



Multi-level Circular
Process Chain for Carbon
and Glass Fibre Composites

MC4 101057394

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for Carbon and Glass Fibre
Composites

Deliverable D7.4: Final demonstration and evaluation report

Due date of deliverable: 2025-03-31
Actual submission date: 2025-03-05

Start date of project: 1st April 2022

Duration: 36 months

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Revision 1

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AMURA, MANAGING COMPOSITES, IRES

Project co-funded by the European Commission within Horizon Europe Framework Programme		
Dissemination Level		
PU	Public	X
SEN	Sensitive information	

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1. INTRODUCTION & OBJECTIVES

Europe's competitive position in carbon and glass fibre manufacturing is relatively weak. Currently, 80% of these fibres are produced outside of Europe, and around half of the remaining 20% is manufactured under foreign licenses, leading to significant reliance on external sources. The MC4 project offers a valuable opportunity to innovate and safeguard manufacturing processes utilizing recycled materials. This initiative aims to enhance the competitiveness of European companies in this sector while reducing their dependence on foreign suppliers.

The significant cost difference between carbon fibre (approximately €50/kg) and glass fibre (approximately €1.5/kg) necessitates distinct recycling approaches for these materials. The MC4 project focuses on developing tailored short- and long-term technological solutions to address the recycling challenges for each material. Overall, the MC4 project aims to establish short-term and long-term circular approaches:

- for carbon fibre to re-use waste material directly in the production line and to recover the fibre from end-of life parts for use in new products.
- for glass fibre to re-use shredded material in new parts and to establish a new type of resin that allows the re-shaping and thus re-purposing of parts without separating matrix and fibre.

This deliverable has the objective of presenting all processing and recycling steps, as well as the quality grading systems and auxiliary processes for recycling that have been developed during the MC4 project. Besides, after summarizing the results obtained through the evaluation of these recycling processes, an assessment of the project results relative to the expected outcomes will be provided.

2. CF SHORT-TERM: RECYCLING OF UNCURED CARBON FIBRE

The Carbon Fibre Short-Term (Objective O1 of the MC4 project) process aims to reduce the significant waste typically generated during the production of carbon fibre components, especially in industries like aerospace and automotive. Traditional carbon fibre composites production often results in waste amounts ranging from 20-40%, mainly from the offcuts, trimmings, and surplus material from the manufacturing stages. This waste occurs due to the precise shapes and sizes needed for individual parts, leading to excess material that is not directly usable.

To facilitate the reuse of waste materials, specialized technologies have been developed. These include advanced methods of cutting, aligning, and layering the uncured carbon fibre materials so that they can be integrated back into the manufacturing cycle. Other technologies involve re-rolling the cut-off materials into intermediate products, which can then be used in the creation of new parts.

The process can be applied across various industries where carbon fibre is used, such as in the aerospace, automotive, and sports sectors, where high-strength, lightweight materials are essential. It is especially important for the aerospace industry, where carbon fibre parts are costly, and manufacturing processes need to be optimized for minimal waste.

2.1 Full circular process chain

Two different processes have been developed to recycle scrap prepreg material. The first approach (Figure 1a) is suitable for the reshaping of scrap material coming from the manufacturing of Automatic Tape Layup (ATL) processes, while the second one (Figure 1b) is adequate for the recycling of prepreg residues coming from any kind of cutting operations in the manufacturing of carbon fibre components.

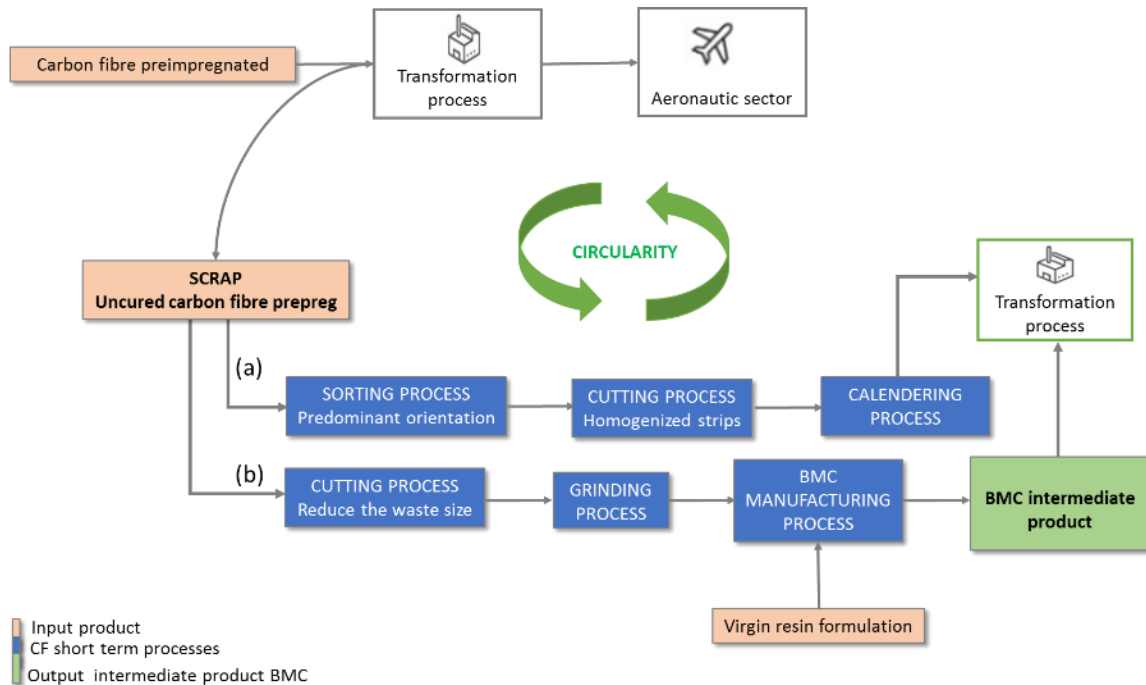


Figure 1. Material flow chart describing a) reshaping and b) recycling processes of uncured CF scrap

2.1.1 Composite part by re-shaping of uncured CF scrap

Within MC4 project, FIDAMC has developed a new reused material from scrap carbon fibre (CF) multiaxial prepreg adapting the conventional calendering technology to process uncured scrap, which stands out by tack behaviour. The control of the temperature and the velocity of the rollers is the critical phase of the process due to the small working range, the inability to considerably increase these parameters were considered a disadvantage, leading to new developments and adaptations of the technology. The contribution to innovation is the possibility to reuse or recycle the multiaxial laminate scrap that is characterized by very high thicknesses.

In terms of uncured CF scrap re-shaping, the MC4 study field is focused on the current production of the stiffeners for the AIRBUS A320. The scrap generated is then applied as a raw material for calendering technology. After processing the scrap, a manufacturing feasibility study was carried out focusing on the manufacturing of complex geometry aerospace part. The front rib placed on the leading-edge of the horizontal stabilizer was selected as an aerospace use-case.

As was commented before, the reused material development from scrap CF multiaxial prepreg is based on the A320 stiffeners manufacturing. The production chain starts with the flat CF multiaxial laminates manufacturing by Automated Tape Laying (ATL) technology. These multiaxial laminates are produced by several unidirectional prepreg plies oriented in four distinct angles to optimize mechanical performance (+45°, -45°, 90°, 0°). After laying up, they are cut to obtain the stringer preforms and the rest becomes waste. In this field of study, the scrap amount is around 20% per laminate, as shown in Figure 2. Each laminate leads to a high quantity of waste, around 50 kg. Therefore, a total of 500 kg of waste is available considering only the A320 stringers project scope.

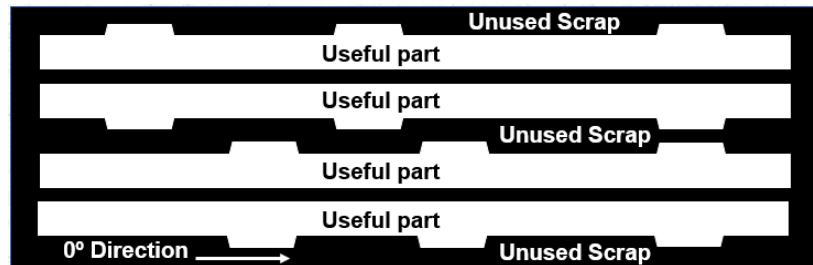


Figure 2: Stiffeners scrap waste material: uncured trimming off-cuts (black area)

Based on the scrap architecture, the full circular process chain of the leading-edge rib manufacturing was defined as shown Figure 3. It consists of several steps, starting from waste production and ending up in manufacturing reused aerospace products.

Waste Generators: They are responsible for ensuring that waste is provided in an optimal condition for reprocessing. Recovering that waste internally in the manufacturing plant and reprocessing it as a by-product is the efficient way to avoid additional steps to change the waste category, otherwise it should be handled as a toxic product. Currently, prepreg scrap is discarded directly into a container, resulting in a compacted mass of material. Therefore, it is mandatory to adapt the waste manipulation because it should be preserved as aligned or as flat as possible. This role should be assumed by aerospace component manufacturers, such as AIRBUS, EMBRAER, LEONARDO SpA and BOEING and/or their Tier 1 suppliers, as AERNNOVA, ACITURRI, SONACA, among others.

Waste management company: They perform prepreg scrap management in terms of collecting, sorting, cutting and storage. In the MC4 consortium, there is no partner that can manipulate this kind of waste because it requires a cold chain for transport and storage. External organizations may have to be outsourced

to deal with it, such as the current waste managers of the aeronautical industry which should be willing to adapt their handling and collection processes.

Company for transformation process: They establish the scrap CF prepreg transformation at industry level. This competence is the value chain core considering all the technologies developed in the MC4 scope, but more mature and able to be industrialized. The transformation process is divided into two disruptive technologies:

- The calendering process involves squeezing the scrap CF prepreg between heated rollers to create a thin carbon fibre strip, reducing the thickness from around 2.2 mm to 1 mm. It is important to mention that the scrap CF prepreg must be previously cut into homogenous and uniform rectangular strips to be processed. Regarding the strip width, it needs to be adjusted according to the machine size, load capabilities and the size of the scrap material. Throughout the development process, several widths have been experimented, and it has been found that approximately 20 mm aligns best with both the machine capabilities and material characteristics. Some trials were carried out to establish the key process parameters, such as processing temperature, calendering speed or cutting parameters, to minimize the defects formation as wrinkles, fibre distortion and resin accumulation and/or lack in each strip.
- When calendering process is finished, a flat panel is produced stacking the strips next to each other with an overlap of 2-3 mm. Heating and vacuum pressure are applied to consolidate the uncured flat panel. This can now be supplied to the composite parts manufacturer to use it as raw material for the hot-press technology.

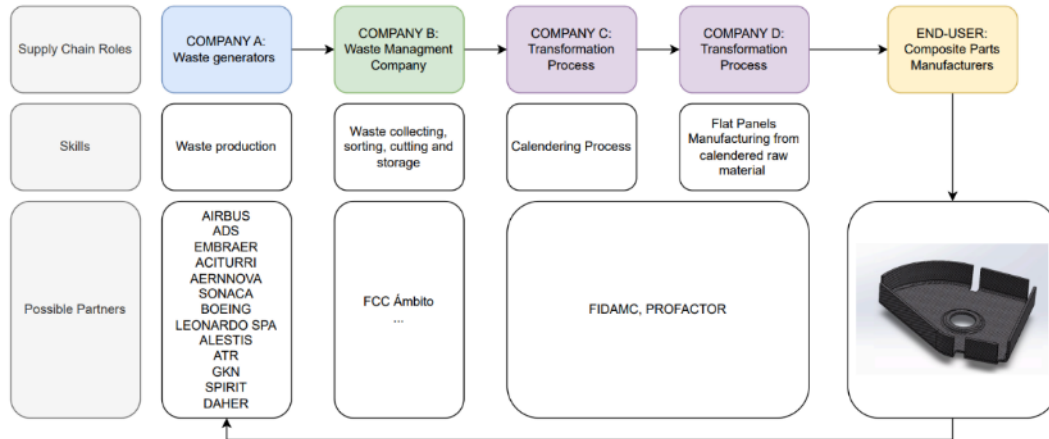


Figure 3: An Overview of Value Chain Approach for the reused material production focused on leading-edge rib application

Composite Parts Manufacturers: The hot-press technology was selected to process the calendered material because the strip thickness is much higher than conventional aerospace prepreg plies (1 mm versus 0.1 mm or 0.2 mm). Significant compaction pressure being needed to reach the required tolerance for thickness of the part, the hot-press is an optimum technology. The sequence of manufacturing methodology can be observed in Figure 4.



Figure 4: Manufacturing methodology for hot-press technology using reused material

2.1.2 BMC intermediate material manufacturing from uncured CF scraps

In the initial pre-treatment stage, the uncured prepreg scrap is cut into strips of approximately 500-600mm in length. This step is essential to facilitate the subsequent grinding process, as larger strip pieces cannot be processed efficiently in this type of equipment. The grinding process is designed to produce short fibre strips, which enhance blending with the added virgin reins. This step is critical, as it must not adversely affect the polymerization of the scrap material. To ensure this, key parameters such as grinding duration and the geometry of the incorporated scrap – including thickness, size, and stiffness- must be carefully controlled. The ground material is then mixed with a virgin resin formulation and processed into bulk moulding compound (BMC) (Figure 5a). The final carbon fibre content and the type of resin used will significantly influence the properties of the resulting BMC intermediate. Therefore, to characterize the material and check its feasibility, round trays have been manufactured after thermoforming the BMC intermediate (Figure 5b and Figure 5c).

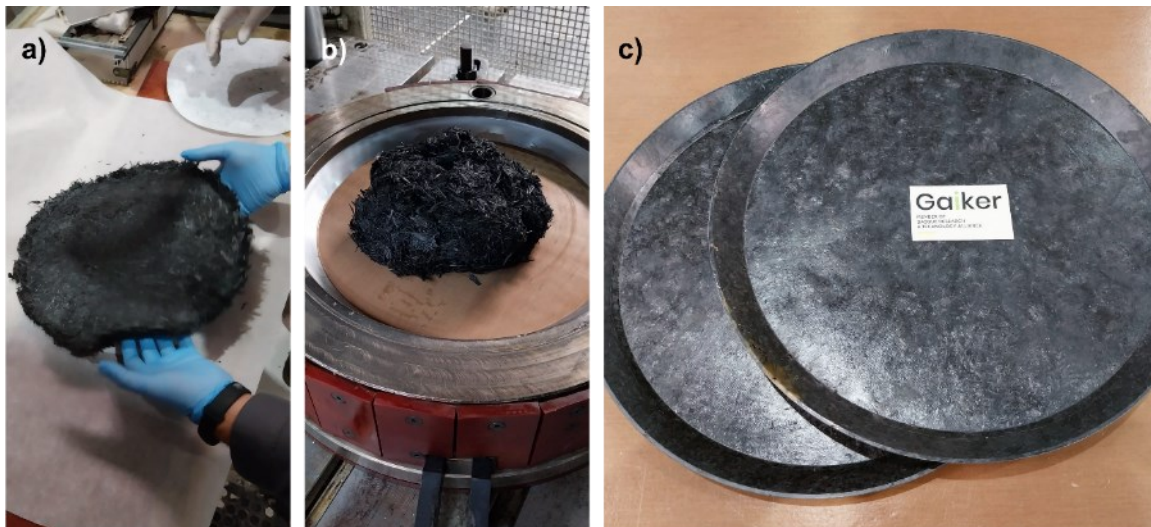


Figure 5. a) Obtention of r-BMC intermediate. b) Thermoforming process of r-BMC. c) Round tray demo cases manufactured from r-BMC.

2.2 Evaluation of the processes

2.2.1 Composite part by re-shaping of uncured CF scrap

Performance of the process at a technical level:

The reused material developed within MC4 project was characterized considering thermal, physical-chemical and mechanical behaviour. The FVF reported was from 63% to 65%; this value is significantly higher than the nominal fibre volume fraction of 57.4%, indicating that the reused material contains 7.1% more fibre than the original material. This discrepancy is primarily attributed to resin loss during the calendaring process. The tackiness of the resin leads to its adhesion to the calendaring rollers, reducing the resin content and consequently increasing the fibre fraction in the final reused material. This change in composition can influence the mechanical behaviour of the material, as seen in the variations in Young's modulus, strength, and elongation at break across different loading conditions. Regarding the porosity, it remains significantly higher than the aerospace sector requirements (equal or less than 2%), suggesting that the material formulation may need to be adjusted, as resin loss could be influencing void formation. The void content was around 4% considering the procedure of the hot-press manufacturing optimized. Regarding mechanical properties, the baseline material exhibits a significantly higher modulus in tensile 0° and compression 0° directions, with values exceeding 120 GPa. However, in the reused material, the elastic modulus at 0° tensile loading is reduced by approximately 50%, indicating a considerable decrease in stiffness along the fibre direction. On the other hand, the modulus in the 90° tensile direction increases by around 60%, suggesting a redistribution of stiffness properties due to changes in fibre orientation or resin content during the reuse process. Additionally, compression at 90° shows a moderate increase compared to the baseline, while compression at 0° is reduced, further indicating altered material behaviour. In the case of mechanical strength, the baseline material demonstrates superior strength, particularly in the tensile 0° direction, exceeding 1800 MPa. However, for the reused material, the strength at 0° tensile loading is reduced by approximately 70%, showing a significant loss in load-bearing capacity in the fibre direction. Conversely, the 90° tensile strength increases by around 50%, aligning with the trend observed in the elastic modulus, which suggests improved transverse strength properties. In compression, the reused material exhibits lower values in the 0° direction but higher values in the 90° direction, further highlighting the structural transformation in mechanical performance due to the recycling and reprocessing effects.

As a summary, it can be suggested that the material formulation may need to be adjusted, as resin loss could be influencing void formation, and then the FVF is too high in comparison with the nominal FVF. Therefore, the lay-up design should be modified including a resin film to adjust the FVF. This new trial is currently developed.

The hot-press technology for the aerospace use-case made in reused material follows a carefully controlled sequence to ensure high-quality and consistent results, incorporating a specialized metallic tool. Initially, calendared strips are arranged with slight overlaps to bond and consolidate them in a flat panel, with the aim to facilitate the preform manipulation. This consolidation phase is achieved by simultaneously applying heat around 60 °C and vacuum pressure. This promotes adhesion, forming a uniform layer that is then cut to match the tool dimensions. The tool employs a two-part tool with male and female components, one made of aluminium and the other of steel. This tool is specifically designed for hot demoulding, utilizing the difference in the coefficients of thermal expansion between the two metallic materials. The aluminium expands more than the steel due to its higher coefficient of thermal expansion enabling the cured part to be positioned on the male which is easier to demould. In addition, the aluminium contracts more rapidly than the steel, creating a natural separation between the mould components and the part, facilitating demoulding without causing damage.

The forming process begins with the preparation of the hot-press, where a protective layer of A4000 or kapton film is placed on the bottom plate, followed by orthogonally arranged layers of metallic wool to ensure even pressure distribution. The preform, with the part shaping, is positioned on the top of the tool, ensuring full coverage to prevent misalignment during forming. A clamp secures the tool to maintain the

desired thickness, and an additional layer of metallic wool is applied on top to mirror the bottom configuration. The tool is heated during the forming cycle to cover the curing cycle. When the temperature of 80°C is reached, the compaction pressure is applied (around 8 bar). The press temperature has to reach 190°C to ensure a curing temperature of 180°C. The curing cycle is 2 hours at 180°C. Then, the controlled cooling phase begins. The pressure remains at 8 bar throughout both heating and cooling to ensure uniform temperature distribution and minimize defects.

The definition of the hot-press control parameters and the method of tool design using two metallic materials enhance the efficiency of the demoulding process and reduces the risk of surface defects on the final part. The standardization of this curing process, with precise temperature and pressure control, ensures consistent mechanical and structural properties in the final demonstrator, optimizing its performance while maintaining high reproducibility and reliability.

At an economical level, within the Life Cycle Cost Analysis (LCC) of the reused material, the manufacturing cost emerges as the overwhelmingly dominant factor, contributing over 90% to the total life cycle cost, while the cost of raw materials accounts for approx. 10%. Conversely, in the baseline, the manufacturing phase remains the primary cost contributor, though at a comparatively lower level of 62%. Additionally, raw materials represent a significant cost component in the conventional process, contributing 38% to the total LCC. This stark contrast underscores the differing cost structures between the two approaches.

The comparative analysis shows that under the operational parameters applied during the manufacturing of the MC4 aerospace use-case, the LCC is 88% higher than the conventional process. This is primarily attributed to the higher labour cost. However, when the improved productivity scenario is considered, the LCC of the circular demo decreases, becoming 8% lower than that of the conventional process (*Figure 6*).

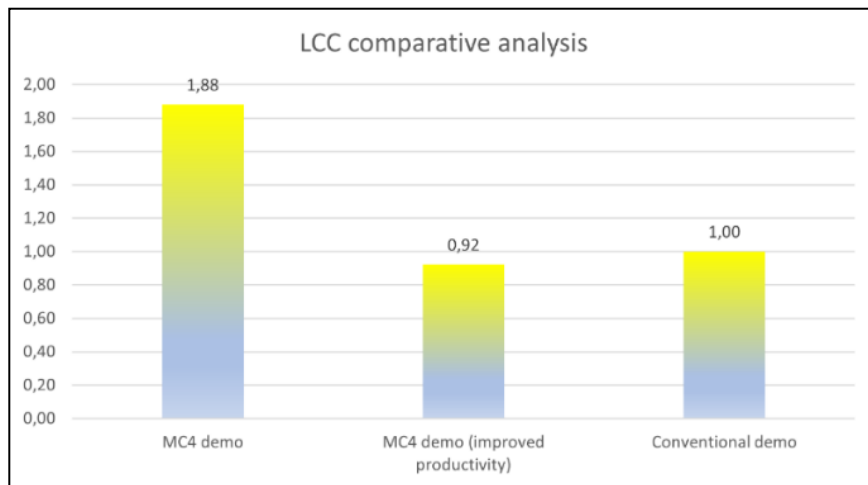


Figure 6: LCC comparative analysis

At the process and environmental level, the manufacturing of leading-edge ribs from re-used materials in the hot-press contributes to sustainability goals by reducing waste and the need for virgin materials. This process is totally energy-efficient due to the optimization and upgrade of the different fabrication steps. From the part preform manufacturing to the cooling cycle, including the hot-press cycle, the process optimization is ensured to minimize the energy consumption. Additionally, the high material recovery rate obtained from using reused scrap positively impacts on the efficiency of the recycling process.

2.2.2 BMC intermediate material manufacturing from uncured CF scraps

Based on laboratory-scale results, approximately 96% of the uncured prepreg scrap is used after the cutting and grinding processes, yielding a BMC intermediate with a total mass yield of over 90%. The thermoformed recycled BMC (r-BMC) demonstrates comparable results to that of a benchmark BMC material when incorporating 67% of uncured scrap material. The carbon fibre content in the BMC intermediate corresponds completely to recycled carbon fibre (rCF) and this translates into 50% of rCF. Although the costs associated with collecting and processing uncured prepreg scrap, along with the addition of virgin resin, amount to approximately 11€/kg of processed material, these expenses are offset by the savings from waste disposal and virgin raw material costs. This results in overall savings of approximately 45€/kg.

The life cycle analysis on the recycled BMC indicated a climate change of 4 kg CO₂eq. /kg, with electricity to be main hotspot contributing by 67% and resin 18%, while the uncured scrap waste is considered as zero impact material. Compared to a benchmark BMC material made from 50% of virgin carbon fabric and 50% resin, the environmental impact of the recycled BMC is reduced by 88%, indicating the environmental benefits of this intermediate recycled material.

2.3 Assessment relative to the expected outcomes

2.3.1 Composite part by re-shaping of uncured CF scrap

FIDAMC is valorising the carbon fibre prepreg scrap from the Automatic Tape Layup (ATL) composite manufacturing technique as a short-term circular approach of carbon fibres to produce a reused leading-edge rib out of 100% reused waste. Therefore, the expected outcome EO1, related to eliminating a significant amount of waste (20-40%) by re-using waste material before it is being cured, was covered.

Regarding EO2 about high-performance applications researching, the tensile strength KPI about tensile strength is not met because the reduction in the tensile strength at 0° is approximately 70% and at 90° is only around 50%.

In parallel, FIDAMC has also demonstrated the manufacturing feasibility of using reused material by the selection of an aerospace complex geometry part and definition of the optimized manufacturing procedure based on composite hot-press technology. This activity meets with the EO3 related to design of typical aerospace products and components. The Fibre Volume Fraction (FVF) of the reused material exceeds that of the baseline aerospace demo, demonstrating that it meets aerospace requirements in terms of FVF. However, considering the void content, the value in the reused material parts remains significantly higher than the aerospace sector standards (equal or lower than 2%), suggesting that the material formulation may need to be adjusted, as resin loss could be influencing void formation. With regards to mechanical properties, they have not been studied in the MC4 project scope for the aerospace demos.

Regarding EO4 about economic feasibility of the product, the LCC has indicated that there is significant potential for manufacturing composite parts using reused CF material offering a cost advantage compared to composites made from virgin materials. This cost reduction is attributed to the lower material acquisition costs of reused scrap CF prepreg and the associated environmental and waste-management benefits. The virgin material cost is around 70 €/kg whereas the reused material will be around 10-15 €/kg. Therefore, savings in the raw material costs considering the reused material is around 80%. This KPI meets with EO4 specifications.

The Life Cycle Impact Assessment (LCIA) of the leading-edge rib use-case, made from 100% reused material, includes the following specific assumptions:

- 25-30 rib parts could be manufactured per cycle at hot press (MC4 demo) and approximately 20 rib parts in autoclave curing at the conventional manufacturing. The total electricity at hot press is estimated at 1.6 times the energy required in autoclave per kg of final product due to 50% reduction in weight of MC4 demo compared to reference.
- In both cases, the average time for storage of the uncured prepreg is equal.

The LCIA results indicate a significant reduction that ranges between 17-73% in climate change, 14-59% in resource use and 14-57% in cumulative energy demand, meeting the KPI of EO5 about life cycle analysis. As lessons learnt during the manufacturing process, one can mention the minimum thickness limitation imposed by the calendaring process. It has been determined that the thickness of the calendared material cannot be reduced below 1 mm due to the structural requirements of the multiaxial prepreg scrap. Any attempt to go below this threshold results in compromised fibre alignment and insufficient matrix distribution, leading to difficulties in achieving the desired mechanical properties. Consequently, this limitation has directly influenced the manufacturing strategy for the rib component, as the previous approach led to severe demoulding challenges due to excessive pressure buildup in the mould radii. The adjustment in the laminating sequence was necessary to facilitate easier demoulding and prevent damage to the component, ensuring a more efficient and reliable production process. Another major concern is the excessive resin loss during the calendaring process, which directly affects the final FVF. This loss can lead to reduced matrix content, impacting interlaminar properties and increasing the risk of defects such as porosity or delamination in the final component. The lay-up design should be modified including a resin film to adjust the FVF.

2.3.1 BMC intermediate material manufacturing from uncured CF scraps

Considering that the developed r-BMC contains 50% rCF (67% of uncured prepreg scrap in total) and demonstrates comparable results to a commercial benchmark BMC containing 50% CF, the use of recycled material is fully enhanced (EO3). A prototype using the r-BMC intermediate has been developed and compared to an identical prototype manufactured with commercial BMC in terms of mechanical properties and visual appearance. Additionally, the substitution of virgin CF for rCF would reduce the amount of virgin CF needed to manufacture the BMC intermediate, enabling a recycling rate greater than 60% (EO4).

3. CF LONG-TERM: RECYCLING OF CURED CF

The carbon fibre long-term process aims to develop an advanced chemical recycling method (Objective O2) specifically designed for cured waste and end-of-life (EoL) composite parts. Traditional carbon fibre composites, particularly those with thermoset matrices, are difficult to recycle due to their irreversible cross-linked structure. This process seeks to chemically break down the resin without significantly harming the fibres, allowing them to be extracted in a high-quality state. Its primary goal of this process is to recover carbon fibres with minimal degradation, preserving their mechanical properties to maximize their potential for reuse. Unlike mechanical recycling, which often shortens fibre length and reduces performance, chemical methods aim to retain the fibre’s original properties, making it suitable for high-performance applications.

Once recovered, the carbon fibres undergo spinning and weaving processes to transform them into various textile formats, such as yarns, rovings, mats or fabrics, that can be used in a wide range of applications, from automotive to aerospace. By advancing this chemical recycling process, the long-term objective is to establish a closed-loop system for carbon fibre composites, enabling more sustainable manufacturing and waste management in industries that rely on high-performance materials.

During the MC4 project, in parallel to the development of the chemical recycling process, the CF recycling sub-processes were developed using CF scraps coming from the manufacturing of CF fabric manufacturing. Therefore, this part of the deliverable will be described on one hand the process for the re-use of CF scraps from CF fabric manufacturing; on the other hand, the process for the re-use of recycled CF from solvolysis.

3.1 Full circular process chain

The full circular process chain established in the carbon fibre long-term process is schematized in Fig. 7.

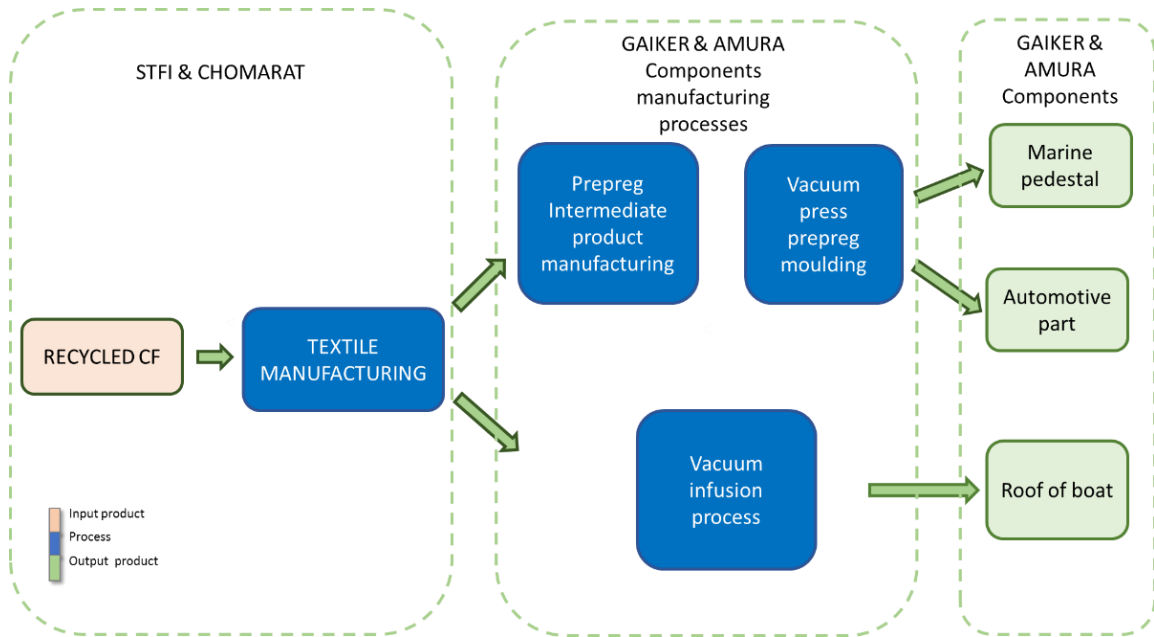


Figure 7: Flow diagram of the carbon long-term process

3.1.1 Recycling of CF scraps from the manufacturing of CF reinforcements

3.1.1.1 Recycling of CF scraps from the manufacturing of CF reinforcements

In the manufacturing processing of carbon reinforcements at CHOMARAT, it exists a wide range of technologies, corresponding to specific textiles structures: woven fabric, non-crimp fabric, braid, stitched tape, etc. The width of the full products range varies from one inch to more than one hundred inches depending on the machinery. A certain quantity of waste is inevitably generated during clamping, cutting... operations for the product creation and some are very interesting to be re-used.



Figure 8: View on the extraction of cut edges on the NCF line at Chomarar by vacuum (Scheme: CHOMARAT)

Carbon non-crimp fabric processing is based on a cut & lay system which handles long carbon fibre tape with angles and has got an operation of edges cutting at the end of the line. These cut edges (right and left on the machine) are sorted and go through a vacuum system in a container. The quality is high because fibres are pure (no other material inside, still with the original sizing) and already cut at an exact length of 80mm. CHOMARAT took MC4 project as an opportunity to re-use them in a short-term loop and provided the project partner STFI several grades of carbon fibres: Toray T700SC 12K 50C, T620S 24K 50C, Zoltek Panex 35 50K W61 and W13 sizing, Mitsubishi TRW40 50K K, 80mm long

3.1.1.2 Textile processing from mechanically recycled CF (STFI)

The uncured carbon fibre waste comes directly from a non-crimp fabric (NCF) production process at project partner CHOMARAT, who delivered the waste material to STFI. To prepare the waste for a smooth nonwoven production, it is opened by means of cutting and tearing to separate it into processable staple fibres. The most important element of material pre-treatment before the tearing process is the cutting of the textile waste. It serves to produce uniform piece sizes and thus to ensure reliable material transport and feeding in the subsequent tearing process. After the cutting step the material undergoes a tearing process. The pin or tooth-shaped tearing elements arranged on the tearing drum enter the textile structure of the waste material clamped on one side by the feeding system and tear the structure under the effect of tensile stress. The opening process is thus based on the interplay of energy input by the machine and opening resistance due to the textile structure and the fibre material. The opening process must therefore be adapted to the textile material to produce optimum results (highest possible fibre length, low distribution). Factors influencing this opening process include the pre-cutting length, the speed of the opening units, the shape and density of the opening units and the number of opening passages. After passing the system, the material is completely opened up, fibres are separated and ready for further processing. Subsequent fibre blending is possible if required.

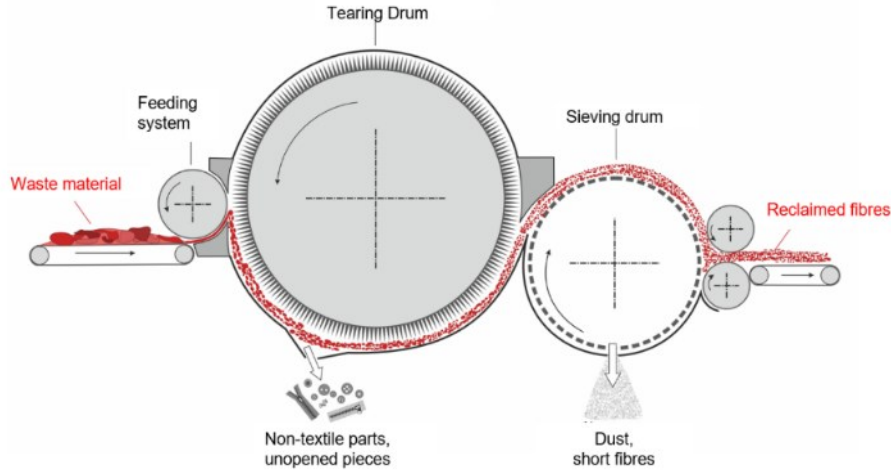


Figure 9: From carbon fibre waste to opened single carbon fibres – principle scheme (Scheme: STFI)

After the preparation steps, the material runs into the carbon fibre nonwoven plant, where carded nonwovens are produced made of fibres oriented in the same direction (laid in an oriented manner). During the carding process, the torn fibres are opened up further, parallelized and finally delivered to the web layer. The web layer lays the corresponding number of web layers on top of each other and thus generates a structure with the desired basis weight (for MC4 project between 150 to 250 gsm). The cross-drawing movement of the layer transports the layers to the needling machine, where they are compacted and bonded by a large number of barbed needles. A characteristic feature of needled nonwovens is the high strength in cross machine direction resulting from the transverse orientation of the fibres after the laying process.

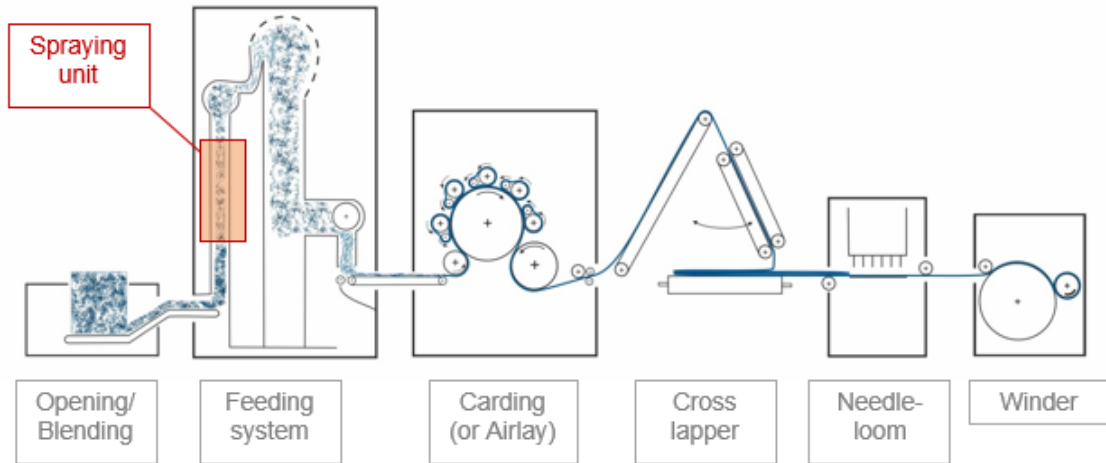


Figure 10: Carbon fibre nonwoven plant (Scheme: STFI)

At the end of the production process, semi-finished roll goods of CF nonwovens (width between 100 and 120 cm) are ready for further processing.

3.1.1.3 Textile manufacturing from mechanically recycled CF

CHOMARAT and STFI had a strong collaboration during MC4 project with several trial sessions at STFI for the evaluation of all nonwoven possibilities with the variety of carbon fibres waste that CHOMARAT supplied. The technology screening orientated to the use of recycled CF nonwovens as raw material for the

NCF line at CHOMARAT. The selected product design at CHOMARAT is a 0/90deg textile orientation which had been set up with several adaptations for the nonwoven using.

Standard NCF line use continuous CF from a spool packaging with a metered length: spread tape is manufactured continuously and feed each weft system insertion with the right angle. With CF nonwovens in 100-120cm width from STFI, the first technical operation is the preparation of cut tapes. All STFI semi-finished nonwoven are unwound, cut in accurate tape and rewind on 6'' core spool for their using on the NCF line with a specific unwinder.

Then, the processing is the deposition cycle of these tapes, layer per layer: the tape roll is unrolled under regulated tension and then tape is pulled in the right direction. In the 0/90deg products development for MC4, we use unwinding stations at 0deg direction and at 90deg direction. Clamping force and pulling force are the key parameters for the settings. With nonwoven tapes, the tensile force management needs to be regulated as low as possible according to the diameter size, to avoid a shrinkage or a breakage of the tape in the cycle. As the STFI nonwoven is about ten times thicker than the continuous spread carbon tape, specific mechanical solution was found for the best cutting, pulling and fixing operations in the deposition cycle.

The last step on the NCF line for the 0/90deg manufacturing is the assembling of the layers by stitching and final product winding. The 0deg layer is continuously unwinding on the conveyor belt (on the top of the 90deg layer) just before the knitting device. Main processing factor is the tension of 0deg and 90deg layers for keeping the right fibres orientation. A second monitoring point is the total thickness of the two stacked layers which need to be regular and not too high. Several STFI nonwoven had been evaluated for defining the maximal allowed thickness and the limit was validated with a maximal area weight of 400gsm for the stacking to stitch. Concerning the other parameters of stitching like the gauge (Density of stitching needles), stitching pattern, stitching yarns, we use the same as standard NCF with continuous tows: E5 gauge with a chain- tricot point, and a polyester yarn of 35dtex.



Figure 11: Views of NCF line with 0/90deg recycled prototype product

3.1.1.4 Manufacturing of composites with mechanically recycled CF through vacuum infusion

During the development of the MC4 project, AMURA implemented a circular manufacturing process aimed at reusing carbon fibre scraps from the production of textile reinforcements. This strategy significantly reduced the amount of discarded material in production, optimised the use of recycled resources, and validated its application in nautical components, aligning with the project's sustainability and circular economy principles.

The complete process followed by AMURA was structured as an optimised material flow, ensuring efficient integration of recycled carbon fibre reinforcements into the vacuum infusion system.:

1. Reception of recycled material: Recycled non-woven carbon fibre reinforcements were received, having been processed by STFI from waste generated during the production of structural reinforcements by CHOMARAT.
2. Quality control and material classification: A dimensional and structural analysis of the received material was conducted, verifying its uniformity, weight, and fibre distribution. Any irregularities that could compromise impregnation in the vacuum infusion process were discarded.
3. Cutting and material arrangement: Cutting optimisation techniques were employed to minimise waste generation. The material layers were then arranged according to the component's geometry, ensuring precise lamination that facilitated proper impregnation of the polymeric matrix.
4. Management of excess material and return to the value chain: Dry fibre offcuts generated during the cutting process were separated, packed, and labelled in accordance with internal traceability standards. These excess materials were then returned to STFI for reintegration into the production of new recycled reinforcements.
5. Vacuum infusion process: The part was manufactured through a vacuum infusion process, using an optimised green epoxy resin supplied by NOMA. This manufacturing system minimised excess resin, ensured homogeneous impregnation of the reinforcement, and reduced the operator's exposure to volatile emissions, improving working conditions in the production environment.
6. Demoulding and component finishing: Once the material had fully cured, the component was removed from the mould, and the trimming of edges and elimination of excess material was carried out to ensure compliance with dimensional specifications.
7. Management of excess material and return to the value chain: The waste generated after demoulding and finishing, consisting of cured material offcuts, was classified and sent to GAIKER, where it underwent a chemical recycling process through solvolysis to recover carbon fibre. This procedure allowed the recovered material to be reintegrated into new applications, closing the recovery cycle and reducing the need for virgin raw materials.
8. Waste management and traceability: All non-reusable waste was managed in accordance with ISO 14001, ensuring its traceability and compliance with established environmental standards, and its disposal through authorised channels to minimise environmental impact.

3.1.1.5 Vacuum pressing of pre-impregnated material based on mechanically recycled CF

The textile manufactured by STFI and CHOMARAT has been impregnated with a resin to obtain a prepreg material. This allowed demonstrating the possibility to use the non-woven in manufacturing processes different from the infusion process (AMURA's use case), such as the thermoforming of prepregs. First, the nonwoven textile is cut to the width limitations of the impregnation equipment while maintaining its full length. The dried roll is then impregnated with a vinyl ester resin formulation, ensuring long-term storage stability at room temperature, and enabling subsequent short curing cycles.

The impregnation process has been adjusted according to the characteristics of the nonwoven textile received from CHOMARAT. In this case, the manufactured parts, either the insulated top cover for back seat or the boat pedestal, have been manufactured using the obtained prepreg from the nonwoven textile register as R BT300 CT3 (OCI1535) from CHOMARAT. In Figure 12 the prepreg manufacturing process can be seen where the nonwoven textile is impregnated with own developed vinyl ester-based formulation. During the manufacturing process the material has been compacted through different rolls to ensure fibre impregnation. The manufactured prepreg material has been covered with a three-layer film (PE-PA-PE) to prevent its drying.

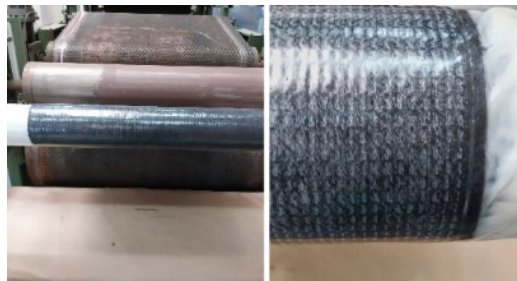


Figure 12. Developed prepreg material from recycled CF reinforcement

Then, the impregnated material has been patterned and cut to cover both moulds, the back seat cover (Figure 13a) and the pedestal (Figure 13b). In both cases, the prepreg material has been placed over the mould and compressed by the silicone membrane of the vacuum press.

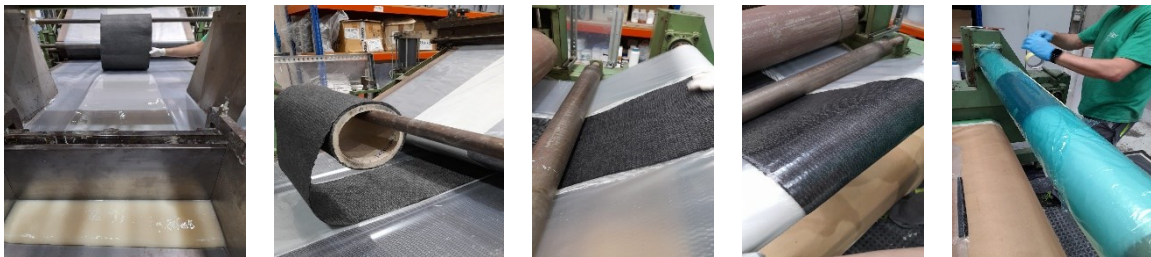


Figure 13. Prepreg manufacturing process

Two parts with different levels of complexity have been selected to assess the suitability of this fabric for manufacturing both simple (back seat cover) and complex components (pedestal). The manufacturing steps of both demonstrators are illustrated in Figure 14.

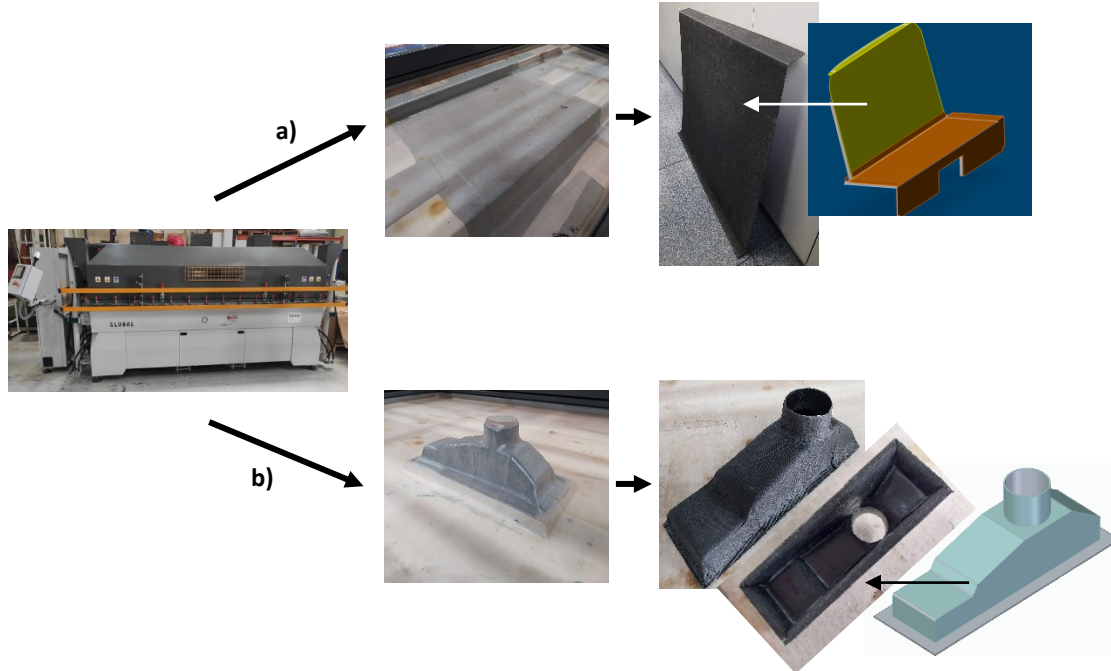


Figure 14. Manufacturing of a) back seat cover and b) boat pedestal from recycled CF reinforcement

3.1.2 Chemical recycling of cured carbon fibre composites

3.1.2.1 Chemical recycling of cured CF composites

The solvolysis process to recycle waste carbon fibre reinforced plastics (CFRPs), by depolymerising the resin, has been designed to produce: (1) recycled carbon fibres (rCFs) as main product, (2) liquids including organic compounds (generated after the chemical reaction of the organic matrix) as by-products.

Around the solvolysis process, a complete recycling scheme was defined, Figure 15, including the following steps: (1) the initial treatment required to prepare the waste CFRPs for entering the chemical recycling process, (2) the solvolysis reaction of the CFRPs, (3) the separation of rCFs and liquids, (4) the treatment of the raw rCFs to produce clean rCFs, (5) the recovery of the solvent and the liquids containing the organic compounds.

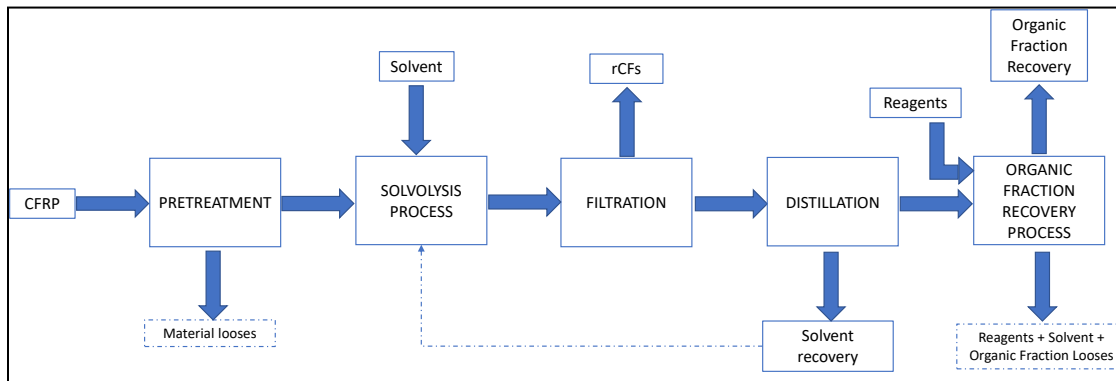


Figure 15: Block diagram of the developed solvolysis process to recycle waste CFRPs

At laboratory scale, studying references and actual waste CFRPs samples, two solvolysis routes have been validated in terms of (1) reaction performance (levels of resin decomposition and fibre recovery), (2) quality of the rCFs (clean surface and mechanical properties) comparable to the one of virgin carbon fibres (vCFs):

- Route #1: solvolysis media were based on mixtures of acetic acid (organic acid) and hydrogen peroxide (oxidising agent), is effective for CFRPs with a medium degree of crosslinking in the thermoset resin and a thickness less than 6 mm
- Route #2: solvolysis media were based on solutions of nitric acid (inorganic acid), is effective for CFRPs with a high degree of crosslinking in the thermoset resin and a thickness over 6 mm

After analysing the results of different solvolysis tests, and assessing both technical feasibility and safety requirements, it was decided to focus on the solvolysis Route #2 to upscale the developed process.

A pilot plant, including a 300 L tank reactor (allowing high L/S ratios and favouring the L-S contact) made of stainless steel (AISI 316) to withstand acid media, was designed, constructed and operated to run the scaled up solvolysis process. The pilot plant incorporated a circuit for circulation of the solvolysis medium and a sample holder, placed inside the reactor, to load waste CFRPs and unload rCFs with a length > 85 mm. This minimum length was a necessary specification to integrate rCFs in new textile products as yarns, rovings, mats and fabric through spinning and weaving processes. The pilot plant was placed inside a standard “shipping container 20 ft HC”. The ancillary equipment in the pilot plant (pre-conditioning vessel, buffer tank and neutralisation tank) was defined and arranged considering the volume of the reactor and the available space inside the container.

3.1.2.2 Textile processing from chemically recycled CF at STFI

Project partner GAIKER delivered the chemically treated carbon fibres to STFI. They come from cured carbon fibre reinforced plastics (CFRP) and are recycled by a solvolysis process.

The preparation and the production of nonwovens is done in the same way as described in chapter 3.1.1.2. for the CHOMARAT carbon fibre material. The only difference is that the solvolyzed fibres have to be resized before processing, to reduce the brittleness and to improve the processability. Otherwise, the fibres will break more frequently due to the high mechanical stress during the production process steps. The resulting shorter fibres will lead to lower mechanical properties such as lower strength. It is standard to size fibres to improve their processability, even with virgin fibres. The existing sizing of the fibres was just removed during the solvolysis step. The application of the sizing agent (silkol) is done by spraying to get an even distribution of the sizing. The fibres are placed in a barrel and after spraying it is closed and rotates by means of a winding unit until the carbon fibres are sufficiently resized.



Figure 16: Resizing of solvolyzed carbon fibres from GAIKER

3.1.2.3 Textile manufacturing (non-woven) from chemically recycled CF at CHOMARAT

The entire process development was achieved with the waste NCF source, but an experience with solvolyzed fibres from GAIKER had been done at the end of the WP5 period. The project partner STFI had high technical difficulties for working with these fibres and concluded an impossibility to work with a pure batch of solvolyzed fibres. A mix with 80% of fibres (from CHOMARAT waste) and 20% of solvolyzed fibres was achieved by STFI in a 150gsm nonwoven structure. The evaluation at CHOMARAT confirmed all the observations of STFI: higher heterogeneity, higher brittleness and weakness in dry tensile of the nonwoven, pollution of other fibres (coming from the variety of fibres inside the composites parts), ... It led difficulties in the different processing steps at CHOMARAT: cutting and rewinding the oriented nonwoven, cut & lay without shrinkage or breakage and correct stitching operation linked to the high thickness variation. A prototype 0/90deg 300gsm reinforcement was produced and delivered to the project partner AMURA to make comparison, but the maturity level of the NCF processing is a lot of lower (Estimated TRL4). The product Quality is a lot of lower and should be demonstrated in the technical evaluation at AMURA and at the laboratory.

3.2 Evaluation of the processes

3.2.1 Recycling of CF scraps from the manufacturing of CF reinforcements

3.2.1.1 Textile processing from mechanically recycled CF

At the technical level, the pre-treatment of fibres (cutting, opening and tearing) as preparation for the production process has been done for both waste materials (CHOMARAT & GAIKER) without any problems. The opening/tearing had no remarkable influence on the fibre surface. No additional damages were observed. Both waste materials could be produced into nonwovens. But it has to be stated that the GAIKER fibres can only be processed if they are blended with mechanically recycled CF from CHOMARAT. The technical trials for the nonwoven production have been done at semi-industrial scale. Transformation to industrial scale is possible.

The waste material from CHOMARAT comes directly from the NCF production process. The fibres were not exposed to any chemical treatment and thus still had the sizing at their surfaces. This led to a better processability since the fibres are less brittle and stiff. The nonwovens made from TORAY fibres delivered by CHOMARAT show better results concerning the tensile strength compared to the GAIKER material.

Sample	Tensile strength MD [N]	Tensile strength CD [N]	Mass per unit area [g/m ²]
Nonwoven carded 100% rCF/TORAY T700SC sized (fibres CHOMARAT)	8.83	25.06	170.87
Nonwoven carded 100% rCF/TORAY T620SC sized (fibres CHOMARAT)	7.23	14.07	182.54
Nonwoven carded 100% rCF unsized Solvolyzed, fibre type unknown (fibres GAIKER)	3.76	6.54	252.17
Nonwoven carded 100% rCF resized Solvolyzed, fibre type unknown (fibres GAIKER)	4.37	7.51	236.76

Table 1: Comparison of tensile strength

At the economical level, by providing textile semi-finished products (nonwovens) out of production waste to NCF producers, fibre waste can be reused instead of an expensive disposal in landfills which is calculated with hundreds of Euros per ton. The throughput at industrial scale for the nonwoven production is estimated at around 60 kg/h. Discussions with nonwovens producers show that the process costs for carbon fibre nonwovens from recycled carbon fibres are approx. 20 €/kg. Compared to a virgin material at approx. 30 €/kg which reduces the cost by 35%. With these cost savings it should be possible to get the material back into a material cycle and to find applications for the semi-finished products.

3.2.1.2 Textile manufacturing from mechanically recycled CF

At CHOMARAT plant, the waste collection and sorting of CF edges on actual NCF production (with virgin CF) is realistic at industrial scale. It can enter in a new supply chain with an industrial nonwoven manufacturing, having similar processing to STFI. Technical assessment of recycled 0/90deg stitched structures made with STFI semi-finished nonwoven had been demonstrated with several products delivered to the project partner AMURA. TRL 4 level was achieved on products in 300gsm and 400gsm with different fibres (Toray, Zoltek, Mitsubishi).

The manufacturing process implemented by AMURA was evaluated in relation to the technical requirements established in D.2.2, ensuring compatibility with the vacuum infusion technique and its integration into the production of nautical components. The analysis carried out indicated that the key steps defined in the project specification were followed, including the reception, classification, arrangement, and infusion of the recycled reinforcements. However, a significant difference compared to the initial planning was the modification of the reinforcement material used. The initial objective of the project was to develop both a recycled unidirectional fabric and a non-woven recycled fabric. However, the woven fabric was not developed due to the limitations in processing recycled carbon fibres with the available weaving technologies. The fragmented nature of the recycled fibres and their insufficient friction properties led to instability during processing, preventing the formation of a structurally coherent woven fabric. As a result, the available options were restricted to a non-woven fabric stabilized through stitching.

In terms of processability, the recycled material proved to be compatible with vacuum infusion, meeting the requirements established in D.2.2. Nevertheless, the absence of woven fabric constrained its applicability in high-performance structural elements, particularly in configurations subjected to high mechanical loads or where weight reduction was a critical factor. In this context, the comparative analysis between the recycled reinforcements used and conventional primary materials revealed significant differences in terms of mechanical behaviour and processability.

From a structural perspective, the stitched stabilised recycled non-woven fabric exhibited a random fibre arrangement, in contrast to the controlled orientation of woven or unidirectional fabrics used in applications requiring strength in specific directions. This characteristic directly affected the material's load-bearing capacity and its efficiency in applications subjected to high mechanical stresses, reducing its viability in structural components.

Furthermore, during vacuum infusion, the recycled non-woven fabric showed resin absorption up to 82% higher, or even more, compared to conventional reinforcements such as twill. This behaviour directly impacted the final weight of the component and the efficiency of the process, being particularly critical in thick laminates, multi-layer configurations, or complex geometries, where polymer matrix consumption increased significantly, reducing fibre-to-matrix efficiency and compromising the structural performance of the material.

In conclusion, the use of recycled non-woven reinforcements was validated in nautical applications, demonstrating its compatibility with the vacuum infusion technique. However, its lower mechanical properties and high resin absorption limited its application in structures subjected to high loads or where weight reduction was critical. Nevertheless, this type of reinforcement could be used as a complementary

material in hybrid configurations, combining it with structural fabrics to improve load distribution and impact absorption.

From an economic perspective, the implementation of recycled reinforcements in the roof manufacturing process presented both advantages and limitations that influenced its commercial viability. According to the LCA analysis (D.7.3), the acquisition cost of the recycled material was positioned between virgin carbon fibre and glass fibre, with the former being up to three times more expensive than alternatives such as glass fibre or natural reinforcements. However, the recycled material was not competitive against virgin carbon fibre due to its lower mechanical performance and the absence of a weaving process, which limited its application in structures subjected to high mechanical demands. Furthermore, its impact on manufacturing costs was not only restricted to the material itself but also extended to the production process, as its high resin absorption increased polymer matrix consumption, affecting process efficiency and the final weight of the component.

Despite these limitations, the recycled material represents a viable alternative to glass fibre in scenarios where sustainability plays a significant role in decision-making. Its integration into hybrid laminates, combining it with other structural reinforcements, allows for performance optimization and an expanded range of applications within the marine sector. Specifically, this type of material is suitable for secondary boat structures, floating platforms, or components exposed to inland water environments, where the sustainability benefits justify its use. The economic feasibility of the process depends on balancing material costs, manufacturing efficiency, and environmental impact reduction objectives, factors that influence the decision to integrate these recycled reinforcements into commercial applications.

3.2.1.3 Vacuum pressing of pre-impregnated material based on mechanically recycled CF

The manufacturing process of a pre-impregnated material based on mechanically recycled CF has been successfully achieved. After several attempts and by controlling the resin grammage (g/m^2), the impregnation of the nonwoven supplied by CHOMARAT was obtained. However, during the manufacturing of both components (back seat cover and pedestal) some issues have been detected. On the one hand, the back seat has been only partially manufactured due to the lack of nonwoven material received. The achieved part has a size of 0.75x0.85m, while the original part was 0.75x2.15m. Despite that, the manufacturing of the whole part could be done without any problem if there were enough material. Overall, the back seat cover has been successfully manufactured, as it shows good compaction and stiffness.

Regarding the pedestal, more difficulties have been observed due to the complex geometry of the part. In this case, although the nonwoven material has a specific stitching to provide some consistency and orientation to the carbon fibre, it is not optimal for parts with complex geometries, such as the manufactured pedestal. The chain-tricot stitching used by CHOMARAT hinders the adaptation of the textile to the mould, so the following compression step with the silicone membrane is affected. The same part has been manufactured with a commercially available recycled carbon fibre nonwoven with chain stitching (benchmark). In this case, the nonwoven material has been better adapted to the mould resulting in a superior compression and appearance.

It should be noted that the fabrication of the prepreg material with the nonwoven from CHOMARAT has not differ from the benchmark nonwoven, suggesting its appropriate use for the fabrication of pre-impregnates. However, as previously mentioned, the manufacturing of parts with complex geometries from this pre-impregnate is limited, being better to manufacture simple and flat parts.

The life cycle analysis for both recycled CF components (back seat cover and pedestal) indicated that the environmental impacts in terms of Climate Change are significantly lower compared to benchmark nonwoven materials by 62%.

3.2.2 Chemical recycling of cured carbon fibre composites

3.2.2.1 Chemical recycling of cured CF composites

After the completion of the pilot plant start-up phase, a sequence of steps associated with a single reaction cycle was defined. It lasts 7 h and comprises the reaction itself as the central step (1 h 30 min), a group of “pre-reaction steps” (3 h 15 min for sample loading and reaction initiation) and a group of “post-reaction steps” (2 h 15 min for reaction termination and sample unloading), Figure 17 illustrates two selected steps of the sequence. Total operating cost at pilot plant has resulted as 770.3 €/batch (personnel 36.4 %, solvent media 25.4 %, reagents to control emissions and neutralise 3.8 %, liquids waste management 32.8 %, energy and utilities 1.6 %)

The global yield of the solvolysis process referred to fed material was confirmed in the range 62-65 % since after loading a batch of 4.00 kg of conditioned CFRPs (inlet) 2.48-2.60 kg of clean rCFs (outlet), once rinsed, washed and dried, were recovered. As it was proved that, in practice, the solvolysis medium can be used at least four times without apparent loss of activity, reactions were organised in series of four batches.

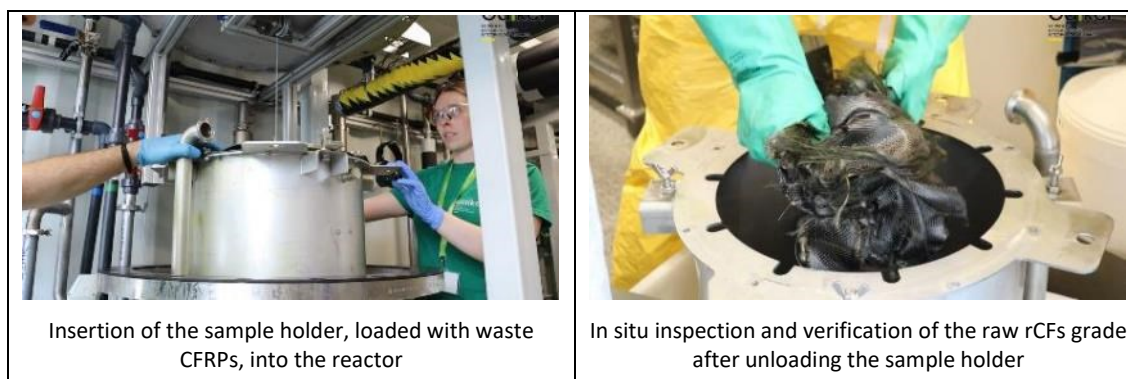


Figure 17: Solvolysis of waste CFRPs at the MC4 pilot plant

3.2.2.2 Textile processing and manufacturing from chemically recycled CF

At the technical level, the nonwoven technology in general suitable for recycled carbon fibres coming from solvolysis processes. The disadvantage is that after this treatment the chemically recycled fibres are nearly free of sizing. This influences the processing negatively and the production of nonwoven is not possible due to the stiffness and brittleness of the fibres. An additional process – the resizing – follows the fibre preparation steps of cutting and tearing leading to additional labour cost and cost for the sizing agents. Even after the resizing the STFI conclusions is that the solvolized fibres from GAIKER can only be processed in mixtures with the mechanically recycled fibres from CHOMARAT. Further explanations for the assessment of the preparation and nonwoven process are detailed in paragraph 3.2.1.2

At the economical level, by now the use of solvolized fibres from GAIKER with material cost of about 36 €/kg compared to 4 €/kg for the fibres from CHOMARAT needs further optimization of the chemical recycling process. Further explanations for the nonwoven production are provided in paragraph 3.2.1.2.

For CHOMARAT that is processing the intermediate textile after STFI transformation, no real assessment was achieved: due to low quantities of solvolized fibres, the evaluation of the processing on the NCF line wasn't realized.

3.3 Assessment relative to the expected outcomes

3.3.1 Recycling of CF scraps from the manufacturing of CF reinforcements

3.3.1.1 Textile processing from recycled CF

The waste collection and sorting of CF edges at CHOMARAT plant, was demonstrated and open industrial opportunities with industrial partners. Initial discussion started with a leader company in the nonwoven industry which manufacture and sell already a range of carbon nonwoven. A real need of new supplier is requested for this new market. Depending on fibre type and length, selling price level of had been evaluated between 2 and 4€/kg and collaboration is in progress for starting business in 2025. For CHOMARAT, it'll be the first opportunity to eliminate to reject CF waste by selling them to a new supply chain. EO1, EO2 and EO4 could be covered with the new circular market for CF waste recycling.

With the production of nonwovens made of waste material of both mechanically and chemically recycled fibres, the technical outcomes EO1, EO2, EO3 and EO4 can be covered. The reuse of material in the production line (EO1) and a contribution to EO2 (Establishing a circular life cycle) as well as EO3 (Enhancing the use of recycled material) could be proven through the development of semi-finished nonwoven products out of waste material from the NCF or composite production. The developed products are further processed into NCF again which are finally used in lightweight parts for the application in boatbuilding. EO4 (Economically feasible and patented process technologies) is covered through the reduced material cost arising when waste material is used (see section 3.2.2.2).

3.3.1.2 Textile manufacturing from mechanically recycled CF

CHOMARAT passed the technical assessment of new CF recycled reinforcements based on the STFI semi-finished products, themselves made with the CHOMARAT NCF waste. Thanks to the multiple trials operated in MC4 project, industrial data were collected on the processing and an industrial plan is realistic for targeting the TRL6-8 in the coming years. After industrialization of the complete product manufacturing processing, a selling price estimation for a 0/90deg 300gsm product made from recycled nonwoven (Hypothesis with an industrial nonwoven company) is estimated at 13,5€/m² (about 45 €/kg). This cost estimation is a key entry point for the next steps of development: it was counted in the LCA and shared with the project partner AMURA. It confirms today that EO4 with target price at 25€/kg is not demonstrated and requires deeper investigation.

3.3.1.3 Manufacturing of composite parts with recycled CF through vacuum infusion

The manufacturing of the T-Top roof for the MC4 demonstrator by AMURA using recycled carbon fibre for motorboats contributed to achieving several of the expected outcomes defined in the project. One of the key objectives was to establish a circular lifecycle for carbon and glass fibre materials (EO2). As described in section 3.1, AMURA implemented a circular manufacturing process that integrated recycled carbon fibre into a new nautical component, reducing the reliance on virgin materials and minimising waste. The process demonstrated that it is possible to reintegrate waste material into the production chain, aligning with the principles of sustainability and circular economy promoted by the project.

Regarding the objective of enhancing the use of recycled material through the design of at least 5 typical products and components (EO3), the results obtained with the roof manufactured by AMURA showed both achievements and limitations. While the development proved the feasibility of using recycled carbon fibre in the boatbuilding sector, the absence of a recycled woven fabric restricted the material's mechanical

performance, preventing it from fully replacing virgin fibre in high-performance applications. Additionally, the higher resin absorption of the non-woven reinforcement impacted the final weight and efficiency of the manufacturing process, which were critical aspects in structural applications.

Finally, in relation to the objective of demonstrating that the re-use of carbon and glass fibre parts and materials would reach up to 60% within the supply chain represented by the project partners (EO5), the life cycle analysis (D.7.3) indicated that replacing virgin fibre with recycled reinforcements reduced the carbon footprint of the process. Although the recycled material used in the roof exhibited higher resin consumption, its use contributed to reducing emissions and diverting carbon fibre waste from conventional disposal streams. The integration of this material helped increase the overall carbon fibre recycling rate within the project, but further efforts were required to optimise the process and expand the applicability of recycled reinforcements in the marine sector.

3.3.1.4 Vacuum pressing of pre-impregnated material based on mechanically recycled CF

The manufacturing of the pre-impregnated material from the nonwoven material fabricated by CHOMARAT has achieved one of the outcomes defined in the project. The cost to manufacture the pre-impregnated material has not varied since the amount of resin formulation to impregnate the nonwoven has been kept the same when comparing to a benchmark. Therefore, the manufacturing of this pre-impregnated is economically feasible and it enables a recycling rate of at least 60% (EO4).

The manufacturing of both parts (back seat cover and pedestal) with the pre-impregnated nonwoven from CHOMARAT on the other hand, has achieved the objective of enhancing the use of recycled material (EO3). However, as previously mentioned, the nonwoven material should show a different stitching to validate its use in the manufacturing of parts with complex geometries, but it is highly suitable for the manufacturing of simple and flat parts that also want to offer lightweight properties.

3.3.2 Chemical recycling of cured carbon fibre composites

3.3.2.1 Chemical recycling of cured CF composites

A solvolysis process for achieving the chemical recycling of waste CFRPs based on epoxy resins and amine hardeners has been designed, developed, demonstrated and scaled up. The process was developed at laboratory scale to run at low temperature (60 °C) and atmospheric pressure using solvents (containing inorganic acids) to produce high grade rCFs and liquids including the organics generated after the depolymerisation of the resin.

The process scale-up has been realized through the establishment of a pilot plant that has been designed, constructed, set-up and run to demonstrate the chemical route to recycle waste CFRPs. The pilot plant that, as main equipment, has a tank reactor including a sample holder to feed and react the waste CFRPs and filter, rinse and retrieve the rCFs and separate the solvolysis liquids. The solvolysis liquids were far from the ideal fraction in terms of concentration of desired organic compounds and undesired salts. The quality of the rCFs produced in the plant was confirmed to be equivalent to the one of the rCFs coming from the laboratory tests and rCFs were verified as processable by incorporating them into nonwovens products through spinning and weaving processes.

3.3.2.2 Textile processing and manufacturing from chemically recycled CF

The assessment of the process performance related to the project expected outcomes for the use of solvolyzed CF is summarized in section 3.3.1.1. Due to the low quantities of solvolyzed fibres, no real assessment was achieved for CHOMARAT in the processing of new recycled carbon fibres reinforcements.

4. GF SHORT-TERM: SHREDDING OF CURED GLASS FIBRE

Unlike carbon fibre, recycling glass fibre-reinforced composites presents significant economic and technical challenges, primarily due to the difficulty in separating the fibre from the polymer matrix. Additionally, glass fibres require a protective surface treatment, known as sizing, which enhances their bonding with the matrix and improves mechanical performance. Unfortunately, any recycling process that involves fibre recovery would inevitably damage this coating, leading to a loss of performance and making direct reuse impractical.

To address this issue, MC4 proposes a glass fibre – short term strategy (Objective O3) that focuses on mechanical recycling methods rather than chemical or thermal processes. The goal is not to recover the glass fibres intact but rather to repurpose the cured composite material by grinding or shredding it into chopped material. This chopped material can then be incorporated into new composite parts, reducing waste and improving resource efficiency.

4.1 Full circular process chain

4.1.1 GF composite shredded material re-use in a modified RTM process

The end of life (EoL) material from the bus side wall is shredded into “fibres” of 1 to 10 cm. This is achieved by transporting the side walls to the external company CRC for mechanical shredding and then delivering them back to VDL Fibretech. These fibres still contain the foam and resin used for the original part. They are used as a chopped material and to provide extra strength in the new side skirt of a bus. The RTM mould is first layered with virgin unidirectional glass fibres. After this, the shredded fibres are placed in the mould. The foaming resin is then applied, followed by the final layer of virgin glass fibres. After this the mould is closed for 4 hours. The final product comes out from the RTM mould is a side skirt ready for post processing. Here, the excess material is removed, and the side skirt is processed to dimensions. The hook piece is glued to the side skirt. This hook piece has a specific angle, making it impossible to place it in the mould initially. After these steps, the part is ready to be attached to the bus. The shredded GF was sent also to 2 other partners NOMA and LAB23 to produce parts with different methods and technics. NOMA used the shredded GF composite and virgin epoxy resin to produce a joining collet with the technique of the compression molding. LAB23 used the shredded GF composite and virgin polyester resin to produce a soul urban bench with the technique of hand lay-up.

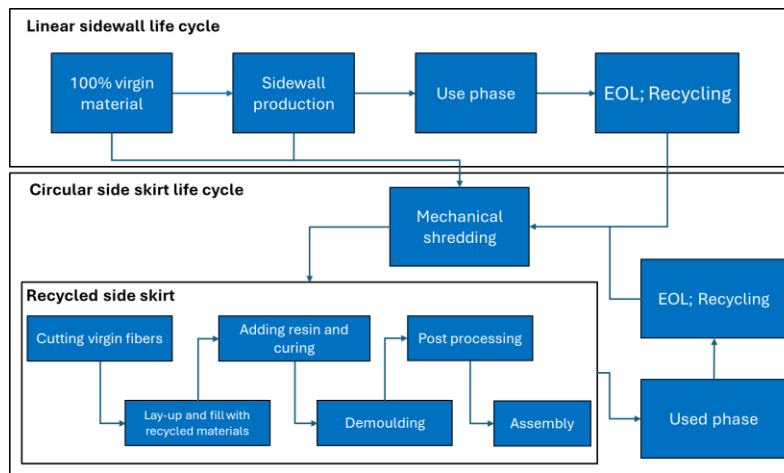


Figure 18: Material flowchart for the process toward bus side skirt demo

4.1.2 Compression moulding of shredded GF composite with epoxy resin

In this section, the general overview of the fabrication process of joining collets by means of pressing material into moulds is presented. The fabrication of composite joining collets begins with material selection, where shredded rGFRPs particles are combined with NOMA amin epoxy resin. Next, the reinforcements and matrix are prepared by mixing particles for uniform distribution. A metal mould is then prepared to ensure durability and precise shaping. The mixing stage follows, ensuring an even arrangement of reinforcements within the matrix. The material is then pressed into the mould using cold or hot pressing to achieve compactness and strong interfacial bonding. During curing, the polymer hardens according to resin specifications for maximum strength. Afterward, the composite cools and is demoulded, with excess material removed. Finally, post-processing such as annealing ensures complete curing and optimal mechanical properties.

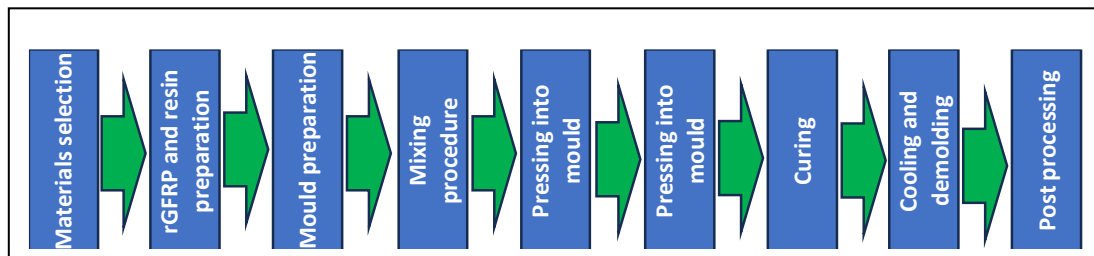


Figure 19: Material flow chart describing processing chain for joining collets fabrication.

4.1.3 Hand lay-up and casting of shredded GF composite with polyester resin

Here's the circular process chain for hand lay-up and casting of a shredded GFRP urban bench, focusing on recycling and sustainability:

1. Waste Collection:

- Sourcing: a partnership has been established by VDL with his customer, who will supply end-of-life GFRP automotive parts (specifically from buses). For future scale-up, local recycling centres, manufacturers, and demolition companies will be targeted as key waste sources.
- Collection: a GFRP waste collection system has been set up, which may include partnerships with local waste management companies.

2. Shredding & Processing:

- Shredding/Grinding: an industrial granulator was used to reduce the GFRP waste into smaller pieces (flakes/strands) suitable for the "Soul" bench. Effective dust control is essential during this stage.
- Cleaning (Optional): if necessary, the shredded GFRP would be cleaned via air blasting to remove any remaining contaminants or loose fibres.

3. Composite Preparation:

- Resin Preparation: unsaturated polyester resin is prepared according to the manufacturing manager's instructions, using 55kg per bench.
- Mixing: 100kg of shredded GFRP is thoroughly mixed with the prepared resin, ensuring even fibre distribution throughout the resin matrix. The fibre-to-resin ratio will be carefully controlled to achieve the desired strength and properties in the final product. A mechanical mixer is used. Fillers (e.g., recycled glass powder) are added to extend the material and enhance specific properties.

4. Mould Preparation & Casting:

- **Mould Design & Fabrication:** the urban bench mould is designed and fabricated from Glass fibre as suitable material. The design will consider demoulding and the desired surface finish.
- **Mould Release:** A mould release agent is applied to prevent the GFRP from adhering to the mould.
- **Lay-up/Casting:**
 - **Hand Lay-Up:** for hand lay-up, a gelcoat resin layer is applied to the mould, followed by 25kg of virgin glass fibre, ensuring homogenous distribution. The shredded GFRP mixture is then applied, again ensuring even distribution and consolidation. These layers are repeated until the desired thickness is achieved.
 - **Casting:** for casting, the mixture is poured into the mould, taking care to ensure complete filling and minimise air bubbles.
- **Curing:** the composite is cured according to the resin manufacturer's recommendations, with careful control of temperature and humidity for optimal results.

5. Demoulding & Finishing:

- **Demoulding:** the cured GFRP bench is carefully removed from the mould.
- **Finishing:** any necessary finishing operations, such as trimming or polishing, are performed to achieve the desired surface finish and dimensions.

6. Installation & Use:

- **Installation:** the finished GFRP bench is installed in its intended location. Features such as integrated armrests (like the prototypes fabricated by CIDETEC), USB and wireless chargers, or Bluetooth speakers can be added to meet customer requirements.
- **Use & Maintenance:** the bench is ready for use. Regular cleaning and maintenance will extend its lifespan.

7. End-of-Life:

- **Collection:** when the bench reaches the end of its life, the GFRP material will be collected.
- **Component Separation:** features such as integrated armrests (as in CIDETEC's prototypes), USB and wireless chargers, or Bluetooth speakers will be separated for reuse or recycling.
- **Reprocessing:** the GFRP can be shredded and reused in new composite products, closing the loop. This may involve mixing it with virgin materials like resin, glass fibre, and gelcoat, or using it in less demanding applications.

Circularity Considerations:

- **Material Tracking:** Records of GFRP waste sources and final products will be maintained to track the circular flow.
- **Collaboration:** collaboration between stakeholders, including waste management companies, manufacturers, designers, and end-users, is crucial for the success of this circular process.

By implementing this circular process chain, LAB23 can create sustainable urban benches from recycled GFRP, minimising waste and contributing to a circular economy.

4.2 Evaluation of the processes

4.2.1 GF composite shredded material re-use in a modified RTM process

VDL's approach involved conducting multiple tests with different fibre contents and proportions, and with different resins, to achieve the desired qualities for bending and tensile strength. From the test of the resins, the best way to impregnate all the fibres in the mould and the fibre content were found. Particularly,

different resins were tested for various purposes, such as epoxy foam for light weight, PUR resin, epoxy resin and vinyl ester resin, polyester for durable products. It turned out that the epoxy foam was very suitable for the side skirt of the bus, because it needed to be lightweight, but also had reasonably high stiffness. However, it was also concluded that the addition of virgin fibres is essential to meet the desired qualities.

The side skirt for the bus is still in the lab scale, conducting multiple tests to find the optimal ratio between as little virgin fibre as possible and the desired qualities for the side skirt and to properly impregnate the complete side skirt. The fraction of waste used into the side skirt product is 50 % because the virgin fibre used is also left over from the making of the side wall of the bus. The fraction of waste used into the rain barrel is 54%, if the virgin fibres used in the product are also left over from making the side of the bus the fraction of waste is 81%.

The cost of the process of the side skirt is expected to be quite high because of the hand labour. The process cost will be around 90.48 euro, adding the material cost. This makes the total cost of the process of the side skirt 100 euro. If this process is automated, the costs will be reduced. However, significant investments in equipment, such as new moulds, automated scatterers, and resin applicators, will be necessary to achieve this.

4.2.2 Compression moulding of shredded GF composite with epoxy resin

The fabrication of composite components containing recycled GFRP fractions presents several challenges, primarily due to poor compatibility between the neat resin and recycled fractions, low wettability of the recycled surfaces, variations in infiltration behaviour during the processing of liquid resin, and differences in viscosity caused by the non-standard geometry of the recycled fractions. These factors can significantly impact the overall quality and performance of the final composite material.

As in the case of joining collets, considering the availability of shredded materials and the results of extensive measurements, an optimized composition of 50 wt.% recycled material in the virgin composite was selected. This composition was determined to offer the best balance between sustainability and mechanical performance. Scanning Electron Microscope (SEM) observations of the composite cross-sections revealed a well-formed microstructure, free of pores and discontinuities. These findings confirm that the developed manufacturing method, along with the selected materials, is suitable for producing good quality composite components incorporating shredded rGFRPs. Furthermore, additional tests were conducted using a liquid organic fraction obtained from the solvolysis process, in which the resin was dissolved. These tests aimed to assess the potential of utilizing the recovered liquid fraction in the composite fabrication process, contributing to the circular economy approach and enhancing the sustainability of GFRP recycling methods showing potential for further investigations in this area.

4.2.3 Hand lay-up and casting of shredded GF composite with polyester resin

The Soul Bench recycling process shows promise but requires further development for economic viability and scalability. Economically, initial waste collection costs are low due to the VDL partnership, but future expansion requires investment to build a strong supply chain. Shredding, processing, and composite preparation involve material and operational costs, still necessitating optimization. Moulding and casting costs encompass both material and labour, with hand lay-up possibly being less efficient when scaled up. End-of-life costs and potential material recovery value need consideration to build a strong business model. To establish a robust business model, throughput must be optimized, as it is currently limited and may require automation. Initial investments focus on equipment and mould fabrication, with future investments needed for scaling up production. Technically, controlling the consistency of shredded GFRP flake size and managing dust are essential. The mixing process and the fibre-to-resin ratio play a key role in determining the quality of the recycled GFRP composite. The quality of the final bench is also affected by hand lay-up

and casting techniques. Comprehensive performance testing, including visual inspection, dimensional accuracy, mechanical testing, and durability evaluation, is crucial.

Key challenges involve maintaining consistent properties of recycled GFRP, ensuring it performs at a level comparable to virgin materials, and successfully scaling production. Moving forward, a thorough cost analysis, in-depth performance testing, process optimization, and a life cycle assessment will be vital for the success of the Soul Bench project.

4.3 Assessment relative to the expected outcomes

4.3.1 GF composite shredded material re-use in a modified RTM process

The quality of the scrap depends on the material of the EoL parts. If these parts contain a lot of PVC foam, the recycled fibres contain a lot of dust. It also depends on which resin is used in the EoL parts. If epoxy resin is used, the recycled fibres that are shredded are much cleaner than with polyester resin. The process developed to produce the side skirt involves a lot of hand lay-up, hand machining and hand mixing, which takes quite some time. For the small RTM mould (1 meter) this process is the most optimal. This is needed because the recycled fibres will otherwise stand up straight and will damage the mould. Since hand lay-up products are costly due to high manpower requirements, some steps have to be taken into consideration when this product is going to be mass produced.

The cost of the materials needed to make the side skirt is relatively low. The recycled fibres are around 250 euro per ton. The foaming resin reduces the amount of resin needed, resulting in lower costs and the virgin fibres can be internally recycled from the bus side wall production. The investment needed includes a much larger RTM mould to produce multiple sizes and multiple side skirts at the same time. Another necessary investment is an automatic fibre dispenser. The price of the recycled side skirt is lower than the price of the original because the correct colour can be incorporated into the side skirt during production, eliminating the need for painting and reducing extra costs. Key focus areas include finalizing production readiness, conducting essential validation tests, and ensuring product compliance with automotive standards. For setting up the serial production of the side skirt and to market the product, further testing is needed. A production-grade mould (dimensions: 4 meters (length) × 1 meter (width)) has been commissioned to accommodate larger component prototypes and simulate high-volume manufacturing conditions. Because of the aforementioned, the mould is designed and ordered. The testing exists for automating the fibre and resin distribution, making bigger side skirt pieces (4 meter instead of 1 meter) and strength tests. The above steps are critical for transitioning the side skirt from prototype to a market-ready product.

The quality of the side skirt made with recycled materials is comparable to the original side skirt. It is even stiffer than the original. The expected results are in line with EO2 and EO3. The expected outcome is to establish a circular recycling process for the glass fibre composites. The biggest challenge is to produce high-quality products. This can be addressed by using new materials or fibres in addition to the recycled material to reinforce products, making it possible to use recycled material in high-performance applications. The product produced is an automotive application (side skirt). This design will demonstrate that parts can be manufactured from recycled material, with the same level of mechanical performance and visual appearance as those made from virgin material. Furthermore, VDL expects to have an operational production line for these products and to train experts in the field with the educational material about the use of recycled material.

4.3.2 Compression moulding of shredded GF composite with epoxy resin

In the case of joining collets made of recycled shredded GFRPs, the product specifically addresses the following expected outcomes namely, EO3: Enhancing the use of recycled material and EO5: the project

will demonstrate increased re-use of carbon and glass fibres parts and materials. Pipes with a 2-year warranty often remain in use for over 8 years, reducing installation safety. A solution is composite based pipes and components, such as joining collets. The Composite pipes market size is forecast to reach US\$1.5 billion by 2027 after growing at a CAGR of 5.1% during 2022-2027, driven by composites' advantages, including customizable properties, low weight, and high resistance to corrosion and chemicals. Composite structures weigh significantly less than traditional materials, reducing the need for heavy equipment and lowering costs. Their durability exceeds 50 years, retaining at least 80% of initial strength. Their installation is also simpler pipes can be unspooled, eliminating welding, cutting installation time by 40-80% and costs by 35-65%. Fewer workers are needed, and radiographic inspections of welds are unnecessary. Composite pipes are also corrosion-resistant, making them ideal for transporting aggressive chemicals. The results show the possibility to produce joining collets containing min. 50 wt.% of shredded material saving the same amount of virgin materials in the form of glass fibres and epoxy resin.

4.3.3 Hand lay-up and casting of shredded GF composite with polyester resin

The Soul Bench directly addresses the circular lifecycle for glass fibre by utilizing recycled GFRP and aiming for 100% recyclability. This is a significant step towards closing the loop for this material, aligned with EO2 Circular lifecycle. Moreover, the Soul Bench serves as a tangible example of a product (furniture) made from recycled glass fibre, demonstrating the feasibility of using recycled materials in a new application (aligned with EO3-enhanced use of recycled material) and reducing CO2 emissions compared to using virgin materials (EO5-environmental impact). The project aims for a 60% reuse rate, and the Soul Bench contributes to that goal.

The project aims also for 95% of the tensile strength of virgin material for reuse (EO2, high-quality reuse). The description lacks details on testing the mechanical properties of the recycled GFRP used in the Soul Bench. Data demonstrating the achieved tensile strength and other relevant mechanical properties (flexural strength, impact resistance) compared to virgin GFRP is essential to validate its suitability for high-performance applications. The long-term performance and durability of the recycled GFRP in outdoor conditions also need to be assessed.

Regarding economically feasible recycling (EO4), data on the cost of the recycled GFRP itself in the “real market” is needed. The target cost range for recycled materials (40-60% of virgin materials) needs to be addressed. The Soul Bench itself raises awareness and the development of educational materials for part designers, reflecting EO6 on awareness at part designers. Sharing the knowledge gained from the MC4 project in trade fair and Green Public Procurement conferences, including material properties, processing techniques, and design considerations for recycled GFRP, would be crucial for achieving this outcome.

5. GF LONG-TERM: RE-SHAPING OF CURED 3R GLASS FIBRE

Recycling glass fibre-reinforced composites presents significant challenges, primarily because separating the fibre from the polymer matrix is often economically unfeasible. Traditional thermoset resins, such as epoxy, form irreversible chemical cross-links, making them difficult to break down and repurpose once cured. This limits the possibilities for recycling, often resulting in landfill disposal or downcycling into low-value applications.

One of the key objectives of the MC4 project (Objective O4) was to propose a process avoiding the need for fibre-matrix separation by integrating a vitrimer-based matrix material instead of traditional epoxy resins. Vitrimers are a revolutionary class of polymers that retain the strength and durability of thermosets but also possess a dynamic network of covalent bonds that can rearrange under heat, allowing reshaping and repair while maintaining material integrity.

5.1 Full circular process chain

The circular process chain begins with the formulation of a vitrimer resin tailored to meet the specific requirements of the chosen demonstrator, which in this case is a kayak produced via vacuum infusion. This resin is not only designed to match the structural and performance characteristics needed for the kayak but also to ensure that it allows for the reshaping of the kayak parts into new products, such as paddles, through thermoforming. As the kayak reaches the end of its life (EoL), it is disassembled and trimmed into smaller pieces. These pieces, now considered waste, are then reprocessed and thermoformed into new composite parts, such as kayak paddles. This step ensures that the original material is given a second life, reducing waste and making the process more sustainable.

Once the paddles themselves reach the end of their life, they can be further processed through mechanical recycling. This means that the paddles can be broken down and reused in new applications, continuing the cycle of material reuse. This circular process not only maximizes the lifespan of the materials but also minimizes waste, contributing to a more sustainable and efficient lifecycle for composite products.

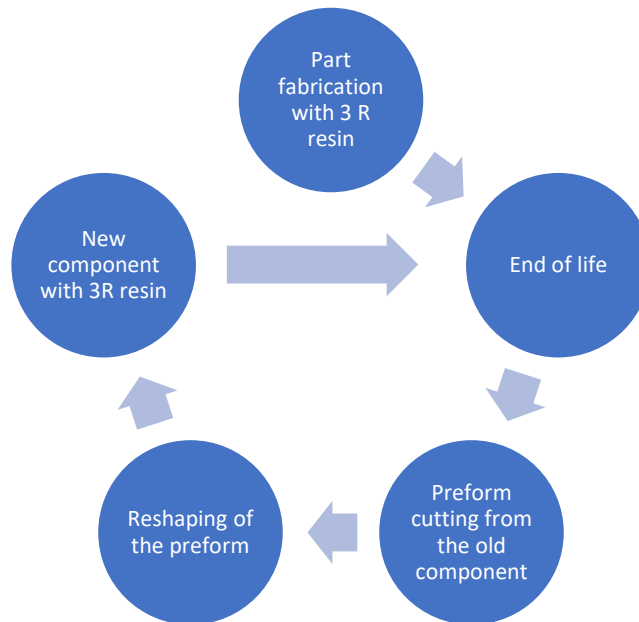


Figure 20: Material flowchart for the process toward kayak paddle, from repurposed GF composite material from EoL kayak

A novel process has been developed to reuse glass fibre and epoxy-based vitrimer composites that have reached the end of their service life without having to separate the fibre from the matrix. This process begins with the design of the composite part, the formulation of the 3R epoxy resin, and the manufacturing of the composite part itself. This involves impregnating reinforcing glass fibres with the 3R epoxy resin matrix and curing the material to obtain the final composite part. The specific curing conditions, such as temperature and time, depend on the properties of the newly developed 3R epoxy. When the final product reaches its EoL, the product is collected by the manufacturer for dismantling and trimming into composite parts (preforms) with the dimensions required for repurposing into the previously designed new product. The repurposing of the EoL GF composite material is done through thermoforming (Figure 21), a relatively straightforward process in terms of its sequence of steps. During the thermoforming process, flat or near-flat composite parts are placed in a heated mould of a given shape, a press is used to apply pressure

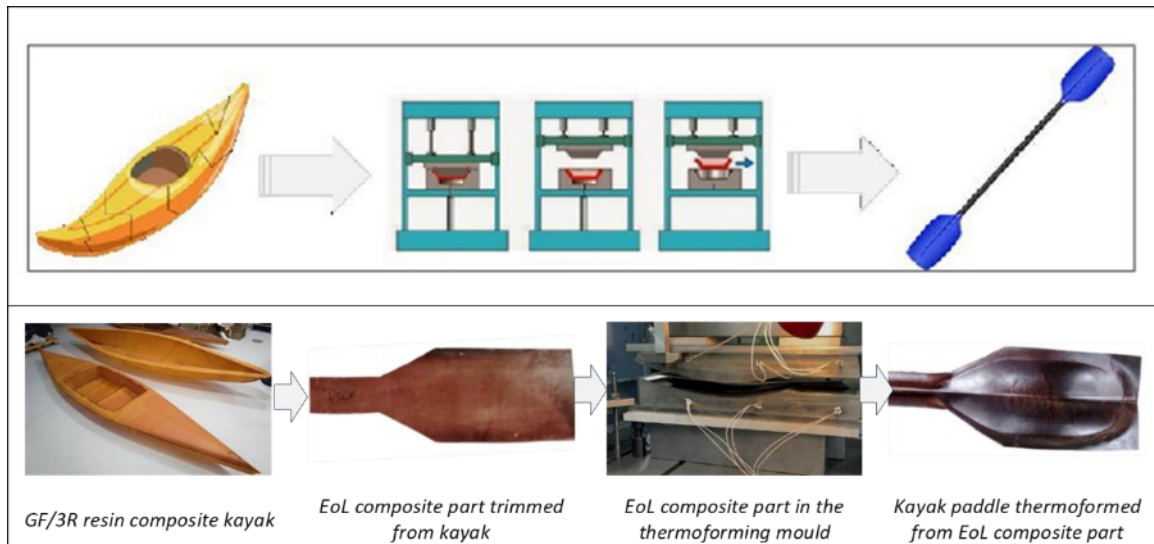


Figure 21: Illustration of the repurposing process of 3R GF composite material through thermoforming

In order to maximize the amount of material to be reused, a two-step pressing process was followed when the original curvature was too sharp. This optional first step involves a flat mould, thermoforming the sharp curvature into a flat form, while the second mould with the final desired shape is used to thermoform the second life product.

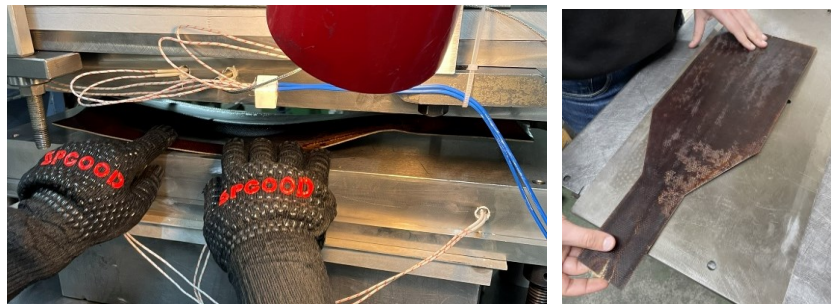


Figure 22: Optional step to flatten sharper shapes

The process starts with the pre-heating of the recovered parts to 180°C in an air heated oven. The part is pressed within a mould heated at 180°C during 3 minutes for single layer laminates, and 13 minutes for double layer laminates. The last forming step consists in letting the part cool down in an external closed cooling mould to maintain the correct shape while it is getting cold. This allows to set free the pressing mould, to be used for the next operation.

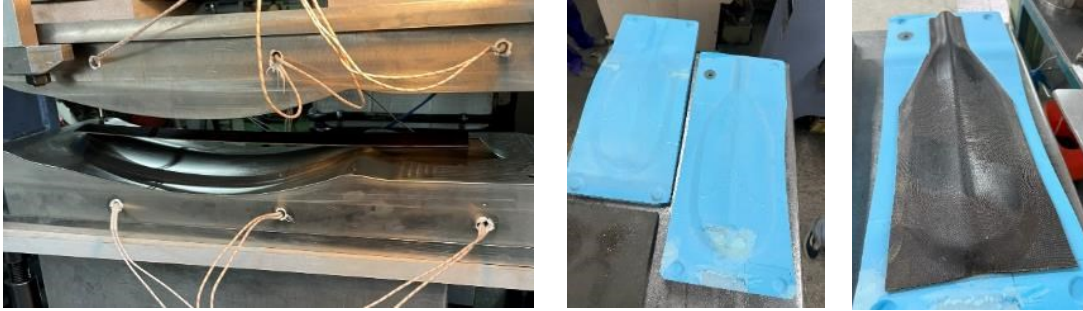


Figure 23: Final shape thermoforming and cooling

Once the shaped part has fully stabilized, any necessary post-processing steps are performed, such as trimming the excess material, refining the edges, and ensuring that the final part meets the required dimensional tolerances. Additional finishing treatments, such as surface coatings or quality inspections, may also be carried out at this stage.

5.2 Evaluation of the process

Regarding paddle process cost, re-shaping paddle process differs very much on the type of process needed so different types of equipment and skills would be needed. The following table compares investment and recurring costs for both options. It is worth mentioning that skills for benchmark part production are more demanding than for the press thermoforming process.

Cost type (per 2 paddles)	Investment cost			Recurring			Total cost (Euro)
	Mould + RTM or autoclave process (euro)	Heated press (euro)	Laminate cutting system (euro)	Virgin material	Lamination and curing	Press and heating	
Benchmark	16	0	3	8	75	0	102
Re-shaped	8	7	0	0	0	25	40

Table 2: Paddle manufacturing cost comparison

From a technical level point of view, the characteristics of the 3R laminate are different from the benchmark material, having similar strength, but lower elastic modulus, resulting in products which suffer more deformations, while suffering less stresses, so they are less likely to be broken. This can be positive for certain products, although it is not a positive characteristic for a paddle, for which a high stiffness is appreciated.

Performance under same loads	Max deformation (mm)	Composite failure index (failure >1.0)	Weight (kg)
Benchmark	20.2	0.86	Equal
Re-shaped	34.0	0.69	Equal

Table 3: Paddle performance comparison

From a quality point of view, even if the thermoforming process is less manual than the benchmark material lamination process, the outcome has resulted being less robust. Resulting parts are less consistent with regard to the visual aspect, as well as the number of wrinkles which can appear on the surface.

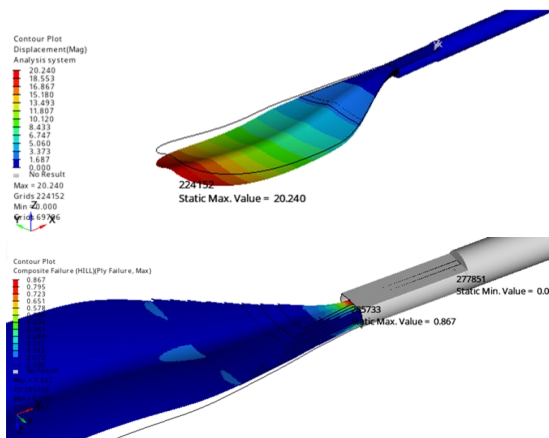


Figure 24: Max. deformations and stresses for benchmark material

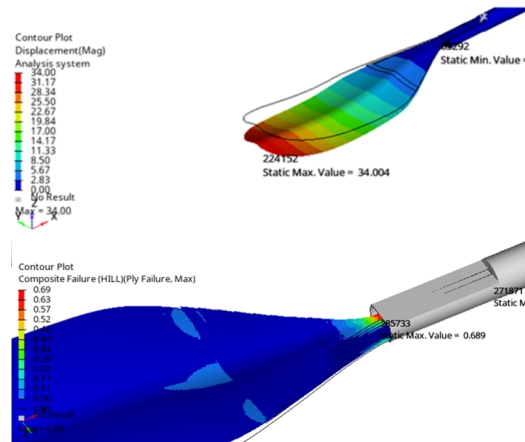


Figure 25: Max. deformations and stresses for 3R material

5.3 Assessment relative to the expected outcomes

The reshaping of glass fibre composite based on 3R epoxy resin has been demonstrated to align with the technical outcomes of the MC4 project. Indeed, the use of 3R epoxy resin instead of traditional epoxy resin for the manufacturing of the initial composite part has showed to allow for the subsequent re-shaping of GF composite material into a new product, without the need for matrix/fibre separation (O4).

The MC4 kayak has been designed with a circular lifecycle, enabling its components to be trimmed and reshaped at the end of their life (EoL) for reuse in the sports equipment industry, particularly in the production of kayak paddles. Notably, a single decommissioned kayak provides enough recycled GF composite material to manufacture ten paddles. This approach underscores the potential for material reutilization and cost efficiency while promoting sustainability through a closed-loop system that seamlessly extends product lifecycles (EO2).

Furthermore, this reshaping process significantly extends the lifespan of GF composites (EO2). Once manufactured, the GF composite material serves not only for the typical lifespan of a composite kayak but also for the duration of a paddle's use. Eventually, it can be further repurposed into another reinforced plastic product in the form of shredded GF composite filler from mechanical recycling. The typical lifespan of a glass fibre epoxy composite kayak ranges from 10 to 30 years, influenced by factors such as usage intensity (frequent exposure to rough waters, UV radiation, and impacts), maintenance and care (proper storage, regular cleaning, and avoiding prolonged sun exposure), and environmental conditions (saltwater exposure, extreme temperatures, and humidity). While the kayak's structural integrity can endure for decades, performance degradation—such as loss of stiffness and increased brittleness—may begin after 10–15 years with heavy use. Similarly, a glass fibre epoxy composite kayak paddle typically lasts between 5 to 15 years, depending on the same factors as the kayak. Under heavy use, a paddle's lifespan is estimated at 5–7 years before noticeable performance loss occurs. Based on these estimates, reshaping one-tenth of a kayak's composite material into a single kayak paddle effectively doubles the lifespan of that portion of GF composite material.

The MC4 project results have also demonstrated that the re-shaped GF composite material exhibits very good properties retention ratios, with values > 85% when measuring tensile, flexural and interlaminar shear properties, therefore tackling the key challenge of getting high-quality recycled materials.

The reshaping process has proven effective in integrating recycled material (EO3), facilitating the production of a kayak paddle—originally crafted from virgin material—using recycled components without compromising mechanical performance or visual quality. Notably, this method enables the reuse of 94% of end-of-life (EoL) kayak material, whereas composite kayaks are typically disposed of in landfills at a rate of 100%.

At an economical level, the LCC analysis highlighted that the MC4 kayak is 5% more expensive than the conventional version, but the MC4 paddle is 62% cheaper. When considering one kayak and ten paddles, the MC4 circular process proves to be 21% more cost-effective overall. Therefore, considering the high-quality of the recycled kayak parts in terms of mechanical performance, the cost/performance ratio for the paddle is particularly good (EO4).

From an environmental perspective, the paddle is produced using almost 100% reused materials from decommissioned kayaks, with less than 1% of the total material consisting of epoxy adhesive for bonding the sections. Since composite waste is typically landfilled with no inherent value or environmental impact, manufacturing the paddle through this circular supply chain results in an 85% reduction in climate change impact (see D7.3), demonstrating significant potential for CO₂ emission savings (EO5).

In general, the paddle re-shaping process has been satisfactory. The process proposed by CIDETEC has been applied to the full-scale product without major adaptations. Temperature and pressure have been under control throughout the process in a repetitive way. However, two points need to be highlighted. It is a key factor that the second life parts must have less structural needs than the original part, which was not the case for this application. So, a careful selection of second life items is a must. Secondly, the double axis bending of the paddle surface, even if it looks mild, is quite demanding for the fibre accommodation during the re-shaping process. Quality output would be improved if bending axis were studied or simulated during the design phase. These considerations should be introduced as key data to be known by experts to facilitate the design of new parts to be manufactured (EO6).

6. SORTING OF PARTS & QUALITY GRADING METHODS

One of the critical challenges in composite recycling is the heterogeneity of resin systems in end-of-life (EoL) parts. To address this, the MC4 project proposed the development of an advanced sorting technology to distinguish different resin types before these parts undergo the matrix/fibre separation process (Objective O5). A second focus has been on differentiating vitrimer resins from conventional thermosets, enabling a more efficient and targeted recycling process.

Another challenge in composite recycling lies in the quality control of recycled CF for their integration into high-performance industries such as automotive, aerospace, and sporting goods, where consistent quality is essential. Indeed, due to variability in fibre length, orientation, and mechanical properties, the quality of mats and fabrics produced from recycled carbon fibre can vary significantly. To address this challenge, AI-driven quality grading methods have been developed to provide real-time, automated quality assessment of recycled carbon fibre mats and fabrics, ensuring that they meet the requirements of various applications (Objective O5).

6.1 *Sorting of EoL composite parts*

The material- and/or property-preserving recycling processes that have been (further) developed as part of this project are strongly affected by the resin system present in the composites. The chemical recycling process developed by GAIKER for the separation of matrix (resin) and fibres of end-of-life carbon fibre composite parts focuses on epoxy resins with amine hardeners. For successful processing, it has to be ensured that no other resins – especially no epoxy anhydrides – enter the chemical process. The thermo-mechanical re-shaping process used for the recycling of end-of-life glass fibre composite parts requires that the parts have been made with the 3R resin (amine-based epoxy vitrimer) developed by CIDETEC. If glass fibre parts made with standard thermoset resins are used in the process, this will damage the equipment. As a result, both carbon fibre and glass fibre composite parts need to be sorted according to their resin system (and therefore their chemical composition) prior to processing.

The basic requirement for reliable mechanical sorting is reliable in-line material recognition. A promising method for resin identification was developed by i-RED with the help of partners who provided sample parts and materials. The method is based on near-infrared (NIR) spectroscopy, a non-destructive optical technique for the chemical analysis of materials by point measurements. This approach is easy to automate, permits high measurement speeds (for high-throughput applications, such as measurements on a conveyor belt), enables the use of glass waveguides (to reach inaccessible areas of a plant), is harmless to humans (because no laser radiation is involved), and is insensitive to ambient/extraneous light.

For the application of the NIR method, an optimised fibre-coupled reflection optics is placed near the sample surface. The measuring principle is diffuse reflection. The sample is illuminated with a halogen light source. The light reflected from the sample surface is collected via the optical fibre and forwarded to an industrial FTNIR process spectrometer ("light analyser"). This results in a characteristic NIR spectrum that can be used to identify the types of molecules in the resin and thus the type of resin. The entire sorting process therefore consists of the following sub-steps: spectra generation (spectroscopic measurement), spectra evaluation (material identification / classification), mechanical sorting. Resin classification models utilizing the PLS-DA method were developed for the automated identification of the resins. PLS-DA is used to analyse / optimise the separation between different groups of samples by linking the two data matrices X (raw data, spectra) and Y (class memberships, groups); it can be viewed as an adaptation of the well-known PLS regression method to the problem of supervised clustering. Supervised models are built using prior knowledge about important sample features, e.g. membership of experimental groups. The creation of classification models thus required reference materials with known composition.

Using the NIR method, it could be shown that despite the low reflectivity of carbon fibre parts, sufficiently strong measurement signals are received from these materials. In addition, it was found that the spectra of

carbon fibre parts with epoxy amines have many features in common, which differ significantly from the features in the spectra received from parts containing epoxy anhydrides. This means that the requirements are met to clearly identify parts with epoxy amines and to distinguish them from parts made of epoxy anhydrides. It could also be shown that the NIR spectra of glass fibre parts produced with the 3R resin contain several spectral features and regions that are characteristic for this particular type of resin and thus enable its unambiguous identification. The same is true for glass fibre composites with a polyester resin matrix, which can be clearly and easily distinguished from parts containing other resin systems.

The project objective of finding the optimum method for rapid and non-destructive identification of the resin system of carbon and glass fibre composite components at laboratory level was successfully achieved. In addition, it could be shown that the method can handle both light and dark (e.g. grey/black) coloured components. The NIR reflection optics developed as part of the project can deal with the harsh conditions in a recycling plant and provides the high energy input needed at the measuring point. The verification of the measurement concept for large-scale implementation was not part of this project.

6.2 AI-based enhanced quality control methods for recycled fabric

Encouraged by the sustainability benefits, many industrial manufactures adopted the carbon fiber (CF) materials as a standard material for the components manufacturing across various domains. However, these materials are likely to reach their end-of-life in the upcoming years. To enhance the optimal usage of resources and reduce the CO₂ emissions many companies are looking to extract, reprocess and reuse these end-of-life CFs at an industrial scale. During the manufacturing process of virgin or recycled CF materials, several unwanted defects can be introduced, which may consequently result in the reduced strength of the manufactured end-component. Thus, the inspection of the CF material prior to final component production represents an essential quality control step.

Profactor GmbH, as a part of this project, developed the modular vision-based sensor and AI-based inspection system, that can inspect and identify the defects on both virgin fiber and recycled carbon fiber materials. Additionally, material grading approach was developed to assess the quality of the manufactured recycled materials.

The modular vision-based sensor system (Fscan-M2) incorporated nine individual cameras, each with its

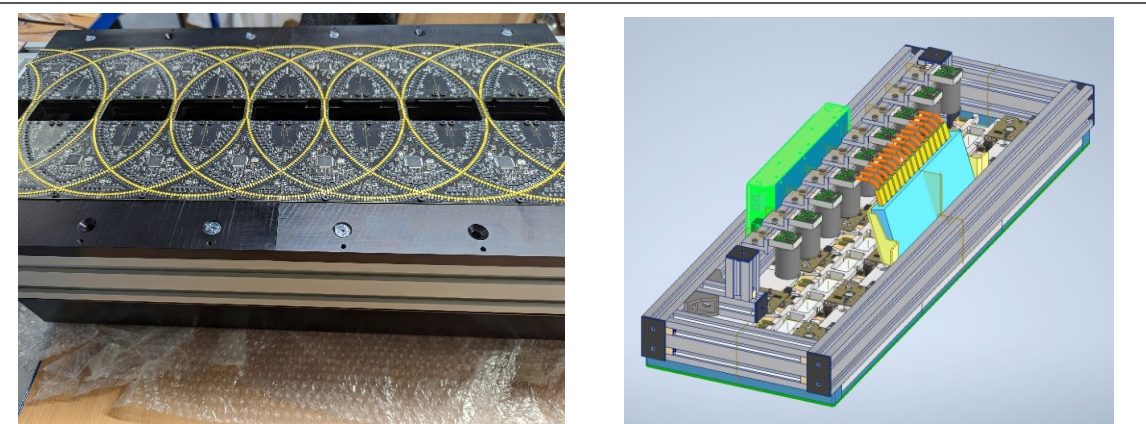


Fig.: Cameras with adjacent processing boards, switch and power supply

own dedicated processor unit and a light ring, with the ability to cover the total field of view of 700mm in width, with the extension possibility of up to 2.5 meters. The sensor performs a patch-based scanning procedure which offers core advantages such as: efficient inspection of curved surfaces, employment of load balancing, scalability/ reduction of the system memory requirements, fast detection of rejects and ability to show defect span over multiple patches. The sensor was integrated at the Chomarat premises, where its abilities for continuous scanning of the NCF material during production process was tested.

AI-based defect detection system for both virgin and recycled carbon fiber materials was designed to automatize the process of current parametric defect segmentation system. The development of such system addressed and resolved the following challenges: (1) visual and textural differences between the carbon fiber material samples; (2) both virgin and recycled carbon fibers are very diverse materials which vary in terms of visual, physical and chemical properties; (3) existence of the non-rigid materials, where defects itself might deform the sample, leading to mis-classification; These constrains introduce a distribution heterogeneity in the dataset, which creates difficulties for proper analysis of such data.

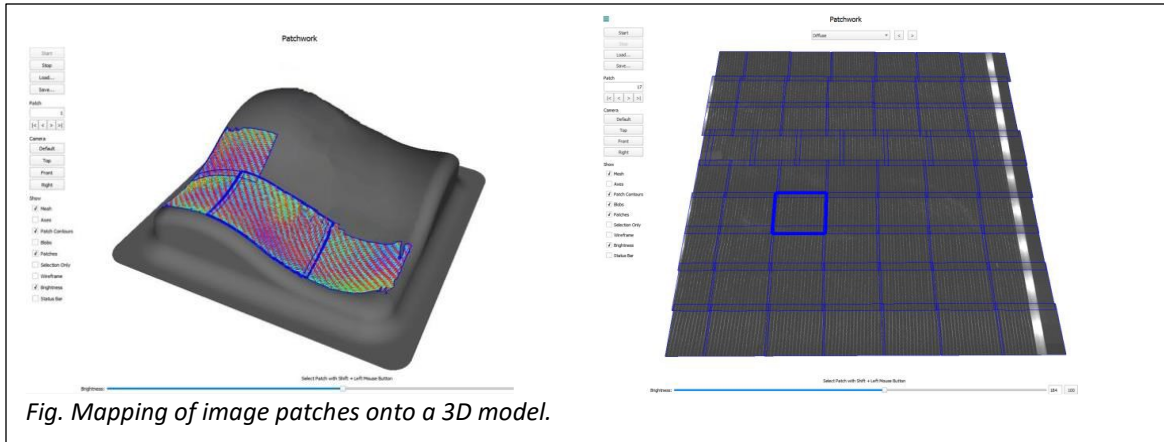


Fig. Mapping of image patches onto a 3D model.

However, the main pre-requisite for high-performance establishment of AI-based classification models remains the availability of large batches of data samples to support the training process of these models. Creating such data collection is a challenging endeavour, given that defect occurrence during production processes is not present in high frequency, and deliberate production of defective sample is an expensive and unwanted item for the manufactures.

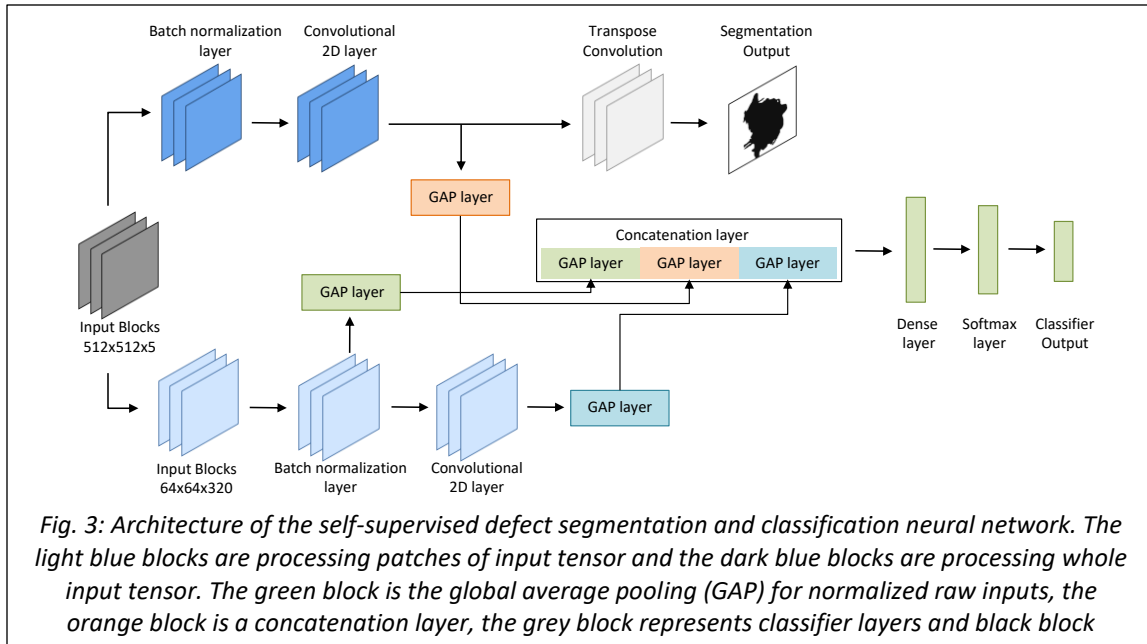


Fig. 3: Architecture of the self-supervised defect segmentation and classification neural network. The light blue blocks are processing patches of input tensor and the dark blue blocks are processing whole input tensor. The green block is the global average pooling (GAP) for normalized raw inputs, the orange block is a concatenation layer, the grey block represents classifier layers and black block

To tackle the aforementioned challenges, several iterations of the data acquisition and annotation processes were conducted to maximize the sample count for each defect category. Furthermore, comprehensive experiments were conducted, where a custom AI-architecture was designed and implemented to enable optimal segmentation and classification of various defects. The proposed convolutional neural network (CNN) architecture was iteratively optimized for accuracy, inference time,

parameters, and multiply-accumulate (MAC) operations, where enhancement in model’s performance was achieved through multi-head, multi-task neural network optimization. By creating a custom shared embedding model, the network reduced inference time and MAC operations, while the incorporation of a hard attention mechanism notably boosted the accuracy of defect classification.

Table. Performance comparison of training a classifier alone vs training in combination with segmentation network.

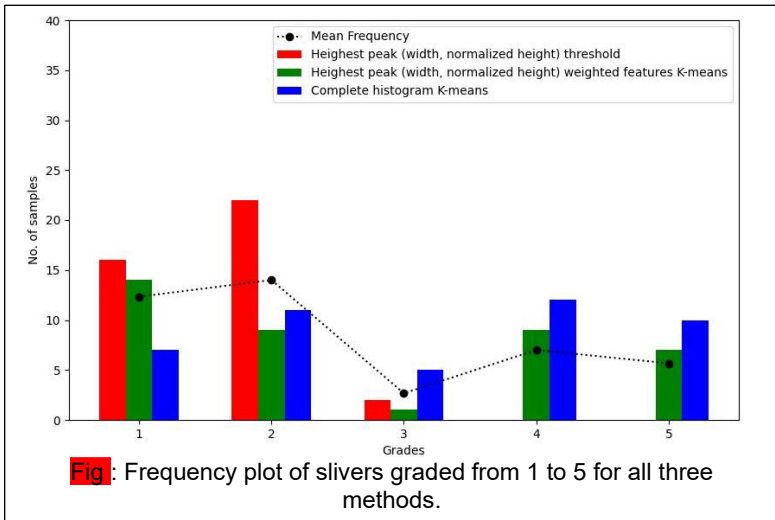
Scenario	Mean Accuracy for 100-fold
TopK Classifier Only	95.78
No TopK Classifier Only	82.19
Segmentation Pretrained + Classifier	81.05
Segmentation + Classifier Trained Together	92.36

The results demonstrated high ability to correctly classify various defect types, with evaluated performance of up to 92% accuracy. Additionally, the benchmarking analysis against standard AI models was conducted, where model built for the MC4 project purposes outperformed other models by up to 30% accuracy. This refined CNN architecture demonstrated a clear advantage in both efficiency and accuracy, making it a key advancement in the project’s objectives. The dataset created for this project is open sourced and available at Zenodo.

Table. Performance benchmark of defect classification only task.

Model	Size	Parameters	Accuracy (%)
Xception	88MB	22.9M	40.00
InceptionV3	92MB	23.9M	60.00
MobileNet V2	14MB	3.5M	40.00
Compact Convolutional Transformers [†]	2.68 MB	0.7M	42.00
CompactConvNet (ours)	143.64 KB	36,771	77.59

Given that the relationship between fibre orientation and the strength of carbon fibre composites is crucial for determining their mechanical properties and that the alignment of fibres within the composite directly affects its ability to withstand forces in various directions, the newly created (recycled CF) material had to be evaluated and graded. For this purpose, a dataset of ten sliver samples was collected. Each of the slivers was carefully sliced and examined from both interior and exterior side. The examination was done with the Fscan sensor, where fibre orientation angles are obtained. Three methods (feature-based thresholding, raw histogram k-means clustering and k-means with weighted feature computation) were designed and evaluated to estimate the sliver grading ability. The results for all the three methods are illustrated in the form of a bar plot for the directions (Inside and outside) of the sliver.



7. AUXILIARY PROCESSES FOR RECYCLING

Recycling methods, often focusing on fibre recovery, leave behind resin-rich waste fractions that are difficult to reuse. In the MC4 project, vitrimerization was proposed as a novel solution for transforming these waste fractions into dynamic, reprocessable materials, enabling circularity in composite recycling. This approach has been applied not only to the solid resin waste fraction coming from the shredding of glass fibre composites, but also to the liquid organic fraction (LOF) from the solvolysis of carbon fibre epoxy composites. To do so, both fractions undergo chemical modifications that introduce dynamic covalent bonds, allowing them to be reshaped, repaired, and recycled while maintaining their crosslinked structure.

As for the case of recycling glass fibre-reinforced polymer (GFRP) composites through shredding, this often presents significant challenges due to the inherent difficulty of reintegrating shredded composite waste into new polymer matrices. One of the main issues is the lack of adhesion and compatibility between the recycled shredded GFRP and fresh epoxy resin, which leads to poor mechanical properties in the resulting composite materials. To address this in the MC4 project, liquid chemical modifiers were proposed to be used as compatibilizers to improve the interfacial bonding between shredded GFRP and epoxy resin, enhancing the dispersion, adhesion, and overall mechanical integrity of the reprocessed composite.

7.1 Transformation of resin rich fraction through vitrimerization

7.1.1 Full circular process chain

The vitrimerization process was applied on the one hand to the resin rich fraction coming from the shredding of GF composite by VDL, and on the other hand to the resin rich fraction coming from GAIKER's solvolysis process.

In the former process, the EoL material is solid form and is composed of about 70 wt.% glass fibre and 30 wt.% epoxy resin. Because the fibre-resin separation is not economically relevant, the approach is to use this EoL material as it stands after shredding. CEA designed a vitrimer epoxy resin composed of anhydride and amino-alcohol hardeners that strongly catalyzes the ester bond exchange within the material. This vitrimer resin is intrinsically reprocessable. When mixed with the EoL material, the ester bonds of the epoxy vitrimer resin are capable to exchange with the ester bonds contained in the leftover resin on the fibre. Upon heating and compression, with the help of the chemical dynamic bond exchange, the two resins constitute only one covalently bonded network. The EoL material is therefore incorporated in the epoxy vitrimer resin, and then the final composite material also displays reprocessability capability for further recycling loops.

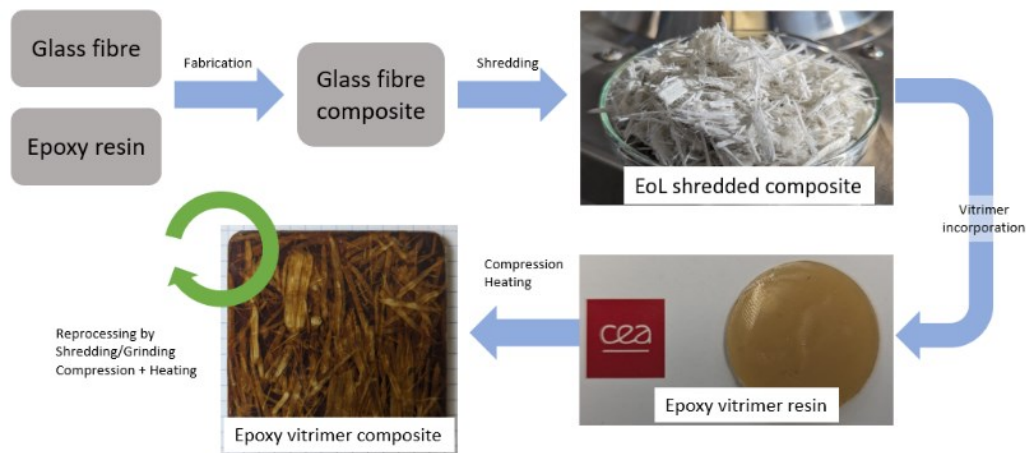


Figure 26 - Block diagram of the circular process chain for the valorisation of shredded glass fibre composite by vitrimerization

In the latter process, the resin rich fraction, obtained from GAIKER's solvolysis process, is an organic liquid fraction. The solvolysis process developed by GAIKER enables the recovery on the carbon fibre present in composites. This process also produces a liquid residue mainly composed of the solvolysis media (water and nitric acid), as well as salts and organic molecules generated by the degradation of the composite epoxy resin. The ideal circular process diagram for this valorisation route is presented in the figure below.

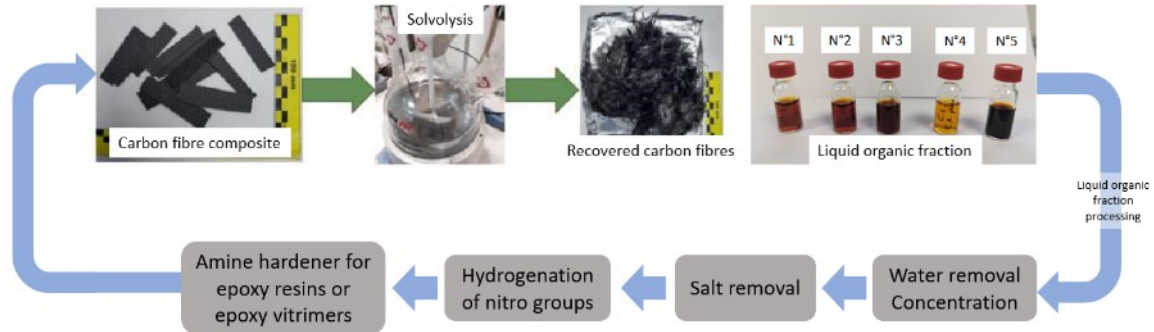


Figure 27 - Circular process for the valorisation of solvolysis organic fraction into amine hardeners for epoxy resins

Based on the feasibility study carried by CEA, it was shown that the liquid organic fraction contains high concentration of salt (198.3 g/L) due to the use of carbonates to neutralize the media after solvolysis. Also, the concentration of organic material from the initial epoxy resin is 16.7 g/L with a resin recovery rate 35.5 %. For that matter, it is essential to process the liquid organic fraction to remove salts and concentrate the solution. The study also demonstrated the presence of nitro groups on the organic molecule in the liquid fraction. This is due to nitration effect of nitric acid on the polymer chains of the epoxy resin. The nitro groups are valuable, because it is possible to convert them into amine groups by hydrogenation. These amines can then be used as hardeners for the cure of classic epoxy resins or epoxy vitrimers.

7.1.2 Evaluation of the materials

In the case of the vitrimerization of the resin rich fraction from the shredding of GF composite, the synthesis of a vitrimer epoxy resin was successful. The formulation using triethanolamine at a concentration of 0.75 mol/g of amine shown to be the toughest, with a T_g at 133 °C and with Young's modulus of about 2.2 GPa, ultimate strain of 7.8 % and stress of 100 MPa. Also, the vitrimer resin showed satisfactory reprocessing capacities, being able to be reprocessed in 15 minutes at 180 °C under a 240 bars pressure. At this temperature, the material shows good creep resistance with a viscosity of $2,5 \cdot 10^9$ Pa.s. These data are summarized in the table below.

	TEA 0,75 Vitrimer epoxy resin
T_g (°C)	133 °C
Young's modulus (GPa)	$2,25 \pm 0,44$
Ultimate strain (%)	$7,8 \pm 1,7$
Ultimate stress (MPa)	100 ± 20
Viscosity at 180 °C (Pa.s)	$2,5 \cdot 10^9 \pm 0,9 \cdot 10^9$
Reprocessing conditions	15 min at 180 °C and 240 bars

Table 4: Characteristics of the epoxy resin obtained after vitrimerization of shredded GF composite

However, the composite material mechanical properties could not be assessed. Indeed, the production of tensile specimens proved to be difficult, due to the presence of the fibres in the material. Laser-cutting

technic used previously for the non-reinforced resin failed because the laser was not capable of cutting fibres. Die-punching yielded poor quality specimens with poor edge quality. Nevertheless, we can assert that due to the shredding of the fibres, this composite will present lower performances than composites made of woven continuous fibres.

In what concerns the vitrimerization of the organic liquid fraction coming from the solvolysis process, its feasibility has been assessed by the complete analysis of the liquid residue. It was demonstrated that the nitric acid solvolysis process yields a product with a dry mass content of 215 g/L, of which 198.3 g/l are salts from the neutralization of the solution. The organic molecules represent only 16.7 g/L. This number is low, but it still represents a 35.5% resin recovery yield. Indeed, composite parts are composed of only 20 to 40 % resin in weight, so the total recoverable material is already low. In addition, the solvolysis proceeded in the degradation of the resin to allow fibre-matrix separation. It is then understandable that the final organic residue is found in low concentration.

In terms of composition, the solvolysis process spares partially the molecular backbone of the resin, as aromatic rings can be found, as well as esters and ethers. Finally, the solvolysis proceeded to the nitration of the residue, hence the presence of nitro groups. This is an important feature, as these groups can be hydrogenated to yield amines, that can be directly used as epoxy resin hardener, epoxy vitrimer monomer, or for further chemistry. The data of the liquid fraction analysis are summarized in the table below.

	Nitric acid solvolysis	Ideal organic fraction
Efficient fibre recovery	Yes	Yes
Dry solid (g/L)	215	>750
Salt (g/L)	198,3	<5
Organic fraction (g/L)	16,7	>750
Resin recovery yield (%)	35,5 %	As high as possible
Amines	No	Yes
Nitro	Yes	Yes
Ester and ethers	Yes	Yes
Aromatic rings	Yes	Yes
Aliphatic chains	No	Yes

Table 5: Data obtained from the liquid fraction analysis

7.1.3 Assessment relative to the expected outcomes

The properties of the vitrimer epoxy resin obtained from GF composite shredding residue are satisfactory, as it displays mechanical performances equal to classical epoxy resins, with the added reprocessability capabilities. Nevertheless, the impossibility within the project time frame to measure the properties of the composite materials obtained from this resin and the EoL shredded composite prevent from drawing a complete conclusion. Composite can be fabricated, but the good cohesion between the fibres and the matrix is an important point, that is usually evaluated with mechanical testing.

As for the analysis of the liquid organic fraction obtained from the nitric acid solvolysis process, it showed that the organic material concentration is low, and the salt concentration is rather high. This can be explained by the fact that the focus of this process is to recover clean and usable carbon fibres. In addition, the material requires additional chemical treatment, i.e. hydrogenation, to yield valuable amines. For an economically viable valorisation of the organic fraction, the salt removal as well as the concentration of the liquid by water evaporation is key to purify the material to be hydrogenated. Also, the optimization of the solvolysis process, by reducing the residence time of the composite and therefore the degradation state of

the organic molecules in the liquid fraction, would benefit to its valorisation, as more organic material could be recovered after the fibre-matrix separation.

7.2 *Compatibilization of shredded composite with epoxy resin via liquid chemical modifiers*

7.2.1 Full circular process chain

The developed process for surface modification of rCFs and rGFRPs aims to improve their compatibility with epoxy resins. In this study, modifications were applied to all materials following the same procedure, but with varying concentrations of modifiers. The primary difference lay in the selection of modifiers, as their functional groups were tailored to the distinct chemical compositions of the recycled products.

For the organosilicon treatment, the first stage involved preparing solutions containing the organosilicon modifier dissolved in isopropyl alcohol. The prepared solution was then combined with shredded rGFRPs and rCFs in a plastic container. The deposition of the modifier was carried out by spraying the solution onto the shredded fibres while continuously mixing the system to ensure even distribution. This procedure was repeated until the entire modifier solution had been applied. Following the modification process, the treated recycled materials were placed in a laboratory dryer at 55°C for 24 hours to ensure proper drying and adhesion of the modifier to the fibre surfaces. This step helped to enhance the interfacial bonding characteristics of the modified rCFs and rGFRPs, improving their overall compatibility with epoxy resins in composite applications.

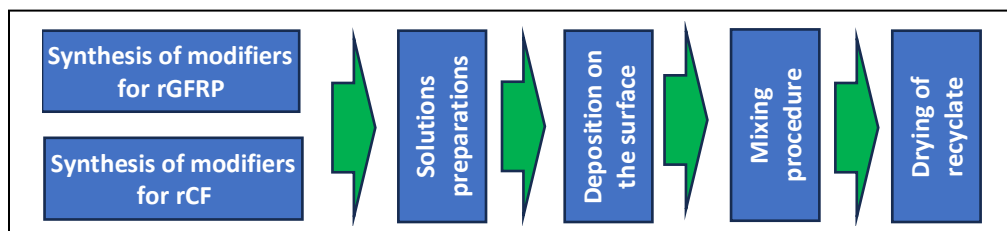


Figure 28: Material flow chart describing processing chain for modification of recycled materials.

7.2.2 Evaluation of the materials

Three different approaches (methods) for the surface modifications of shredded materials from different suppliers were investigated and composite samples for mechanical verifications were manufactured. Taking into consideration the obtained results, it was found that the method of spraying modificatory on the surface of shredded GFRPs according to developed method gave the best results in improvement of the compatibility between resin and shredded materials after chemical modifications. The highest improvement after application of some chemical modifiers on rGFRPs was noted over 100% in comparison to reference samples.

Based on the conducted studies, it was determined that the most effective method for treating rCFs, considering both processability and economic feasibility, was the surface treatment with liquid modifiers. Subsequent testing was performed with varying rCFs content to identify the optimal composition for mechanical performance. Among the tested samples, composites containing 50 wt.% of rCFs exhibited the highest mechanical properties, including flexural strength and modulus. Fabricated composite samples based on rCFs utilizing modifiers demonstrated the noticeable improvement of flexural strength. Despite this noticeable improvement in mechanical properties, such as increased flexural strength and modulus compared to unmodified samples, SEM observations of the composite samples showed that the liquid modifiers were unable to completely prevent the formation of dry spots and voids within the structure.

These voids had a detrimental effect on the mechanical properties, partially counteracting the benefits of the applied treatments and highlighting the need for further optimization of the fabrication process.

7.2.3 Assessment relative to the expected outcomes

In the case of auxiliary processes dedicated to shredded GRRPs and rCFs in the form of liquid modifiers, the obtained results answer especially following expected outcomes namely, EO3: Enhancing the use of recycled material and EO5: the project will demonstrate increased re-use of carbon and glass fibre parts and materials. The obtained results confirmed the positive effect of the synthesized modifiers in enhancing the compatibility between the reinforcement and the NOMA epoxy resin.

Comprehensive testing revealed that adding shredded rGFRPs materials without surface modification significantly reduced flexural strength compared to the reference pure resin sample. This confirms the positive impact of the designed modifiers and their beneficial effect on the mechanical properties of manufactured composites. That brings closer achievement of expected outcomes in both EOs, giving opportunity in wider exploitation of recycled materials for further design and development new components. However, modifying the resin with the developed liquid organosilicon modifiers with combination with rCFs brought only limited improvement of mechanical properties fabricated composites indicating poor compatibility between the rCFs materials and NOMA resins. Despite these limitations, the study demonstrates the potential of liquid modifiers to enhance composite performance in future applications allowing to reach aims of EOs. It also highlights the need for further refinement of current methodologies to improve the integration of rCFs materials. Future research should focus on optimizing modifier formulations to maximize both strength and reliability in composite applications and support of fulfilling EOs with those auxiliary processes.

8. PRODUCTS MANUFACTURED FROM RECYCLED MATERIALS

















	Final part	Source parts/materials	Technical Performance <i>(Properties retention rate; Properties versus commercial material, etc.)</i>	Economic impact (IRES, LCC) <i>(costs; investments, throughput, etc.)</i>	Environmental impact (IRES, LCA) <i>(climate change impact (%))</i>														
Automotive	 Bus side cover	Shredded GF composite Virgin epoxy resin	<table border="1"> <tr> <td>Property</td> <td>Retention ratio</td> </tr> <tr> <td>Weight</td> <td>86%</td> </tr> <tr> <td>Max. strength</td> <td>96 ± 10%</td> </tr> <tr> <td>Tensile strength</td> <td>125%</td> </tr> <tr> <td>Young modulus</td> <td>90%</td> </tr> <tr> <td>Bending strength</td> <td>100%</td> </tr> <tr> <td colspan="2">+low water absorption: 3% after 17 days, 23°C</td> </tr> </table>	Property	Retention ratio	Weight	86%	Max. strength	96 ± 10%	Tensile strength	125%	Young modulus	90%	Bending strength	100%	+low water absorption: 3% after 17 days, 23°C		Reduced total manufacture costs by 25% compared to aluminum benchmark.	Reduced total GWP impact by 52% compared to virgin composite benchmark
	Property	Retention ratio																	
Weight	86%																		
Max. strength	96 ± 10%																		
Tensile strength	125%																		
Young modulus	90%																		
Bending strength	100%																		
+low water absorption: 3% after 17 days, 23°C																			
	 Bus seat backrest	CF recycled from CF scraps Virgin vinyl ester resin Catalyst and additives	Suitable fibre compaction and appearance of the part. Optimal for moulding simple and flat parts.	Reduced material cost due to waste valorization	Reduced total GWP impacts by 62% compared to benchmark														
Boat building	 Boat T-Top roof	CF recycled from CF scraps, Green epoxy resin Catalyst from NOMA	Retention of mechanical properties below virgin CF and glass fibre virgin due to non-woven structure. Increased resin absorption, affecting weight and efficiency. Suitable for non-structural and hybrid applications.	Higher resin consumption increases production cost by approx. 20%. Recycled material costs are estimated to be higher than virgin GF. .	Reduction in CO ₂ emissions by 15% compared to Fibre Glass virgin part .														
	 Boat pedestal base	CF recycled from CF scraps Virgin vinyl ester resin Catalyst and additives	Difficult compaction of the pre-impregnated and not completely optimal appearance. Limitations with complex geometry parts	Reduced material cost due to the use of recycled CF from scraps	Reduced total GWP impacts due to substituting high-impactful virgin CF to recycled CF from scraps														
		<table border="0"> <tr> <td></td> <td>GF short-term</td> <td></td> <td>CF short-term</td> </tr> <tr> <td></td> <td>GF long-term</td> <td></td> <td>CF long-term</td> </tr> </table>		GF short-term		CF short-term		GF long-term		CF long-term									
	GF short-term		CF short-term																
	GF long-term		CF long-term																

Table: Some facts about the products made from recycled materials for automotive and boatbuilding










	Final part	Source parts/materials	Technical Performance <i>(Properties retention rate; Properties versus commercial material, etc.)</i>	Economic impact (IRES, LCC) <i>(costs; investments, throughput, etc.)</i>	Environmental impact (IRES, LCA) <i>(climate change impact (%))</i>						
Aerospace	 Leading-edge rib	Uncured CF composites scraps	Meeting aerospace requirements in terms of FVF (58%) and porosity (1.9%). Stiffness: 50% decrease at 0°; 60% increase at 90°. Tensile strength: 70% decrease at 0°, 50% increase at 90°. Compression: worse at 0°; better at 90°.	Reduced total LCC by 10% compared to virgin CFRP benchmark	Reduced GWP impacts by 75% compared to virgin CFRP benchmark						
Sports equipment	 Kayak paddle blade	GF composite parts based on 3R epoxy resin, trimmed from kayak.	Properties retention ratio > 85%. Good visual appearance despite some superficial wrinkles. Design to be improved for better fibre accommodation. Lower stiffness of 3R GFRPs versus benchmark.	Reduced manufacture cost by 61% compared to virgin GFRP benchmark	Reduced GWP impacts by 85% compared to virgin GFRP benchmark						
Urban furniture	 Soul urban bench	Shredded GF composite Virgin polyester resin	Composed of at least 50% recycled Content GFRP and 100% recyclable, it offers durability, weather resistance, and long-term outdoor performance.	Comparable cost to benchmark (slightly lower by 2%)	Slightly higher GWP impacts (6%) compared to benchmark.						
Civil engineering	 Joining collet	Shredded GF composite Virgin epoxy resin	50 wt% of shredded rGFRP material, saving of 50wt% in utilization of virgin epoxy and glass fibres. For 2.5 kg joining collet component saving of c.a. 1.2 kg raw materials.	Reduced materials cost due to raw material savings	Reduced GWP impacts by 40% compared to virgin GF joining collet (50wt% of GF and 50wt% of epoxy resin)						
Other	 Small composite part from BMC intermediate	Uncured CF composites scraps	By using 67 wt% of uncured prepreg scrap 50 wt% of CF is saved. <table border="1" data-bbox="743 1482 1003 1640"> <tr> <td>Property</td> <td>Retention ratio</td> </tr> <tr> <td>Tensile strength</td> <td>> 100%</td> </tr> <tr> <td>Flexural strength</td> <td>> 94%</td> </tr> </table> Fibre length: 12mm for benchmark 5-25mm for rBMC	Property	Retention ratio	Tensile strength	> 100%	Flexural strength	> 94%	Reduced materials cost due to the use of uncured prepreg scrap	Reduced GWP impacts by 88% compared to virgin BMC part
Property	Retention ratio										
Tensile strength	> 100%										
Flexural strength	> 94%										
		 GF short-term  GF long-term	 CF short-term  CF long-term								

Table: Some facts about the products made from recycled materials for Aerospace, Sports equipment, Urban furniture, Civil engineering, and some other demo.

9. SUMMARY & CONCLUSIONS

The MC4 project has been dedicated to developing both short-term and long-term circular economy strategies for carbon and glass fibre composites, aiming to reduce waste, enhance material recovery, and promote sustainable manufacturing practices.

Within the Carbon fibre approach - short-term, the project results have demonstrated the possibility to reuse waste material generated during the production process. This involves repurposing cut-off or excess carbon fibre materials before they are cured, integrating them back into the production line either as new components or intermediate products such as BMC material. From this approach, two demos were obtained: one leading-edge rib for the aerospace sector, and a small composite demonstrator from rBMC intermediate.

As for the carbon fibre approach - long-term, a chemical recycling process was developed that recovers fibres from cured and end-of-life carbon fibre parts, with some limitations. Indeed, while this process ensures minimal fibre degradation, it also removes the initial fibre sizing, making difficult the subsequent transformation process toward high-quality recycled yarns, rovings, mats, and fabric for new applications. Due to some delay in the obtention of adequate quantities of rCF from solvolysis, the recycled CF transformation processes were developed and tested with CF scraps coming from CF fabrics manufacturing. In the same way, several demos were obtained from the reuse of CF scraps: one boat T-top roof and one boat pedestal for the nautical sector, and one bus seat backrest for the automotive sector.

In the glass fibre approach – short-term, the MC4 project focused on the development of mechanical recycling techniques allowing shredded glass fibre material to be incorporated as filler into new components. This method enables the reuse of cured waste without requiring complex separation processes. From this recycling route two demos were achieved with good results: one bus side skirt for the automotive sector, one joining collet for the civil engineering sector, one bench for the urban furniture sector.

In the glass fibre approach – long-term, the MC4 project results showed that the use of a new type of resin (vitriimer), instead of the traditional epoxy resin, in the manufacturing of GF composite parts allows reshaping and repurposing of end-of-life parts without the need to separate the matrix from the fibre. This innovation ensures that composite components can be remoulded and reused in various applications, enhancing the circularity of glass fibre products. The demonstration of this recycling process gave rise to two demos: one vitriimer/GF composite made from virgin materials, used for the demonstration of the full process toward the demo made from recycled GF composite material. Both demos are composite parts for the sports equipment sector.

In addition to developing recycling processes, complementary techniques were explored to maximize waste reuse.

- Resin waste transformation into Vitrimers: research focused on repurposing solid resin waste from shredded glass fibre composites and the liquid organic fraction from the solvolysis of carbon fibre epoxy composites. This approach aims to give these waste fractions a second life by converting them into vitrimers, enhancing their potential for reuse.
- Enhancing epoxy/shredded glass fibre composites: to optimize the performance of recycled shredded GFRP in combination with fresh epoxy resin, the use of liquid chemical modifiers was investigated. Results demonstrated that these modifiers significantly improve dispersion, adhesion, and overall mechanical integrity, leading to better compatibility and performance in reprocessed composites.

To address other key challenges in composite recycling, advanced technologies were developed for upstream sorting of composite parts and downstream quality grading of recycled carbon fibre products.

- Spectroscopic sorting technology: this innovation significantly improves the efficiency, quality, and sustainability of the recycling process by precisely identifying different resin types—including

vitrimers—before they undergo matrix/fibre separation (solvolysis). By ensuring that each material follows the most suitable recycling pathway, this system enhances overall process effectiveness.

- AI-driven quality grading: a real-time, automated quality assessment system was developed to evaluate recycled carbon fibre mats and fabrics. This AI-powered technology ensures that recycled materials meet the required standards for various applications, increasing their reliability and usability in new products.