three states of what a selected component for reuse may look like:

1. Components that are severely damaged cannot be reused. These would therefore be sent to a thermal or mechanical recycling process.
2. In the case of very minor damage, only optical defects exist. Here, the structure itself is not damaged. As a repair, for example, an optical reconditioning in the form of a new paint or coating can be carried out.
3. Components with minor damage can be repaired. Specific processes and machining steps are necessary for this.

This third case, minor damage to the structure of a component, is described in detail in Chap. 10 “Composite repair and remanufacturing”. In summary it can be said that repairs to fiber composite structures have been carried out in aviation for a long time and are accordingly established. These processes can be transferred to the repair of automotive fiber composite components. A more detailed analysis is explained in the corresponding Chap. 10.

4.3 *Reuse of the Structures for New Vehicles*

After the described reprocessing of the individual components, it is possible to start a new life cycle. For this purpose, the components must be integrated into the overall structure. In principle, this should be done accordingly to the same instructions or boundary conditions as the initial new build. As a consequence, the same support materials, processes and competencies that already exist can be used.

The more life cycles a component experiences and the more often it is reprocessed as a result, it must undergo a more precise reprocessing of the surface. This is because the reprocessing of an old adhesive layer that has been removed, for example, may damage the fiber layers: The more that is removed, the deeper the fiber layer must be penetrated. As a result, the strength of a composite component is affected, and must be considered in the design process.

Tensile shear tests on bonded specimens showed a good behavior if the component was carefully and well prepared. In contrast, a component that has only been cleaned without further preparation gives low values in the case of rebonding. The numerical values of tensile shear strength corresponding to the types of failure are shown in Fig. 11. The values for the samples without removing the adhesive and the first layer are visible in blue, the values for a good preparation of the surface by milling are shown in red. The values for the initial bonding are shown on the left, and the values for the two repair cases are shown on the right.

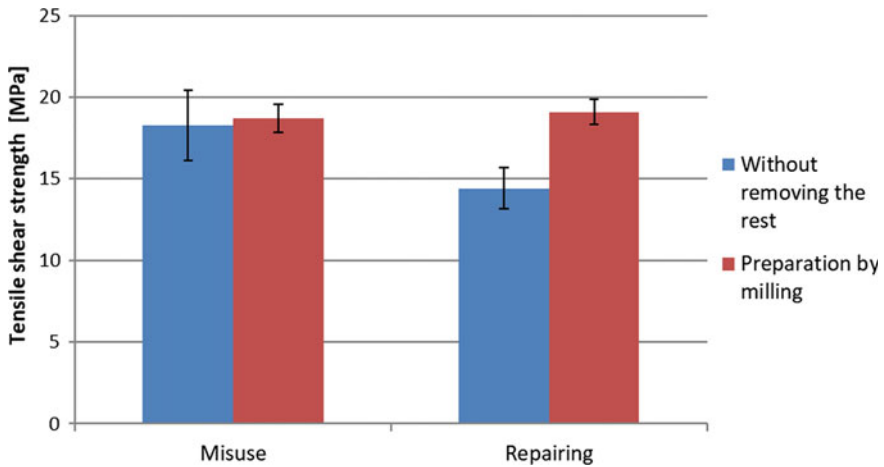


Fig. 11 Numerical results for repairing faulty separated adhesive bonded samples

This figure shows, that a precise reprocessing will allow a wide reuse of composite materials. This usage of composites would greatly reduce pricing pressures in the automotive industry and could therefore be used more widely in large-scale automotive production. As a result, the use of these lightweight materials will lead to a reduction in vehicle mass, resulting in more energy-efficient vehicles.

5 Life-Cycle Assessment

The mission of circular economy is to reduce impacts for the environment. Reducing the waste is the usual objective, but on the other hand the impact can be measured by emissions. The concept is proven by a life-cycle assessment, which is carried out exemplarily for the platform.

The new defined life-cycle of the platform is supposed to lower the overall emissions. The basic idea is to reduce the parts of a car being produced. Electric cars cause low emissions if they are fueled with renewable energies. The production of the car itself is still very energy consuming and causes emissions due to chemical processes.

Not producing a new platform for the next generation of the vehicle lowers the emissions if the inspection and remanufacturing procedure causes lower CO₂ than the reproduction of the platform. On the other hand, a platform lasting for the desired 30 years and more than 1 Mio. km must be designed very robust. In a life-cycle assessment it will be shown if it is possible to lower the emissions and when a break-even point will be reached. Thus, a comparison of the new lightweight platform with a steel-based platform will be made.

5.1 *Boundary Conditions*

The basis of the examination is a strict set of boundary conditions. These conditions are derived from the purpose of the vehicle in car-sharing. The basic condition is the supposed lifecycle of the vehicle. Here, a standard value is about 180,000 km. This is the distance when the costs for maintenance start to exceed the cost for a new car. Considering that the car is used in public and by people with low experience in driving this car model causing smaller and larger accidents, 180,000 km seems to be a realistic value.

The velocity of the car being used mainly in the city will be about 30 km/h. The energy of the car will be the standard-mix of Germany as the largest country in Europe. The production of the fibers will be in the US using hydrogen power. This is similar to a large CF-producer from central Europe. For the aluminum and steel parts, the up-to-date recycling rates are included. This is lowering the emissions by far. The manufacturing processes and the used media like oil are also included.

The object of comparison is not the whole car, but the platform only. The passenger cell and the suspension can be seen as similar. Even the fuel consumption due to air resistance is equal. Hence, the energy consumption was calculated for the whole vehicle. The sum was divided by weight so that the two different platforms will show slightly different consumptions. The weight difference is 30 kg resulting from the lightweight design for the much more durable new platform.

5.2 *Life-Cycle*

The life-cycle with the said boundaries is set up in a LCA-tool. Here, the software Gabi was used. Others show similar results. The basis of the examination are databases for materials and processes. Here, the standard-database and in addition the database for reinforced plastics were used.

In Fig. 12 the model for the new CFRP platform is shown. The basic phases of the life-cycle are shown. This picture shows the first life-cycle of the platform. After the use-phase the materials are put to recycling—or to reuse.

The result in absolute numbers for the defined Scenario 2 of 40,000 km per year can be seen in Fig. 13. It shows that the production of the lightweight design platform causes much more emissions during production. The reason is the production of the carbon fibers that must be produced without recycling in a very energy intensive process. During the first use-phase a quite similar slope of emissions can be detected since both platforms show only a medium difference in weight.

After 4 years, the vehicle must be exchanged. This means a new production of the steel-based platform, while the lightweight platform will be remanufactured. This is the point, when both diagrams show an intersection. The new production of the steel platform causes further emissions, while remanufacturing can hardly be seen

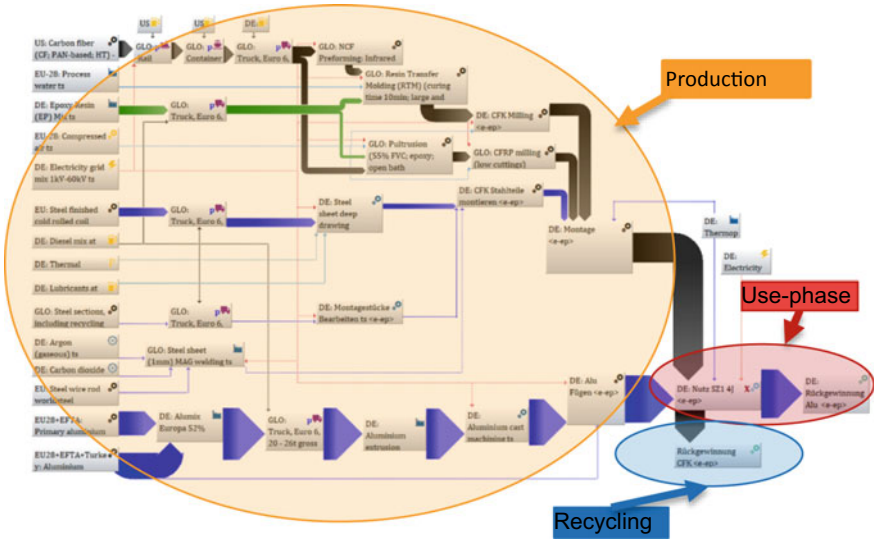


Fig. 12 Life-cycle model of the CFRP platform

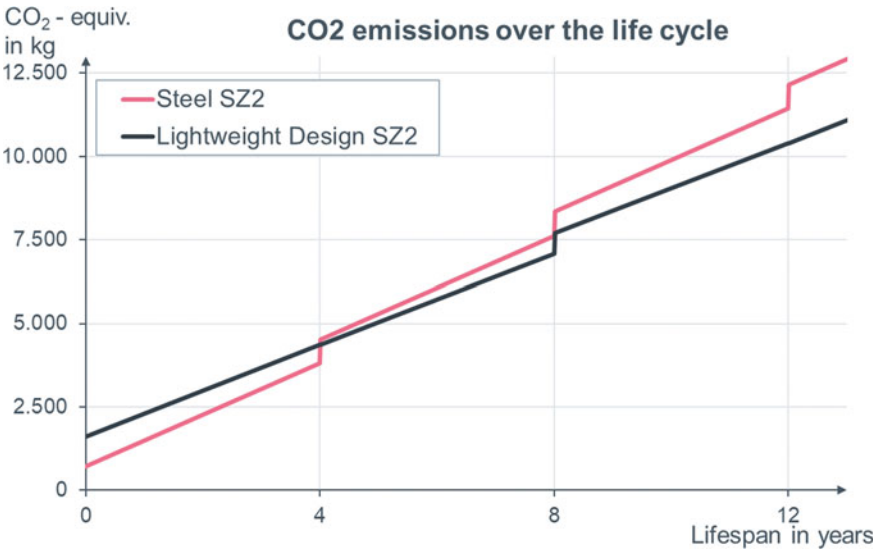


Fig. 13 Emissions of both platforms during the first life-cycles

in this scale. After 8 years, the front-end and the back-end made of aluminum must be exchanged, too. This causes also emissions for the lightweight design platform.

After 12 years, the difference of both diagrams is about 2000 kg CO₂-emissions. This is the amount of the whole production of the lightweight-design platform. For the next 16–18 years, this platform will still be in use and remanufactured saving another about 4000–6000 kg of emissions.

5.2.1 Interpretation

The life-cycle assessment has proven that the new circular design platform will save high amounts of emission during the long lifespan. Similar results are expected for the seating structure. Some points must be discussed upon this.

The production of carbon fibers is a very high CO₂-intensive process. In Fig. 14 the specific emissions are visualized. It becomes clear that lightweight design in a first step is causing more emissions. This is relevant for aluminum, too. The lower emissions during the use-phase can equalize these first emissions. It must be noted that in many cases, lightweight design will not cause a positive effect on the emissions, but on the performance.

Lowering the emission for the production of CFRP is the goal of many other research projects. Here, bio-based precursor materials are used. The resin can also be bio-based. This means the consumption of fossil fuels. Since these materials today are not produced in higher amounts, it must be shown that they cause lower emissions, too.

The batteries of the electric powered car were not under examination. New battery generations with better properties are presented every year. In the near future the batteries will reach a productive level. Hence, it may be possible also to keep the batteries for more than one lifespan. This will reduce the effort for remanufacturing on the one hand and lower the overall emissions of the car by a similar or even higher amount. The reusable platform will be able to support this already today.

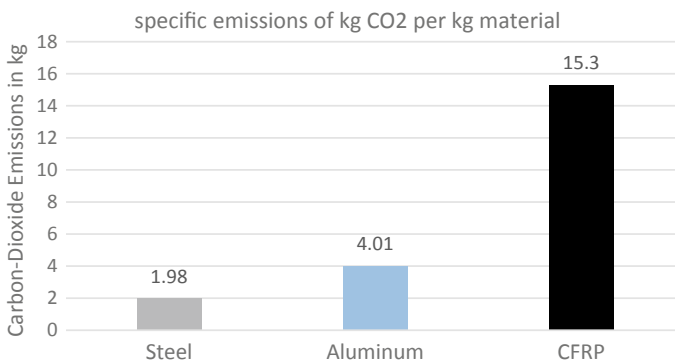


Fig. 14 Specific emissions of the materials

6 Conclusion

The new circular approach for a car-sharing vehicle is shown. The use-case of a sharing vehicle already brings the benefit of lower space consumption in the city and higher utilization per day. In addition, the shared vehicles are owned by the car-sharing provider being able to locate the car and to measure its conditions. Based in this scenario, the basic steps of a reusable platform and a reusable seat are presented. The disassembly, the inspection and repair are the most important phases. New strategies for cutting adhesives, detachable joints, cleaning and inspection are summarized. These technologies lead to the goal to regain as many CFRP platforms and seats as possible to reduce the overall amount of these structures produced.

In a life-cycle-assessment it could be shown that the new circular process pays off in form of much lower emissions. This result was expected and proves the advantages of circular design and remanufacturing instead of producing new parts for the automotive industry.

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